Groundwater Economics

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CRC Press
Taylor & Francis Group

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Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Cover photo: Maryland Geological Survey

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

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Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number: 978-1-4398-0900-6 (Hardback)

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Library of Congress Cataloging-in-Publication Data

Job, Charles A.
Groundwater economics / by Charles A. Job.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-1-4398-0900-6
ISBN-10: 1-4398-0900-3
1. Groundwater--Economic aspects. 2. Water resources development--Economic aspects. I. Title.

HD1691.J63 2010
333.91'04--dc22 2009018916

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This book is dedicated to Avery, Gavin, Sadie, Kylie,
and all the children of the world with the hope that
they will have the water they need!

…And he who waters will also
be watered himself.

Proverbs 11:25

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Preface

Studying groundwater as a hydrologist, one knows that it is considered ubiquitous under the continents, but it varies significantly in depth, quality, accessibility, and availability. Groundwater is essential to the existence of all forms of life, and it has substantial value where alternative sources of water do not exist. Because groundwater is stored below the Earth's surface, many people really do not understand it or its economics. However, in the face of significant competition for surface water and groundwater, for the subsurface environment, from growing populations with tremendous thirst and need for food, we are all most likely to experience the value of groundwater at some point of time.

I remember as a boy in the 1950s, my parents would be concerned during long, hot summers when the creek behind and about eight meters below our house would go dry, and they would wonder whether the well at about 11 meters deep would be deep enough to reach groundwater. We would use less water, changing our activities to respond to our circumstances. They were also concerned about whether the septic tank was operating properly at different times. Each day we would assess as best we could whether we had sufficient water from the ground and whether the water was safe. At the margin of our water use, its value was high and received much of our attention. In their own way, my parents recognized the relationship between the water in the creek and the water in their well. We know today that these relationships hold and that these are global concerns. While one billion people around the world do not receive safe water, groundwater is pumped for irrigation in other places as if it will always be available. Clearly, people from different regions are affected differently by the apparent abundance of groundwater or the lack of it.

Another perspective on groundwater relates to my boyhood community and some businesses' use of the underground environment. We appreciated the few businesses that employed local people. They followed the practices of the time, some of which are not accepted now as the standard way of conducting these activities—a metal barrel–cleaning site and commercial activities using and disposing of solvents on-site. At that time, the community had no central water or wastewater treatment systems and relied on individual wells and septic systems. The drum cleaning site near residences on wells was declared a Superfund site. The practice of disposing of solvents at another site later contaminated a local stream and interceptor wells were installed to capture the contaminated groundwater. Fortunately, the community has had a wellhead protection program for a number of years now. Basically, the disposal capacity of the subsurface was treated as having no cost to use and no value associated with using it. These conditions occurred across the country in communities that were trying to do their best with whatever resources and understanding they had. However, at the time, out of sight meant out of mind. But the marginal cost became high.

Today, nations talk of the transboundary use of groundwater and the impacts that this may have on their residents and local economies. Additionally, they explore the use of the deep geologic strata to dispose of unwanted carbon dioxide that has now reached dangerous levels in the atmosphere and is threatening the way we and our communities live through climate change. Businesses using these groundwaters and organizing to dispose of these waste gases are likely to profit most, benefitting from the low value placed on groundwater that moves under property and national boundaries and on the effects of the disposal in what appear to be otherwise unusable zones of the inner Earth.

This book examines the use, the value, and the vulnerability of groundwater, the aquifers that contain it, and the ecosystem that cycles it for many purposes, some of which we may not currently understand. It does not include new material—it just tries to assemble under one cover most of the existing salient concepts related to groundwater and its economics and use. This book also attempts to document the known costs from a range of sources for development, and the effects of groundwater production and of disposal in the subsurface environment. It attempts to review the subjects and associated references comprehensively but does not provide an exhaustive coverage. It explores and describes the economics of different policy instruments and management approaches to dealing with groundwater use and protection. A central point in the book is that the economic analyses supporting policy development and decisions about groundwater resources should be based on an understanding of groundwater as a component of the larger hydrologic cycle and ecosystem and not on consideration as a separable water domain, which would result in narrow, incomplete and inadequate findings and determinations. The final chapters consider the longer term and the need to look for approaches that will sustain groundwater as a resource among many on which we rely as individuals, corporations, and nations—a resource that our children and their children may increasingly turn to in a very different world in the future.

One point clearly emerges in considering the application of economics to groundwater: groundwater economics is an interdisciplinary field. By necessity it draws on micro- and macroeconomics, hydrogeology, engineering, law, biology, planning, and management, just to name a few of the disciplines key to its understanding and application. The groundwater economist must take a "team" approach to apply his or her techiques usefully to the complex circumstances of groundwater use.

It is my hope that others will build on this book and improve the concepts in it to ultimately become a central part of any community's or nation's resource and ecosystem planning for generations to come and not just for today. I hope that it might be part of a university curriculum for ecological economics, environmental and resources management, and water resource engineering to train future economists, managers, and engineers to carefully consider groundwater in their future positions affecting society. As more people, businesses, and governments compete for the resources that the ecosystem provides, these resources will become more scarce and valuable, and we must become more innovative and creative in their allocation and use to ensure that they will continue to be available to all those who need them.

Charles A. Job

Acknowledgments

Many people have contributed to this book, either knowingly or unknowingly, and I thank them all, but it would be too extensive to mention each one individually. However, I need to identify certain specific individuals who have provided me with encouragement, insight, and suggestions. Most significantly, I am indebted to my wife, Susan, and my family for allowing me to pursue an idea that I had nurtured for 25 years and most intensely for the past 10 years. Next, my father, Richard, encouraged me to enter the environmental field when it was just beginning to be recognized as a focus of study and professional application. My groundwater geology professor, Dwight Baldwin, provided further encouragement. Fletcher Driscoll provided heartening support at different times that gave meaning to what I was doing. Mary Jo Kealy, a coworker in environmental and resource economics, provided positive feedback on the project at its beginning and at its conclusion. John Bergstrom, a groundwater economics professor and fellow coauthor of an article on groundwater economics, gave key perspectives on the completeness of the text. George Hallberg provided encouragement and feedback that helped get the manuscript across the finish line. Irma Shagla, Jill Jurgensen, and Richard Tressider at Taylor & Francis have been most supportive whenever I needed them to be. To you all, I thank more than written words can express!

Author

Charles A. Job grew up in southwestern Ohio drinking water from three domestic wells as his family moved locally in the community of Beavercreek, remembering the great attention the wells and water levels received during dry years. He completed his BS in social science at Michigan State University, his master of environmental science at Miami University, and his master of applied economics at the University of Michigan. Early in his career, Chuck worked on Great Lakes water issues, and then briefly for two Fortune 500 companies, consulted on groundwater matters, and joined the Environmental Protection Agency, in 1984, in its Chicago Regional Office, and then, in 1988, in Washington, D.C. He completed one of the first published cost–benefit analyses of wellhead protection. Currently, he serves as a manager for drinking water system financial assistance, data management, communication, and training. Chuck has authored or coauthored over 40 articles and publications on groundwater and water resources. He is a member of the National Ground Water Association, and serves as a column editor/coordinator for its quarterly journal. He is also a member of its Economics Interest Group and of the American Water Works Association.

Part I

Introduction

1 An Introduction to the Economics of Groundwater

Groundwater—some distance under our feet, available in most places around the world from a well, viewed by some people as having mysterious qualities, often not clearly understood but providing useful as well as ignored services—is a vast resource being increasingly tapped for people's vital uses, becoming ever scarce, and growing in value. It constitutes both an economic opportunity as well as a challenge.

The economics of groundwater is not about an arcane science applied to a liquid substance. It is about people using this significant resource in a multitude of ways for everyday needs. It is about people's decisions regarding their use of groundwater and the factors that influence their choices. The economics of groundwater concerns information affecting the allocation of a resource that is largely not well understood by most people, and yet used directly or indirectly by much of the world's population, affecting some people's health and survival.

BACKGROUND

All water is not the same—this may seem obvious—but is different depending on its temporal location in the hydrologic cycle, and, thus, is treated differently in societies' economic transactions. The largest available source of freshwater is groundwater, and is often an afterthought in developmental plans. In watersheds, it is the principal manifestation of the presence of water—a distinguishing characteristic of the earth which is essential for all life—even maintaining the flow of rivers and streams at times without precipitation. Its existence and access by wells make the human life in areas of the watershed away from streams possible at less cost than installing pipes for water transmission. It may literally be "in my backyard" for many people, even though they do not use it near their homes. As the water of many streams is used for drinking, irrigation, navigation, pollution management, and as a habitat for fish and wildlife, groundwater has likewise been used to provide water for the purpose of irrigation and drinking, the largest economic uses of the resource, and supports these other purposes. Groundwater is in demand and its sustainability for future generations is challenged through its expanding use—as both a source of water for all lifeforms and a sink for wastes. We can use it wisely by incorporating its value through consideration of all the major effects of its use in our economic decisions on a regular basis.

Groundwater has several advantages for water supply (Foster, 1996; Llamas and Custodio, 2003):

- Easily accessible and capable of being captured and managed by individuals or small groups of people.
- Available over extensive areas, most often being developed where needed, rather than installing long transmission lines, and in a staged approach.
- Less expensive and less capital intensive to develop than surface water in most situations.
- More reliable in dry seasons or droughts because of the large storage capability.
- Generally of adequate chemical and microbiological quality with little treatment needed if unpolluted.
- Less affected by catastrophic events.
- Often uniquely provides people with limited means, the capability to sustain life in locations having less essential resources and constrained opportunities.

Why are thorough informative economic analyses necessary for groundwater and all sources of water supply and waste sinks? While groundwater has many advantages, a competition exists for subterranean resource services because:

- Increased demand for groundwater has resulted in measured significant declines in water tables in every European Union country (AGSE, 2007), and in principal aquifers in nearly the entire United States (USGS, 2009).
- Groundwaters have experienced pollutant degradation in every state of the United States and in all the countries of the European Union.
- The growing water demand will drive up the value, with prices likely to rise where water is a tradable commodity.
- Biofuels production may require more groundwater for irrigation and increase the potential for agricultural chemical contamination of the aquifers.
- Groundwaters with naturally occurring arsenic and radioactive substances as well as brackish and saline sources in locations where freshwater is scarce will need to be treated, generating wastes that are often disposed underground.
- Heavy groundwater withdrawals of surficial aquifers may lead to reduced discharge to streams for their baseflow maintenance.
- Using up one source may affect the other sources—with surface sources fully allocated in many regions, more demands fall on groundwater—brackish and ever deeper inland sources in more arid areas, and the oceans for coastal communities.
- Disposal of salts and other minerals from brackish, saline, and sea-water treatment adds to production costs with disposal locations increasingly being considered underground.
- Hydraulic fracturing of deep geologic formations to produce natural gas may require enormous amounts of groundwater which, when produced in the gas drilling process, has toxic contaminants to be treated before disposal.
- Disposal of huge volumes of carbon dioxide in deep geologic formations to mitigate climate change results in further demand on the subsurface portion of the ecosystem and could threaten acidification of overlying groundwaters used for drinking if the disposed carbon dioxide migrates.
- Brackish and saline groundwaters are being considered as disposal zones for carbon dioxide.
- As subterranean brackish and saline groundwater sources are not being recharged by fresh precipitation, they may not be of sustainable use although significant in volume.
- Sea level rise from climate change may motivate the coastal communities to move to inland sources owing to saltwater intrusion in coastal aquifers or to seawater as a source treated through a desalination plant.
- Reusing water may be critical and cost-effective where it receives treatment compatible with other human uses from irrigation to drinking water.
- Infrastructure and activities associated with producing groundwater and managing residuals underground compete with other subsurface activities consuming resources such as mining and energy production.
- Groundwater and the subsurface environment are under stress and their products that provide services are becoming more scarce.

Thus, the water supply chain has become more complex—and water is used for many purposes, necessitating thorough analyses of its economics in each case to be intentional and fully informative of the many effects of not only its potential immediate use but also its more distant impacts on others using water within the watersheds and across adjacent and distant watersheds from which groundwater may flow and wastes may migrate.

Exhibit 1.1 presents a further perspective on the physical, ecological, and socioeconomic characteristics of groundwater that may be compared with alternative water sources. The exhibit

EXHIBIT 1.1 PHYSICAL, ECOLOGICAL, AND SOCIOECONOMIC CHARACTERISTICS OF GROUNDWATER SOURCES

The table below provides the less-understood features of groundwater resources.

Characteristics	Groundwater Description
Hydrogeological	
Storage volumes	Very large storage capacity in aquifers
Resource areas	Ubiquitous under continents
Flow velocities	Very slow, often measured in millimeters, centimeters, or meters per second
Residence times	Measured in decades/centuries depending on the geologic strata and depth
Drought propensity	Typically low depending on the duration of drought
Evaporative losses	Considered low and localized
Resource evaluation	High cost with significant uncertainty with unknown features underground
Production impacts	Occur over periods of time, often dispersed with cumulative effects
Natural quality	Usually high, depending on the nature of the geologic formation
Pollution vulnerability	Variable natural protection, affected by concentrated pollution releases
Pollutant persistence	Often long-lasting
Ecological	
Habitat	Variable with depth
Biodiversity	Wide range, with predominant microscopic species, except in Karst that has macrospecies
Biomass	Very large and vary with depth
Functions	Not fully understood, especially when considered with its containing subsurface environment
Socioeconomic	
Public perception	Resource is mythical, unpredictable, and often forgotten
Development cost	Modest investment is required for most individuals and communities, higher for very large volumes of water needed
Development risk	May be less than often perceived, but depends on the location and impacts on others
Style of development	Typically mixed public and private finance with individual or community operation
Project promotion time	Usually short-to-moderate depending on the project size and availability of water
Irrigation efficiency	Frequently high, depending on the rights to access and availability

Source: Adapted from Foster et al., 2000, p. 2, citing Llamas, M.R., *Water in 21st Century: A Looming Crisis*, UNESCO Congress, Paris, France, 2, 1–20, 1998.

reflects the points mentioned earlier, and suggests that groundwater may be a resource of more flexibility in use with lower developmental cost, while having potential vulnerability.

As a resource, groundwater is often used without charge or cost to the user. Its presence enhances the value of the property under which it lies—yet it can flow away. By flowing in the subsurface—albeit slowly—it carries issues with its use, both as a water source and a waste sink, beyond the property and national boundaries. Thus, it is one of the less visible components of the hydrologic cycle that may supply as much as half of the world's population with drinking water (Llamas and Custodio, 2003, p. 14; UNESCO, 2003, p. 78). Groundwater has become the fastest growing source of additional irrigation water for food production, a critical issue with our planet's expanding population (UNESCO, 2003; Brown, 2004, p. 100). Furthermore, groundwater has contributed to alleviating poverty and public health problems (Llamas and Custodio, 2003, p. 17), while serving as the foundation of the "green agricultural revolution" in Asia (Foster et al., 2000, p. 1; UNESCO, 2003, p. 78). However, once polluted, it is difficult and expensive to clean up for other uses and, in some cases, may cost billions of dollars.

The supply of groundwater is vast—99% of the world's available freshwater exists underground (Gleick, 1996). If it exists under nearly all land and is so ubiquitous, how can groundwater be an issue worthy of economic analysis and discourse? Yet, as Benjamin Franklin stated: "When the well's dry, we know the worth of water," part of the answer lies in the fact that groundwater is subjected to the vagaries of nature—precipitation (or lack thereof), differences in soil types and geological strata, both locally as well as regionally, and use by other people and industry for a range of purposes—some using a small amount of groundwater, while others requiring enormous quantities. Water, as we all know, is essential to life—not just human life, but all forms of life, existing on the ground surface or thousands of meters below it, including the microorganisms. Groundwater is an alternative source to surface water, which often maintains the streamflow, especially when it is not raining, and may be the only water source for many people, animals, and organisms in various locations. Wetlands maintained by groundwater provide habitat for much wildlife, including endangered species. In some places or times, groundwater—or any water—may be scarce, for example, in Saharan Africa or during a drought. Furthermore, rapidly increasing use of groundwater may make it even scarcer and, therefore, the economic evaluation of groundwater has been a focus in recent years. Irrigation uses the greatest quantity of groundwater, resulting in tremendous demand on the resource in particular regions of the world, often mining and depleting it—increasing its scarcity.

The availability of groundwater has health effects associated with its use. Beyond the human body's basic need for water, groundwater may contain trace amounts of minerals (e.g., potassium) that could enhance health. On the other hand, other minerals in higher concentrations may be harmful to humans (e.g., arsenic that can cause digestive and neurological problems) (ATSDR, 2003) and animals (e.g., selenium that can produce neurological and reproductive effects and cause death) (Cornell University, Department of Animal Science, 2001). As groundwater is often obtained through a well, there may be associated costs for having access to it. As more people install and pump more wells, they may interfere with each other's use, requiring laws to assist in guiding its withdrawal. In situations where wastes are disposed of or chemicals are applied on or under the ground surface, precipitation and percolating water in the soil can carry these substances deep into the earth reaching the groundwater of an aquifer, the zone where the minute spaces between the rock grains are saturated with water. As a result, a cost to remove the unwanted substances may be incurred before groundwater is safe to drink or use for other purposes in these circumstances.

Thus, we have all the factors needed for economic analysis—supply, demand, effects on other people and the ecosystem, and increasing scarcity—as well as questions, such as: at what cost? What is the value of the resource? In what quantity? For what quality? At what price? Where? When? What is the balance of supply cost and consumer price, irrigation of intensely farmed cropland versus community water supply, or loss of aquatic and wildlife habitat owing to groundwater mining?

This text attempts to aid both the economic analyst and the noneconomist hydrologist, engineer, and planner in addressing these and other questions. The presentation of economic information and concepts provides guidance for those not as knowledgeable in the foundations of economics to consider the broader sociopolitical-economic implications of their activities. At the core of considering the relation of economics to groundwater issues is a basic understanding of hydrogeology. These core concepts are included in this text for the economist to relate his or her detailed knowledge of the economics discipline to the groundwater portion of the ecosystem and its hydrologic cycle.

APPROACHES TO ECONOMIC ANALYSIS RELATIVE TO GROUNDWATER

The main purpose of economic analysis, whether applied to groundwater development or other evaluations, is to inform a decision maker—an individual deciding between drinking groundwater from a tap and drinking spring water from a bottle, a company evaluating whether to drill a deeper well for a more reliable source of water or to institute water treatment and reuse, a farmer debating on continued rain-fed agriculture or investment in irrigation equipment, or a government considering the options of raising water prices and adopting tax incentives to promote efficient water use to extend infrastructure life. The application of economics to this range of decisions assists in providing additional information to people or groups about the allocation of scarce productive resources (such as money, time, water, or land) among alternative and competing ends over place and time (Samuelson, 1964; Daly and Farley, 2004). It is the interaction of the people trying to satisfy their needs with the ecosystem that supplies the materials available in limited quantity to address those needs that create the scarcity: which needs should be satisfied, in what priority, applying which and *how many* resources, over what timeframe—what is the balance?

The field of economics has matured since the time of Adam Smith (author of *The Wealth of Nations* in 1776, which provided the principles of political economics; see Exhibit 1.2) and has a range of subdivisions useful for evaluating the allocation of groundwater resources. Beginning with Adam Smith, who was concerned about the value of land among other subjects, the *classical economics* school of thought has evolved from the late 1700s to the early 1900s, focusing on the theories of market value and the functioning of market economies, emphasizing economic growth, free competition, and the pursuit of individual self-interest to maximize benefits to society (Farlex, 2005; ENI, 2006). It had a strong cost basis for value (Farlex, 2005). In classical economics, an economy is always in equilibrium, balancing supply and demand through matching prices accepted by both buyer and seller, or moving toward equilibrium (ENI, 2006). The concepts of classical economics can be used to relate supply of groundwater to demand for it when it is sold and purchased at a competitive or market price.

Neoclassical economics subsequently established mathematical relationships and a model of the function of an economy. This branch of economics developed the perspective that people reveal their utility for goods through transactions in the market, which tends to balance supply

EXHIBIT 1.2 ADAM SMITH'S PARADOX OF WATER AND DIAMONDS

Notably, Adam Smith suggested the Paradox of Water and Diamonds, which seems to be well suited to the initial considerations of the application of economics to groundwater. The paradox as stated by Smith is: "The word value, it is to be observed, has two different meanings, and sometimes expresses the utility of some particular object, and sometimes the power of purchasing other goods which the possession of that object conveys. The one may be called 'value in use;' the other, 'value in exchange.' The things which have the greatest value in use have frequently little or no value in exchange; and on the contrary, those which have the greatest value in exchange have frequently little or no value in use. Nothing is more useful than water; but it will purchase scarce any thing; scarce any thing can be had in exchange for it. A diamond, on the contrary, has scarce any value in use; but a very great quantity of other goods may frequently be had in exchange for it" (Smith, 1976, pp. 32–33).

The current economic answer to Smith's paradox is that demand creates value based on utility (or use). An individual tries to maximize their total utility or satisfaction. The answer also depends on how much of one or the other a person starts out with. If the person is very thirsty, a unit of water is greatly valued. Once the thirst is quenched, another unit of water is of less utility and the person will have less demand for it right now. A diamond is a beautiful stone and may satisfy other utilities of the individual, but not thirst. However, its utility may be greater than the second or third or fourth unit of water, and at that point, the diamond has utility value for which the person is willing to incur its price.

Source: Smith, A., *An Inquiry into the Nature and Causes of the Wealth of Nations*, The University of Chicago Press, Chicago, IL, 1976 (originally 1776), 568.

and demand through prices and is therefore an efficient place to allocate scarce resources toward productive ends (Daly and Farley, 2004; ENI, 2006). This school of thought is focused on the utility and value of adding one more unit at the margin of production or other activity (ENI, 2006). Methods refined in neoclassical economics assist in analyzing the effect of producing one more unit of anything, including groundwater. This is referred to as marginalism or marginal analysis (Young, 2005, p. 18).

In the 1980s, *ecological economics* emerged, becoming a distinct branch of economics addressing the relationships between ecosystems and economic systems. The economy is "conceived as a subsystem of the earth ecosystem that is sustained by the metabolic flow or throughput from and back to the larger system." It recognizes that "a good allocation of resources is efficient; a good distribution of income or wealth is just; a good scale [an appropriate physical size of the economy relative to the containing ecosystem] is at least ecologically sustainable." The latter point is not acknowledged in standard (neoclassical) economics (Daly and Farley, 2004). The concepts of ecological economics focus on examining the effects of alternative resource consumption and transformation strategies on the sustainability of the ecosystem, and, in this case, of groundwater resources.

The subdisciplines of microeconomics and macroeconomics operate within each of these branches of economics. *Microeconomics* focuses analyses at the level of the consumer, household, and firm, which communicate their decisions by responding to the prices of goods and factors of production in the market—balancing supply and demand—to allocate scarce resources among the alternative uses (Samuelson, 1964; Bannock et al., 1979; Daly and Farley, 2004). For groundwater, microeconomics addresses the economic actions of water consumers, water production companies and utilities, and firms that dispose wastes into the subsurface. *Macroeconomics* comprises the relationships among "broad economic aggregates, the most important of which are national income, aggregate saving and consumers' expenditures, investment, aggregate employment, the quantity of money (money supply), the average price level [across an economy], and the balance of payments [relative to foreign trade]" (Bannock et al., 1979). A primary focus of macroeconomics is on the evaluation of government policies relative to expenditures, taxation, and money supply, including interest rates. Farm income derived from irrigation and subsidies supporting groundwater production are the subjects of national policies of central governments around the world. However, extensive discussions on these economic subdisciplines are beyond the scope of this text. Many fine references on these subjects are broadly available.

Within the subdiscipline of microeconomics, various fields of study and analysis have evolved which are also relevant to the consideration of the economics of groundwater: natural resource and environmental economics. *Natural resource economics* examines the economic consequences of decisions and policies affecting the biotic and abiotic "endowment," particularly, as these effects relate to the property rights in resources and efficiency of the resource use in specific settings or broadly at a macrolevel (Howe, 1979). Howe (p. 2) noted the importance of evaluating "interactions with other systems and potentially irreversible changes" and provided a useful example of the breadth of consideration in natural resource economics: "When coal is stripmined, flows of groundwater may be interrupted and streams and wells may permanently go dry. Acid from sulfur exposed to rain and air may foul water supplies and kill plants and fish."

Environmental economics encompasses the economic significance, causes, and incentives to "slow, halt, and reverse" environmental degradation (Turner et al., 1993), such as pollution of groundwater and effects on adjacent groundwater and surface water users as well as on the ecosystem processes relied on by all lifeforms. Environmental degradation often cannot be accounted in monetary terms, although money is a convenient measure. The value of environmental processes, and their quantification even in nonmonetary units, may be considered and arrayed with pecuniary measures. An important focus of environmental economics is on governmental policy affecting the actions and property rights of individuals, firms, and jurisdictions engaged, or potentially, in activities that may result in environmental damage or change.

Owing to the fact that natural resource, environmental, and ecological economics have aspects that are related and overlap each other, the distinction is, to an extent, a matter of emphasis: production, degradation, and ecosystem effects, respectively. These related economics fields reflect the evolution in the field, from addressing the basic needs for water supply to other effects at or near the point of use and subsequently to recognition of the larger natural interactions and processes that provide the materials of interest and scarcity. This text draws on all three fields by necessity. As Daly and Farley (2004) noted, resources used by people are provided by, withdrawn from, and employed in the ecosystem; transformed to some useful state or product; and, once used or worn out, returned to the ecosystem; with each step potentially or actually changing the ecosystem and the future interaction of people with it. The issue posed by these circumstances for the relevant fields of economics is: can the tools of economic analysis inform any resulting decisions and policies and assist in providing a sustainable future for humankind in the ecosystem that we call Earth?

The approach of applying economics within these fields considers empirical measurement of effects, referred to as "positive" economics, and policy evaluation, referred to as "normative" economics. Normative economics relies on the results of positive economic observation and measurement, as well as forecasts derived from those measurements, regarding the exchange among individuals, firms, and central governing authorities, such as changes in prices or income and their effects on water demand, in this case. Normative economics seeks to evaluate whether improvements resulting from changes in policy or decisions, such as reductions in pollutant release or the addition of another production well should be conducted from an efficiency perspective. As normative economics has broad societal implications, it is also referred to as "welfare" economics. Normative economics, as practiced, for the most part, has a base in Utilitarian ethics (Young, 2005, p. 18). Thus, it provides the decision maker or policy analyst with information in monetized form of changes in the welfare to society from the proposed actions: how large are the benefits and costs and who receives or bears them? (Young, 2005, pp. 17–18).

Groundwater is one "slice," one component, of the ecosystem which is heavily relied on for daily living and survival by hundreds of millions of people and innumerable other animals, aquatic life, and microorganisms, many on which we unknowingly depend. In a larger sense, for the shallow subsurface water, groundwater is more a condition of water with regard to the hydrologic cycle. Some groundwater is stored in deeper ancient aquifers (water-saturated rock formations) which are being drawn on and not replenished; other groundwater nearer the ground surface and being pumped is renewed with precipitation or artificially recharged from other water sources. These groundwaters that move through the hydrologic cycle get mixed with the surface water in streams, lakes, and coastal areas or get evaporated or transpired by plants once drawn from their root zones. This water returns to Earth as precipitation, either running off to streams or infiltrating the ground again. People intercept water that is stored or is moving through the hydrologic cycle for a range of purposes and services, the consequences of which can be evaluated using the tools of economics, as well as the techniques of other disciplines, depending on the necessity.

Hence, at this point, one might ask: if all these tools exist for economic analysis, why should a text be devoted solely to the economics of groundwater? The answer is multifold:

1. Most texts addressing natural resource economics cover a range of biotic and abiotic resources and often have limited or no mention of groundwater.
2. Similarly, environmental economics references scarcely address the economics of groundwater contamination.
3. Ecological economics texts may refer to groundwater but usually in the context of the larger water resource.
4. Increasingly, groundwater is used to satisfy the incremental needs for water of the world's expanding population.
5. The economic aspects of the groundwater production and use processes are not documented well—such as the costs and benefits of different technologies—and are not integrated with the economic examinations of other groundwater considerations in one reference, with the exception of the work done by Custodio and Gurgui (1989) and Llamas and Custodio (2003).

6. Some authors (e.g., Foster et al., 2000; Brown, 2004) point to groundwater as the remaining available water source for much of the world that has limited water resources for drinking and irrigation—groundwater's primary uses.
7. Owing to the limited attention to the economics of groundwater in a unified manner relative to voluminous texts addressing surface water, research on the economics of groundwater, reflecting the entire range of factors important to the use of this resource, may be promoted for the benefit of future generations that may need its services.
8. Thus, this text attempts to bring together the principal aspects of the economics of groundwater as a reference and study guide for the future and is not an exhaustive review of all groundwater economics literature, with the expectation that others will expand on its dimensions as more information becomes available.

SIGNIFICANT GROUNDWATER ECONOMICS ISSUES

The principal question posed by ecological economics relevant to groundwater is: How can the ecosystem be sustained with sufficient groundwater of adequate quality to provide for the economic needs of human and animal populations which are undersupplied now and for similar needs in the future, considering their expanding growth? The amount of water on the earth has been constant, but the world population has grown by 33 times over the last 2000 years (JHSPH, 1998). As of 1998, "31 countries—mostly in Africa and the Near East—face water stress or water scarcity. Population growth alone will push an estimated 17 more countries, with a projected population of 2.1 billion, into these water-short categories within the next 30 years. By the year 2025, 48 countries, with more than 2.8 billion people—35% of the projected global population in 2025—will be affected by water stress or scarcity. Another nine countries, including China and Pakistan, will be approaching water stress" (JHSPH, 1998). About 20–40L of freshwater per person per day is a necessary minimum amount to satisfy drinking and sanitation requirements; however, when water for bathing and cooking is included, the need increases to between 27 and 200L/person/day (Gleik, 1996). From 1999 to 2003, the average per capita water use around the world ranged from 47L/person/day in Kenya to 294L/person/day in Phoenix, Arizona (Worldwatch Institute, 2006). Clearly, the need, expectations, and technology vary from location to location, and these considerations will affect the supply and demand for groundwater (Figures 1.1 and 1.2).

FIGURE 1.1 Well house, Bethany Beach, Delaware.

FIGURE 1.2 Windmill to pump groundwater, Tanana River Valley, Alaska.

This first issue also embraces the cost and benefit of the largest use of groundwater: irrigated agriculture. As much as 8% of the world's irrigated agricultural land draws on groundwater that is being depleted and this proportion is rising, with the United States at 20%–25% (Sundquist, 2006). With irrigation as the largest use of groundwater (and water in general), only a small percent of the irrigated lands have more efficient irrigation techniques applied to them (under 1% in India and China and only up to 4% in the United States) (Brown, 2004, p. 113). Expanding irrigation and water supply demands have shifted groundwater use increasingly toward nonrenewable exploitation of the resource on a worldwide basis, both from fossil aquifers and from what were previously renewable aquifers (UNESCO, 2003, pp. 78–81, 209–210; Sophocleous, 2003, p. 101). Global withdrawal of groundwater for all uses is estimated at 600–700 km^3 annually (UNESCO, 2003, p. 78). Exhibit 1.3 highlights the factors surrounding the depletion of the Ogallala Aquifer used heavily for agricultural irrigation in the central United States. The failure of the economic system to value groundwater for sustainable use is a significant policy challenge in most of the countries. Most local or national markets do not incorporate a capability to value scarce water at this time other than to set its price at the cost of producing it, along with some monetary amount reflecting demand where competitive market factors are involved.

The second issue for economists, hydrologists, engineers, and planners of all related disciplines is how to place groundwater in its larger context of the hydrological cycle: groundwaters are parts of watersheds, often extending to the neighboring watersheds—groundwater that is nearer to the earth's surface is an active part of the hydrologic cycle, even though moving more slowly than the surface water—being channeled through the subsurface environment as more of a condition of its temporary natural or artificial diversion, but as a part of one water system (NRC, 1997, pp. 31–32; USGS, 1999). As noted in Exhibit 1.4, groundwater does exist in ancient aquifers—the geologic strata containing and being saturated with groundwater—which moves imperceptibly slowly or not at all, until it is tapped by a water well. Thus, the following question arises: how to carry out analyses that address the "one water system" or hydrologic cycle concept, recognizing the unique aspects of each condition of water in streams, lakes, wetlands, soil zone, shallow aquifers in different types geologic strata with faster and more slowly moving groundwater depending on the strata, deep aquifers in different geologic strata, and different water-flux zones in which surface and groundwater interact? A significant and operational answer is to focus on *watersheds* in an integrated way—surface, soil, and groundwater—for every decision affecting water and for every evaluation aiding those decisions. This integrated method of addressing groundwater in the watershed needs to incorporate the significant time component: that water withdrawals, additions, and quality factors will take longer to bring about a change on the subsurface condition

EXHIBIT 1.3 IRRIGATION SUPPLY FROM AND DEPLETION OF THE OGALLALA AQUIFER

The Ogallala Aquifer (also known as the High Plains Aquifer) covers an area of 582,747 km^2 in the United States in the central plains states of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas (Wilhite, 2006). The aquifer consists of fine- to coarse-graded sedimentary rocks, with the aquifer water table from 30 m in southern areas to 122 m below the ground surface in northern areas and having a saturated thickness of 0.3 m to 396 m (Guru and Horne, 2000). The U.S. Geological Survey estimates that the total amount of drainable water in the Ogallala formation is about 4000 km^3, but perhaps, an estimate of 15% of that amount is more feasible, given the current technological levels (DIPA, 2001).

The Ogallala Aquifer was first used for agricultural irrigation in 1911. With the advent of inexpensive electric power in the High Plains and the ability to deepen wells, in the 1950s, irrigation expanded. "In 1990, the Ogallala Aquifer in the eight-state area of the Great Plains contained [4589 km^3] of water. Out of this, about 65% was located under Nebraska" (Guru and Horne, 2000). "More than 90% of the water pumped from the Ogallala irrigates at least one-fifth of all U.S. cropland. This water accounts for 30% of all groundwater used for irrigation in [the United States]. Crops that benefit from the aquifer are cotton, corn, alfalfa, soybeans, and wheat" (Guru and Horne, 2000). "While in 1950 the Ogallala irrigated [14,164 km^2] of farm land [in the early 1980s] it is irrigating [64,750 km^2]" (Guru and Horne, 2000). "Irrigation for the farmers in the High Plains region made possible yields that matched or surpassed corn or sorghum production in Iowa or Illinois or California" (Guru and Horne, 2000). In some locations, the water table is dropping at more than 1.5 m per year. "Since people had started to rely on the Ogallala Aquifer for irrigation of their fields, 6% of the aquifer has dropped to an unusable level that can no longer be pumped. If irrigation continues to draw water from the aquifer at the same rate, about 6% of the aquifer will be used up every 25 years. One estimate states that the aquifer is being depleted at a rate of approximately 12 billion cubic meters per year" (Worm, 2004). Falling water tables translate to greater pumping costs which adversely affect farm revenue. By 1987, there was a decrease of over 20% in the irrigated area (DIPA, 2001).

The quality of water in the Ogallala Aquifer generally is suitable for irrigation use but, in many places, the water does not meet the United States drinking water standards with respect to several dissolved constituents (dissolved solids/salinity, fluoride, chloride, and sulfate). Only a small fraction of Ogallala groundwater is known to be contaminated, failing to meet the drinking water standards (DIPA, 2001).

Despite the return to dryland farming in some areas because of the declining water tables and greater pumping costs, the Docking Institute of Public Affairs, using economic modeling, estimated the value of groundwater with regard to the economy of southwest Kansas and found the following (monetary values assumed to be in US$ in the year 2000):

- Without government subsidies or other agricultural operations (dryland, confined feeding, and livestock) being included, irrigated agriculture (96.3% of groundwater use in the area) generated in negative return.
- Agriculture had the third highest earnings after manufacturing and services in the southwest Kansas region.

EXHIBIT 1.3 (continued) IRRIGATION SUPPLY FROM AND DEPLETION OF THE OGALLALA AQUIFER

- The multiplier effect on the rest of the economy of southwest Kansas ranged from 0.3 to 12.5, depending on the county, and averaged about 3.5, generating a direct economic impact of \$14.59 per 1000 m^3 and a total impact of \$64.86 per 1000 m^3.
- Livestock (3% of groundwater use in the area) generated an economic impact of \$405 per 1000 m^3 and municipalities (0.7% of water use from sales to residential, commercial, and industrial consumers) generated an impact of \$365 per 1000 m^3.

Sources:

1. Docking Institute of Public Affairs (DIPA), *The Value of Ogallala Aquifer Water in Southwest Kansas*, Fort Hays State University, Hays, KS, 41, 2001, URL: http://www.gmd3.org/pdf/ogal1.pdf (accessed May 13, 2006).
2. Guru, M.V. and Horne, J.E., The Ogallala Aquifier, The Kerr Center for Sustainable Agriculture, Inc., Poteau, OK, 2006.
3. Worm, K., Groundwater drawdown. *Water Is Life*, University of Wisconsin-Eau Claire, Eau Claire, WI, 2004, URL: http://academic.evergreen.edu/g/grossmaz/WORMKA/ (accessed May 13, 2006).
4. Wilhite, D.A., Ogallala Aquifier Depletion. Center for Agricultural Meteorology and Climatology, University of Nebraska, Leucoln, NE, 2006.

EXHIBIT 1.4 GROUNDWATER FLOW—SHORT AND LONG

Groundwater flow in geologic formations, such as unweathered clay, shale, and unfractured igneous rock may only be on the order of 10 millionths of a meter per day, almost imperceptible movement. On the other hand, groundwater in karst limestone can travel several kilometers per day, measured as what is referred to as “hydraulic conductivity” (Driscoll, 1995, p. 75).

The flow system of the confined groundwater system of the Northern Great Plains of the United States extends more than 966 km from recharge areas in the mountains of Montana, Wyoming, and South Dakota to discharge areas in the eastern Dakotas and the Canadian Province of Manitoba (Downey and Dinwiddie, 1988, p. A17). The regional confined aquifers of the central midwestern United States extend on the order of 1287 km (Reilly, 2006 citing Jorgensen et al., 1997).

The Great Artesian Basin in Australia is one of the largest groundwater basins in the world. It was formed from interbedded sand and clay sediments, with the sandy sediments forming permeable sandstone aquifers between the clay zones. The basin covers an area of 1.7 million km^2 and its longest groundwater flow path is on the order of 1800 km. Age dating indicates that some of the Basin’s groundwater may be 2 million years old (Reilly, 2006; QDNRMW, 2006).

Sources:

1. Downey, J.S. and Dinwiddie, G.A., The Regional Aquifer System Underlying the Northern Great Plains in Parts of Montana, North Dakota, South Dakota, and Wyoming—Summary, U.S. Geological Survey Professional Paper 1402-A, 64, 1988.
2. Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1995, 1089.
3. Queensland Department of Natural Resources, Mining and Water (QDNRMW), Facts; Water Series; The Great Artesian Basin, 2006, URL: http://www.nrm.qld.gov.au/factsheets/pdf/water/w68.pdf (accessed May 14, 2006).

than in the surface waters. This approach is critical to the economic evaluations related to water and to understanding the effect of actions beyond the point or site in which they most obviously occur, such as a well or use in a community. Responding to the water challenges identified in the first issue will necessitate a comprehensive approach to ground and surface waters in a watershed context to address extenuating and unintended consequences of using the resource (Young, 2005, pp. 6, 20).

A third issue focuses on the value of the quality of groundwater: what quality is required for different uses and can we continue to use the subsurface environment of which groundwater is a significant component as a sink for wastes and residuals? A significant aspect of this issue is the shift in drawing groundwater of "increasingly inferior" quality (Howe, 1979, p. 4). In many areas of the world, we can obtain the highest quality, most easily accessible groundwater (Llamas and Custodio, 2003, p. 13). However, tapping deeper aquifers may result in using some groundwaters that are highly mineralized and even brackish (Vrba, 2003). Furthermore, excessive pumping may even draw older saline or current saltwaters, in the case of coastal areas, to the wells (Koussis et al., 2003). Nearly all heavily pumped areas along the coasts of the United States and Europe have experienced problems associated with saltwater intrusion to aquifers previously containing freshwater (EEA, 1999; USGS, 2002, 2006). With the increasing use of groundwater, water that does not have an acceptable chemical composition for drinking may be drawn from the ground for other purposes, or in some cases, not used at all. Furthermore, natural sources of contaminants have transformed groundwater to lower quality, and the use of such water has resulted in illness and death (e.g., see Exhibit 1.5). In the past, disposal of wastes on or under the ground surface was an accepted practice. With the increase in such disposal and the growth of the population density, the disposed wastes have affected groundwater, resulting in levels considered "too contaminated" for use, creating the need for additional treatment or abandoning existing wells for newer water sources. Furthermore, new potential contaminant sources for subsurface disposal by underground injection include (a) carbon sequestration—the United States alone produced an estimated 5.7 million metric tons of carbon dioxide from the burning of fossil fuels by all sources in 2004, about 23% of the total carbon dioxide produced worldwide, and it is expected to increase by about 1.7% per year worldwide (Wilson, 2006)—and (b) desalinization waste from ocean-water treatment for water supply (Yoonos, 2005). The lack of price signals for more complete valuing of differences in water quality or for preventing contamination for the future reflects failure of markets to value qualitative factors of water other than including the cost of treatment in prices.

A fourth issue is "the wisdom of past patterns of resource utilization" (Howe, 1979, p. 3). Considerable investment in the technology of water use has led to excessive water use in some applications—both for households in developed countries and irrigated agriculture worldwide. Reconsidering local infrastructure at the level of the community, household, and individual farm may be necessary to use water more efficiently and productively. Conservation can significantly increase water quantities available (Tsur et al., 2004, p. 12). The cost of conservation may be less than developing new sources of supply, but this is not clear, as the use of water is driven in significant part by the technology to deliver and use it. The value of conserving water may exceed the cost of reducing water use, but this result may need to be evaluated on a site-by-site or project-by-project basis.

There are two other issues paralleling the previous issues: the fifth issue is financing the investment in water-saving infrastructure, that is, finding appropriate funding to deploy conservation technologies to reduce demand. People usually do not try to wastewater, but they do not necessarily have the knowledge or the economic capacity to install conservation measures that require significant capital. Governments typically are challenged for funds for necessary infrastructure investments (UNESCO, 2003, p. 177; USEPA, 2006a). Reinvestment to modify water systems that work but are wasteful may not be reasonable near-term solutions—and they may not be when funds are not available; they are long-term approaches for what appear like long-term problems, but which are rapidly approaching. This concept also applies to promoting local groundwater recharge. For example, current engineering approaches gather wastewater often using gravity flow to a central treatment plant downgradient from the water supply wells

EXHIBIT 1.5 GROUNDWATER AND INFORMATION

1. Arsenic in Groundwater of Bangladesh
   Southern and eastern Bangladesh have one of the most serious problems of arsenic occurrence in groundwater in the world. Arsenic was first discovered in groundwater in western Bangladesh in 1993, next to a region of India in which it had been found in 1988. Arsenic naturally occurs in the alluvial and deltaic sediments of which much of the Bangladesh subsurface geology is composed. Arsenic occurs widely in the earth's crust and as a result is in sediments accumulated from erosion and deposition. Health effects of long-term exposure are darkening of the skin, forming warts or corns which can become cancerous. Other effects include irritation of the stomach and intestines, with symptoms such as stomachache, nausea, vomiting, and diarrhea, decreased production of red and white blood cells, which may cause fatigue, abnormal heart rhythm, blood-vessel damage resulting in bruising, and impaired nerve function causing a "pins and needles" sensation in hands and feet. High doses may result in death. Thousands of persons have been poisoned and tens of millions have been exposed to this chemical in Bangladesh. An estimated 4 million tubewells have been installed in Bangladesh, considered responsible for reducing infant mortality from diarrheal diseases and making the country self-sufficient in food grains production from groundwater irrigation. Approximately 95% of the Bangladesh's population use groundwater as their drinking water source. The shallow aquifer occupying a zone from 10 to 70 m below the ground surface is easily accessed by hand-installed tubewells. The subsurface environment in the silt and clay aquifer is an oxygen-reducing setting resulting in chemical reactions that allow arsenic to be in solution in groundwater. Clearly, the situation is complex and resources to deal with it are in demand. [Other countries with natural occurrence of arsenic which has caused health concerns include Argentina, Finland, India, Mexico, Nepal, the United States, and Vietnam.]
2. *Escherichia coli* in Groundwater of Walkerton, Ontario, Canada
   In May 2000, Walkerton's [Ontario, Canada; pop. 4800] drinking water system, supplied by three wells, became contaminated with deadly bacteria, primarily, *E. coli* O157:H7. Seven people died, and more than 2300 became ill. Conclusions of the Walkerton Commission of Inquiry, prepared by Mr. Justice Dennis O'Connor, include the following:
   - The contaminants, largely *E. coli* O157:H7 and *Campylobacter jejuni*, entered the Walkerton system through Well 5 on or shortly after May 12, 2000.
   - The primary, if not the only, source of the contamination was manure that had been spread on a farm near Well 5. The owner of this farm followed proper practices and should not be faulted.
   - The outbreak would have been prevented by the use of continuous chlorine residual and turbidity monitors at Well 5.
   - The failure to use continuous monitors at Well 5 resulted from shortcomings in the approvals and inspections programs of the Ministry of the Environment (MOE). The Walkerton Public Utilities Commission (PUC) operators lacked the training and expertise necessary to identify either the vulnerability of Well 5 to surface contamination or the resulting need for continuous chlorine residual and turbidity monitors.
   - The scope of the outbreak could probably have been substantially reduced if the Walkerton PUC operators had measured the chlorine residuals at Well 5 daily, as they should have, during the critical period when contamination was entering the system.

(*continued*)

EXHIBIT 1.5 (continued) GROUNDWATER AND INFORMATION

- For years, the PUC operators were engaged in a host of improper operating practices, including failing to use adequate doses of chlorine, failing to monitor chlorine residuals daily, making false entries about residuals in daily operating records, and misstating the locations at which microbiological samples were taken. The operators knew that these practices were unacceptable and contrary to MOE guidelines and directives.
- The MOE's inspections program should have detected the Walkerton PUC's improper treatment and monitoring practices and ensured that those practices were corrected.
- The PUC commissioners were not aware of the improper treatment and monitoring practices of the PUC operators. However, those who were commissioners in 1998 failed to properly respond to an MOE inspection report that set out significant concerns about water quality and that identified several operating deficiencies at the PUC.
- On Friday, May 19, 2000, and on the days following, the PUC's general manager concealed from the Bruce-Grey-Owen Sound Health Unit and others, the adverse test results from water samples taken on May 15 and the fact that Well 7 had operated without a chlorinator during that week and earlier that month. If he had disclosed either of these facts, then the health unit would have issued a boil water advisory on May 19, and 300–400 illnesses would have been avoided.
- In responding to the outbreak, the health unit acted diligently and should not be blamed for failing to issue the boil water advisory before Sunday, May 21. However, some residents of Walkerton were not aware of the boil water advisory on May 21. The advisory should have been more broadly disseminated.
- The provincial government's budget reductions led to the discontinuation of government laboratory testing services for municipalities in 1996. In implementing this decision, the government should have enacted a regulation mandating that testing laboratories immediately and directly notify both the MOE and the Medical Officer of Health of adverse results. Had the government done this, the boil water advisory would have been issued by May 19 at the latest, thereby preventing hundreds of illnesses.
- The provincial government's budget reductions made it less likely that the MOE would have identified both the need for continuous monitors at Well 5 and the improper operating practices of the Walkerton PUC.

In this case, information was critical and affected the response to this groundwater contamination situation.

Sources:

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2. British Geological Survey (BGS), Groundwater studies for arsenic contamination in Bangladesh, 2006, URL: http://www.bgs.ac.uk/arsenic/bphase1/B_find.htm#_Toc442156256 (accessed May 13, 2006).
3. West Bengal and Bangladesh Arsenic Crisis Information Centre (ACIC), The Arsenic Crisis, 2006, URL: http://bicn.com/acic/ (accessed May 13, 2006).
4. Ontario Ministry of the Attorney General (OMAG), Report of the Walkerton Inquiry, Prepared by Justice Dennis R. O'Connor, Queen's Printer for Ontario, Toronto, ON, Canada, 2002, URL: http://www.attorneygeneral.jus.gov.on.ca/english/about/pubs/walkerton/ (accessed May 13, 2006).

and consumers. Rather than allowing water tables to fall because of extensive groundwater use, this treated water could be either recycled for use or injected back to the aquifer to stabilize the water tables at renewable levels. These approaches would require additional investment in water infrastructure.

The sixth issue—coincident with the fourth and fifth—is the asymmetry of information. People do not have a common understanding about groundwater, in general and in their communities. Communities and state or national governments have been confronted with circumstances of depleting and contaminated water resources but do not always ensure that most people or their businesses understand how their decisions impact the critical groundwater on which they depend. For example, both the use of arsenic-contaminated groundwater in Bangladesh as well as the microbial contamination affecting the city of Walkerton, Ontario, Canada, may have been dealt with more effectively with better information to the public (see Exhibit 1.5 for the summaries of these cases). Community groups, such as water user associations in Mexico and other countries and local Groundwater Guardian communities voluntarily established in the United States and subsequently at the international level, can promote understanding of agricultural and community uses and protect groundwater to enhance its future availability and quality. Chapter 16 addresses this subject in more detail. Asymmetric information also applies to uses of groundwater that are not priced in any market, such as for habitat maintenance in wetlands and coastal areas and for baseflow of streams to support aquatic life, navigation, recreation, and aesthetic purposes. As asymmetric information affects the cost of the response to supply, demand, treatment, and ecosystem function related to groundwater, its development and use should rely on the research of the consequences for a range of alternatives, the results of which should be made broadly available.

The seventh issue is the "open-access" nature of groundwater resources in nearly all the countries of the world, which contributes to conflicts over property rights and has threatened international relations (Tsur et al., 2004, p. 18; Jarvis et al., 2005, p. 768). In open-access situations, groundwater can be withdrawn for any use at the cost of production without regard to the ecosystem, market considerations, or impacts on others' uses (Young, 2005, p. 14). Rights to withdraw groundwater should be clear (Tsur et al., 2004, p. 29). If not held by individuals, the state or a central government may hold and manage the rights to aquifers. Rights should promote sustainable use through concepts such as safe yield. In economics terminology, the lack of property rights for a mobile and widely available resource may affect the economic efficiency, equity, and impacts to third parties (referred to as "externalities") (Custodio and Llamas, 2003, p. 212; Tsur et al., 2004, p. 29).

The eighth issue, related to ownership and control of groundwater, is its distribution relative to people who do not have the economic capability to access it directly for their personal needs or those of their animals on which they rely. Water should be available to anyone who needs it for personal bodily sustenance. The United Nations has estimated that 1.2 billion people do not have access to safe drinking water, 2.4 billion people lack proper sanitation, and more than 3 million people die every year from diseases caused by unsafe water (UN, 2006). This need has been recognized in international agreements (UN, 1996, 2000) and reports (UNESCO, 2003) as well as some national laws (see Chapter 5). The United Nations noted that access to water affects health and poverty (UNESCO, 2003, p. 6), and Foster et al. (2000, p. 1) indicated that groundwater specifically "has led to significant improvements in human health and the quality of life in innumerable village communities of Africa and Asia, in particular." Furthermore, adequate consideration for the needs of future generations should ensure that they have adequate and sustainable water options (Daly and Farley, 2003). Thus, equity and distribution issues among people across space and time are critical in addressing rights to water.

The ninth issue is the recognition of groundwater purposes that are nonmarket goods and the market's failure to incorporate these values in prices. Maintenance of land elevations in non-subsidence conditions in which groundwater may exist is important to communities and their infrastructures. Much of the fish and other aquatic life that are consumed require wetland or other aquatic habitat in streams or along coasts supported by groundwater discharge and its physical (temperature) and chemical (nutrient) characteristics. Biodiversity on both local and global scales may be in jeopardy because of water of reduced quantity or quality supplying these zones (UNESCO, 2003, p. 10). Considering the nature of the subsurface, the environment in which groundwater exists may be as complex as that of the surface water. From this complexity, many potentially unknown but important values and services are derived, upon which future research should focus.

The tenth issue is the transboundary conflict over groundwater use (Tsakris, 2003). The fact that groundwater migrates must be incorporated in laws at all levels and in educational curricula. Excessive pumping in one location can reduce the groundwater table and streamflow in adjacent areas. Polluted groundwater can migrate from one place to another, including streams and other water bodies. While most groundwater moves slowly in the subsurface, data demonstrate that groundwater can migrate long distances, albeit over long time periods, under many boundaries, local and national. Some groundwaters have flow paths of as much as 966–1287 km in the northern Great Plains and central midwest areas of the United States and up to 1800 km in northern and eastern Australia (Reilly, 2005). In karstic terrain of limestone and dolomite, groundwater can flow several kilometers in a day. In the aquifers of alluvial valleys, distances of tens of meters per day of groundwater flow are possible. This issue, as well as the eighth issue, relates to the scale of use and its effect on areas far from the points of use. Thus, activities affecting the subsurface in areas considered far from a point of groundwater use can have impacts, the causes of which may have occurred distantly in time and place. The costs of this mobility are typically not factored into decisions about groundwater, ecosystem maintenance, or market transactions, often because of the lack of information about the outcomes in other locations. Exhibits 1.4 and 1.6 indicate that groundwater flow paths can be long, crossing boundaries of adjacent jurisdictions, in some cases in a timeframe of 30–50 years.

The eleventh issue is the "role to be given to market processes in determining how resources will be managed over time" (Howe, 1979, p. 5). Groundwater management and allocation are significantly affected by the "tyranny of small decisions"—innumerable individual wells tapping the resource (Young, 2005, p. 10). While market processes are considered fundamental, even sacrosanct in certain political contexts, for the efficient allocation of resources—derived from the ecosystem—they are acknowledged as imperfect, as will be further discussed, because of a range of impinging factors, such as incomplete (and asymmetric) information and the existence of many effects on other users or natural processes (Tsur et al., 2004, pp. 18–19). The market functions to provide the necessary labor and capital inputs to produce groundwater and distribute it. These inputs may be limited from place to place or over time, but significantly, the quantity and quality of groundwater is typically being supplied in noncompetitive circumstances and demanded in greater amounts than may be replenishable locally. How should market processes be employed to address and balance supply and demand from people as well as ecosystem purposes? This is typically treated as a microeconomic issue but has macroeconomic implications.

The twelfth issue is of scale, an ecological economics concern (Daly and Farley, 2003): How much groundwater can be produced at a level that allows all critical activities to continue, even essential activities in the ecosystem, some of which we are ignorant? Further, how can the result of decisions by millions of individuals to produce groundwater to which many of them may or may not have obtained or received a right, be managed through the economy to provide a sustainable source of water for human and nonhuman purposes, even those that are essential but little or incompletely understood.

The economics of groundwater is concerned with these questions. They are difficult questions to address, because groundwater is becoming increasingly scarce, and many different interests influence their answers. The questions are multifaceted and there are more to ask and investigate. This text attempts to provide perspective on these issues; however, it may not fully provide answers and perhaps raises more questions.

EXHIBIT 1.6 EXAMPLES OF GROUNDWATER CONTAMINATED AREAS

Location	Surface Area Underlain with Contaminated Groundwater	Contaminant Source	Contaminants
New Brighton/ Arden Hills, MN	65 km^2	Munitions production	Volatile organic compounds (VOCs), semi-VOCs, metals, polychlorinated biphenyls (PCBs), cyanide, pesticides, and explosives
San Gabriel Valley, El Monte, CA	78 km^2	Wide range of industrial activities	Tetrachloroethene (PCE), trichloroethene (TCE), and other VOCs
Shelton, Central Platte Valley, NE	2023 km^2	Farming (90% area cultivated, 85% irrigated)	Nitrate–nitrogen levels greater than the U.S. Maximum Contaminant Level of 10 parts per million
Hanford Site, WA	225 km^2 reaching Columbia River	Plutonium production	Nitrate, chromium, carbon tetrachloride, uranium, technetium-99, tritium, strontium-90, iodine-129
Bitterfield, Germany	26 km^2	Open pit lignite mining activities and related chemical industries	Benzene, chlorobenzene, 1,2-dichlorobenzene, 1,4-dichlorobenzene, trichloroethylene (TCE), *cis*-1,2-dichloroethylene (DCE), and *trans*-1,2-DCE sulfate and chloride
Yejsk, Russia	53 km^2	Military reservation petrochemical spills and leaks	Hydrocarbons
Dundigal Town, India	7 km^2	Leather tanning	Tannery waste

Sources:

1. United States Environmental Protection Agency (USEPA), EPA/ROD/R09-00/114 EPA Superfund Record of Decision: San Gabriel Valley (Area 1) EPA ID: CAD980677355 OU 05, El Monte, CA09/29/2000, 2000.
2. United States Environmental Protection Agency (USEPA), NPL Fact Sheets for Minnesota: New Brighton/Arden Hills, 2004, URL: http://www.epa.gov/R5Super/npl/minnesota/MN7213820908.htm (accessed May 19, 2006).
3. Mondal, N.C. and Singh, V.S., *Proceedings of the Asia Pacific Association of Hydrology and Water Resources (APHW) Second Conference*, Singapore, July 5–8, 2004.
4. United States Department of Agriculture (USDA), Water Quality Information Center, Nebraska Management System Evaluation Area, Shelton Site, 1997, URL: http://www.nal.usda.gov/wqic/wgwq/neb1.shtml (accessed May 19, 2006).
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INITIAL ECONOMIC CONCEPTS

To understand the economics of groundwater, some initial economic concepts are useful. These concepts are those that we hear in news media at times. It is important to have a commonly accepted definition for these concepts. For the purposes of this text, the following terms will be useful to keep in mind:

Cost is the expense of producing and providing one more unit of a good or service (Raucher, 2005, p. 93) which derives its existence from changes in the resources of the ecosystem specified in monetary terms for quantitative economic comparison or in descriptive terms for qualitative consideration. Producing and delivering one more (or many more) unit(s) of a good or service may also cause a loss or a disadvantage to society or the ecosystem, which is described quantitatively or qualitatively, and referred to as an external cost (ILRT, 2005) or "externality."

One person's use of the groundwater may indicate that it was not available for the neighboring water company to produce and sell. In this case, the groundwater may have a use value that was foregone. The economist says that this "opportunity cost" of the person's use is the value in the next alternative use that could not occur.

The concept of cost also includes disadvantages or damages to people or to the ecosystem from some action or project. Economists attempt to quantify these costs wherever possible based on economic relationships that have currently been monetized. Examples include the health effects of human consumption from contaminated water or the loss of wetland habitat of fish and other wildlife. Often these costs may not be monetized and can only be counted or qualitatively described.

Price is the monetary amount that a purchaser or consumer pays for a unit of a good or service. Prices are usually based on costs (Raucher, 2005, p. 93). The price charged for a good or service may not be equal to the expense of producing or providing it; the price of a good or service in the market reflects its demand by consumers as well as their tastes and preferences, its relation to other goods and services including substitutes and complements, "distribution of resource endowments," and other factors (Mishan, 1982, p. 28). For example, if a drought has occurred, water may become scarce, and people may have to pay more than $0.37/L for groundwater, bidding against other thirsty human beings. In paying more, the producer's cost may not change, but the exchange value (price) in the market may go up.

Benefits refers to improved welfare or satisfaction from individual or societal advantages or gains owing to a change in the amount or condition of a good or service that derives its existence from changes in the resources of the ecosystem specified in monetary terms (Freeman, 1993, p. 8; RFF, 2002). If insufficient information on the monetary value of benefits exists, then they may be expressed in other units, such as cubic meters of groundwater, number of people affected, and tons of subterranean biomass. Benefits also include the value of services or objects that may be counted in other ways, such as the savings of time or the avoidance of costs. Advantages or gains to those individuals or groups not directly targeted to receive them are referred to as external benefits (ILRT, 2005). In some instances, benefits may have to be qualitatively described if the ecosystem or economic relationships are not or poorly understood. A significant point is that benefits may be based on purposes that are not well defined or described in monetary units but may still have substantial value in decision-making processes.

Value refers to the worth of a result, service, object, or good, the extent of well-being that a person obtains through exchange from having one more unit of a good or service (Freeman, 1993, p. 19; Raucher, 2005, p. 91) of a particular quality (which for groundwater might be based on location, purity, timing, and reliability) (Raucher, 2005, p. 91), as well as sustainability (Daly and Farley, 2003, p. 373). Values may be "extrinsic," derived from human economic and social welfare attainment, or "intrinsic," which are inherent in the object or condition and separate from any human attainment (Young, 2005, p. 24).

Value may be more than the price. If one needs to consume some amount of groundwater to avoid dehydration and becoming ill, then the price one has to pay for the quantity of water consumed may be substantially less than its value. The value of additional groundwater flow carrying important nutrients to a coral reef may be more than the price of that groundwater multiplied by the volume of the maintained flow but may include the survival of an important species of fish and even aesthetic characteristics of the coral and the habitat that it provides, which everyone can appreciate in the future.

The *economy* is the sum of goods and services that are exchanged between individuals as well as among individuals and small and large corporations. Economies can be local, such as within a town, regional as in a state or nation, or can be global. The economy relies on resources provided by nature which people and corporations transform to serve the immediate (ranging from a few seconds to many years) needs and are subsequently returned to nature as used up or worn-out materials and wastes. Nature must somehow deal with these byproducts over time, which may sometimes take centuries and longer (the half-life of radioactive waste ranges from seconds to billions of years depending on the isotope [UICL, 2002]). The economy refines, concentrates, and transforms resources to products useful to people and distributes them through exchange among individuals and corporations.

Economic *efficiency* results when a good or service is produced at a minimum cost. An Italian economist, Vilfredo Pareto, proposed an allocative efficiency criterion that "it must not be possible to change the existing resource allocation in such a way that someone is made better off and no one worse off, since, if this were possible, the existing resource allocation must involve a 'welfare waste' " (Bannock et al., 1979, p. 144). Under this paradigm, economic benefits must exceed the costs for some decision or action without a further change in the amount or condition of the good or service making someone else better off.

Supply refers to the amount of a good or service of a certain quality offered by a seller at a particular price (Bannock et al., 1979, p. 430). For example, a water company may be able to sell a certain number of units of water at $1.00, or a person may be willing to work for a set wage at a well-drilling company.

Demand is "the willingness or ability to pay a sum of money for some amount [and quality] of a particular good or service" (Bannock et al., 1979, p. 119). If water is in short supply, people might be willing to pay more for it. If the quality of water is not high, then people might not want to pay much for it.

A *market* is "an institution in which buyers ['demanders'] and sellers ['suppliers'] … carry out mutually-agreed on exchanges" (Field, 1994, p. 68) and hence is considered to be the convergence of buyers and sellers of goods and services or the services of productive factors (e.g., labor, materials, or capital) for the purpose of economic exchange (Rea, 1999). A "perfect market" is defined as having perfect communication between buyers and sellers, accomplishing instantaneous equilibrium from inputs of all traders' supply and demand functions to obtain "market-clearing" prices for their exchanges, and completing costless transactions with no "middlemen" or brokers (Hirschleifer, 1976, p. 200). In reality, no perfect market exists for economic exchanges. The exchanges in the market usually take place through the use of money paid for a good or service. In the ideal setting, the market provides sufficient information about the good or service exchanged, and the buyers and sellers are mutually satisfied with the value of the exchange.

The *ecosystem* is the sum of all the biotic and abiotic features of the earth, including human beings, fish and wildlife, plants, microorganisms, sunlight, soil and geologic matrix, atmospheric gasses, and WATER, and the processes—hydrologic cycle, atmospheric and oceanic circulation, heat exchange, biochemical degradation, gravitational pull, etc.—to which they inherently contribute, some known and others unknown, which are being understood with the help of science. The ecosystem supplies all the resources, available in finite quantity, used in the economy by people and their corporations.

Sustainability, in both an ecosystem and an economic sense, is the capability of a resource to have a portion removed and yet maintain itself indefinitely, which means that on average, what is removed is replenished over the long term; this is an inherent capability of the resource. For groundwater, if the removal is greater than the natural or artificial replenishment, the aquifer will be depleted. Sustainability in a financial sense is the ability of a firm or individual to have means of obtaining sufficient revenue or support to cover all costs or requirements of operation on a continuing basis; if costs or requirements exceed revenue or support, then a water company is not sustainable.

Partial equilibrium analysis is an evaluation of a small part of the economy, such as one market or industry, without considering changes in the rest of the economy. Such analyses are useful for expositional purposes and show only a static or short-run position in the market.

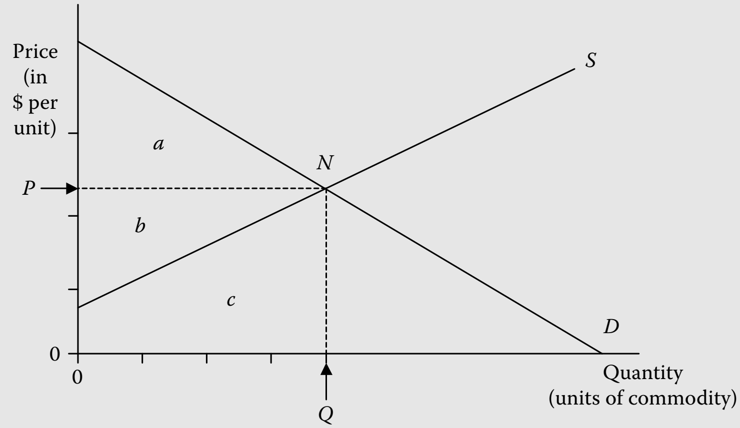
General equilibrium analysis provides evaluation of conditions and consequences throughout the economy from changes in a market or set of markets (Bannock et al., 1979, p. 200). General equilibrium analyses rely on the results from empirical studies to establish relationships among the markets and may use input–output modeling to help describe outcomes of changes. The effects of increasing wheat production, farm implements, and agricultural extension agents may be examined relative to expanding groundwater production, well drillers, and pump manufacturers.

Exhibit 1.7 provides an example of a partial equilibrium analysis of supply and demand relationships for a marketed good or commodity. The economic theory behind such an example is provided in a later chapter. In this example, the cost of supply declines (it costs less to produce a unit of a hypothetical commodity in this case) as more units are produced, which is reflected in the supply curve, S. The supply curve reflects the producers' costs per unit at each quantity made available. The demand curve, D, gives the consumers' willingness to pay for one more unit at each increment of quantity. As explained in greater detail in a later chapter, the demand curve portrays the consumers' willingness to pay for each additional unit, such that it derives a consumer value equal to the price ($/unit) multiplied by the number of units demanded. The graph indicates that the consumer has a high benefit for the first units (the difference between the demand curve, D, for any quantity above its intersection with the horizontal axis) but less so as more units are supplied. At the intersection of the supply and demand curves, the market is considered to be in equilibrium and sellers are just willing to accept the amount that consumers are just willing to pay. As the consumers only pay the price in the market and not a different price at each quantity, the area above the price line is considered to be the consumer's "surplus" benefit, in economic terms.

In the past, generally, water, or, specifically, groundwater, was not typically marketed as a commodity but was treated as a public good with no cost other than to access it. This

EXHIBIT 1.7 SIMPLE EXAMPLE OF PARTIAL EQUILIBRIUM ANALYSIS OF SUPPLY AND DEMAND

a = benefit to consumer at price *P* resulting from market process
b + *c* = total amount paid by consumer for quantity *Q* and revenue to supplier at demand *Q*
c = cost of production to the supplier



S = reflects supplier's cost of providing different amounts of commodity

D = reflects consumers' willingness to pay for each additional unit of commodity demanded

A graph showing two supply lines on a demand curve and the benefits accruing to the consumer.

signifies that many people used groundwater for their individual benefit, rather than for the society, or, where controlled, it was accessed by a central producer and distributed to consumers. Groundwater's low access cost in many situations has contributed to significant and often unconstrained use. Similarly, as groundwater is often viewed as widely available and naturally made pure at no cost, the subsurface has been used for waste disposal, either by directly draining or injecting waste into the underground environment or allowing it to leach into it. It is now recognized that there is a cost of waste disposal to adjacent and future users of groundwater. As groundwater becomes scarce in many locations, it is being treated as a market commodity, being offered for sale to the customer/bidder paying the highest price or in smaller quantities, such as bottled water, in markets with many water suppliers.

While other key concepts are introduced in later chapters, it is important to consider that the discipline of economics attempts to explain exchanges of goods and services among people and corporations, as well as provide information for organized analyses to decision makers. This function of contributing to decision making at all levels and to policy development, thereby influencing the process of transactions in the economy, makes the economics a catalyst for change, facilitating the potential and nature of exchange between individuals as well as within and among societies. Much of what follows examines the economic effects on those who were previously considered as nonusers of immediate local groundwater resources—the effects on adjacent and even distant water users and the ecosystem that supplies the water for those users as well as the natural purposes on which we rely.

BRIEF OVERVIEW OF THE BOOK

This book describes groundwater in an economics context and is organized differently than many economics texts, considering the context in which groundwater is provided from the ecosystem to meet the basic purposes and economic activities. It focuses first on how we observe groundwater in nature, in the economy, as well as in the results that we encounter each day—but from the perspective of pointing to costs and benefits, including access to the resource, legal framework, health considerations, food production, waste sink, and water quality. The subsequent chapters focus on the basic economics of groundwater, primarily from a production standpoint, followed by macroeconomic aspects of the economy that potentially influence groundwater use. Consideration of the macroeconomic aspects of groundwater focuses on throughput and scale of use, relative to the sustainability of the resource. Subsequently, a neoclassical treatment of evaluation of policies using economics as the basis for analysis has been described. Next, the policies factors and principles related to sustainable development of groundwater are addressed. The remaining chapters consider special topics of international, transboundary, and climate-change considerations and provide an outline for approaching the political economy of groundwater to improve balancing the range of economic and qualitative factors in the future economic management of the resource. The key point throughout this book is that for our benefit and that of future generations, we must broadly consider the economic consequences of decisions to produce and use groundwater *sustainably* for water supply or waste disposal and not just consider the immediate effects for the user at the well or the point of disposal—broadly in the ecosystem and its watersheds and the economies that they support into the future.

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Part IIa

Context

Part II provides a context for economic analyses. It reviews groundwater in the ecosystem and the economy. It then considers access to the resource as a major factor in its use, followed by attention to legal frameworks in the United States and selected countries around the world that provide the basis for human actions taken relative to groundwater and its use and misuse. The major uses of groundwater for drinking and irrigation are examined in detail. This part closes with a consideration of the costs associated with groundwater quality, its treatment, and its use as a disposal sink with an emphasis on water quality and disposal. This is the launching point for attention to the economics of groundwater and its portion of the ecosystem.

2 Groundwater in the Ecosystem

PHYSICAL SIGNIFICANCE OF GROUNDWATER

To understand the significance and role of groundwater in the economy, it is first necessary to understand the existence of groundwater in the ecosystem. Groundwater exists as the subterranean component of the hydrologic cycle. Small organisms that are a part of the biochemical web inhabit the dark, low-oxygen underground environment. Even though we cannot see or observe groundwater easily, it exists in a complex subsurface environment that affects its accessibility and use, its quality, and its sustainability as a resource in the economy. What is the magnitude of groundwater in the ecosystem?

Groundwater is the second smallest of the four "pools" of water in the earth's ecosystem. Exhibit 2.1 shows the major "pools" and "fluxes" of water in the global water balance. Aquifers hold 8,336,400 km^3 of groundwater, about 0.6% of all the earth's water (USGS, 1999a,b, p. 2). However, groundwater comprises 99% of the earth's freshwater, excluding the frozen water of the polar ice caps (Gleick, 2000). Exhibits 2.1 and 2.2 provide the estimates of the water supply of the world. The subsurface space exists under most of the world's land, in which the pores of the geologic structure—whether minute fractures or microscopic spaces among silt and sand grains—are filled and saturated with water (USGS, 1984, p. 14). Groundwater interacts with surface water in watersheds that run from mountains to the oceans (USGS, 1999a,b, p. 3). Once thought to be inexhaustible, this resource has reached its limit in many places to supply safe water of adequate quality and quantity to meet human requirements (Danielopol et al., 2003, p. 104), and is now recognized as finite. Groundwater occurs near and at the ground surface, in shallow aquifers and wetlands, respectively, and in deep aquifers hundreds and even thousands of meters below. Groundwater can migrate into rivers maintaining their flow for downstream users. The biodiversity of the groundwater portion of the ecosystem is significant (Gibert et al., 1994a).

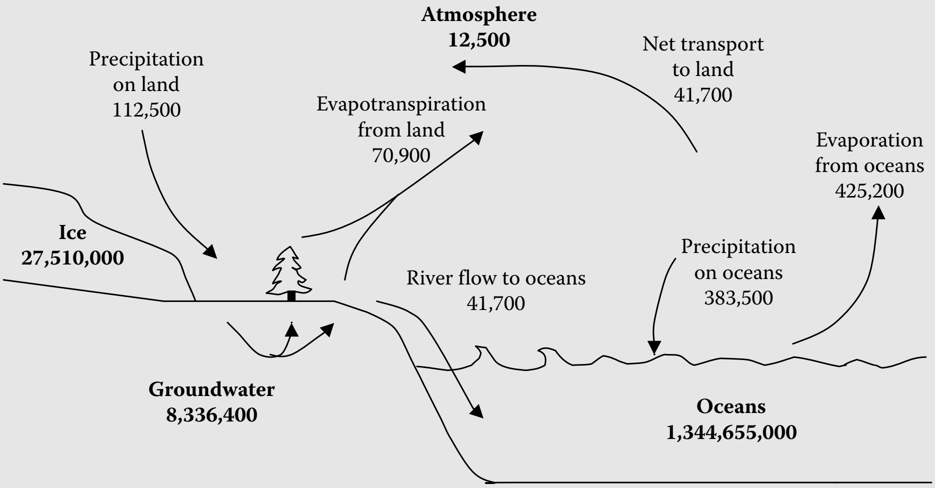
We will first examine shallow groundwater in the hydrologic cycle. Subsequently, we will explore a range of factors that influence groundwater occurrence and use that affects the resource in the economy. Finally, we will develop a groundwater balance to obtain a perspective on factors affecting the economic use of this often misunderstood resource.

THE HYDROLOGIC CYCLE

Groundwater is a fundamental component of the hydrologic cycle. Indeed, hydrology is recognized as a driving variable for the habitats and the ecosystem (Urbanska et al., 1997, p. 366). As described in Exhibit 2.3, water evaporates from bodies of water and from the soil, as well as being transpired by plants. In this vapor phase, it rises and condenses to form clouds. As the clouds become heavily laden with water, they release it as precipitation (rain, sleet, hail, or snow). When the precipitation reaches the ground, it infiltrates the soil zone first. After the soil zone has reached its limit to allow water to infiltrate at the current rate of precipitation, water runs across the surface, becoming overland flow or "runoff." Overland flow fills the depressions on the land surface and moves toward streams and lakes. During the precipitation event, infiltration water that is not held in the soil zone percolates through the ground (called the unsaturated or "vadose" zone, with the pore space taken up by both water and air) to the water table (the upper plane of the saturated zone) of the "first" or "shallow" aquifer as well as its "saturated zone," referred to as groundwater, in which all the pore space is filled with water. An aquifer is a subsurface geologic formation, part of a formation, or a series of formations, which are

EXHIBIT 2.1 GROUNDWATER IN THE GLOBAL WATER BALANCE

Pools in bold, units in cubic kilometers: fluxes with arrows, units in cubic kilometers per year



Groundwater is the second smallest pool water in the global water balance. It is assumed that with global climate changes, the ice–ocean relation is changing, with ice becoming a smaller pool and oceans becoming still larger.

Sources:

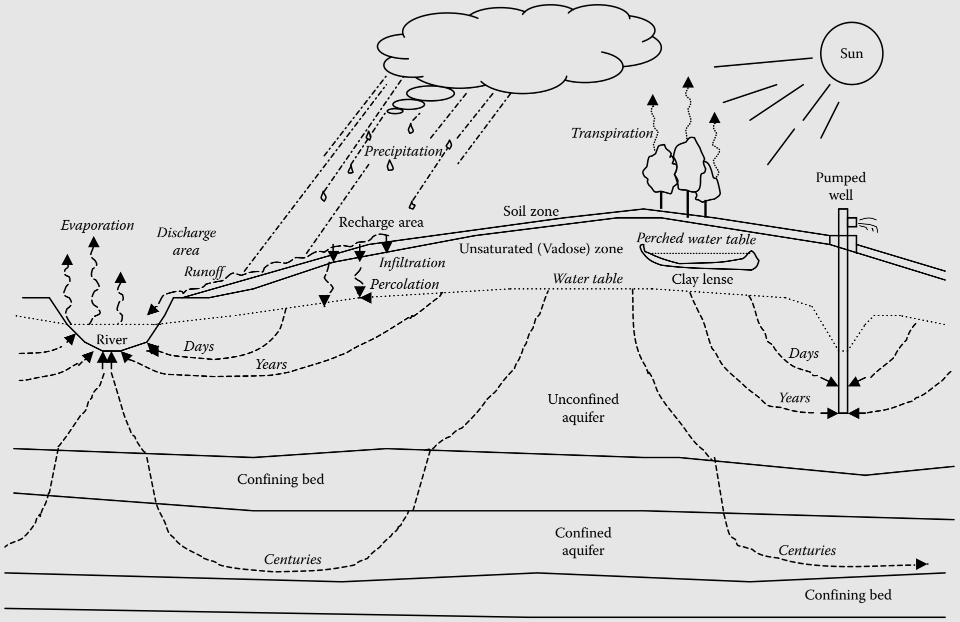
1. United States Geological Survey (USGS), Ground Water and Surface Water, A Single Resource, U.S. Geological Survey Circular 1139, Denver, CO, 1999b, 2.
2. Adapted from Schelesinger, W.H., *Biogeochemistry—An Analysis of Global Change*, Academic Press, San Diego, CA, 1991.

EXHIBIT 2.2 WORLD'S ESTIMATED WATER SUPPLY

Location	Surface Area (km^2)	Water Volume (km^3)	Percentage of Total Water
Surface water			
Freshwater lakes	854,696	125,045	0.009
Saline lakes and inland seas	699,297	104,205	0.008
Average in stream channels	—	1,250	0.0001
Subsurface water			
Vadose water (includes soil moisture)	—	66,691	0.005
Groundwater within depth of 0.8 km	—	4,168,182	0.31
Groundwater—deep lying	—	4,168,182	0.31
Other water locations			
Ice caps and glaciers	17,870,918	29,177,273	2.15
Atmosphere (at sea level)	510,227,658	12,921	0.001
Oceans	361,303,341	571,040,912	97.2
Total (rounded)		1,358,827,281	100.0

Source: Adapted from United States Geological Survey (USGS), Water of the World, U.S. Government Printing Office, 1984-421-618/107, 1984, pp. 10–11.

EXHIBIT 2.3 THE HYDROLOGIC CYCLE EMPHASIZING GROUNDWATER FLOW



Source: Adapted from United States Geological Survey (USGS), Ground Water and Surface Water, A Single Resource, U.S. Geological Survey Circular 1139, Denver, CO, 1999b, 5.

saturated with and hold water. Groundwater moves through the small, microscopic spaces between rock, sand, or silt particles, and depending on the subsurface slope of the water table; percolation water reaching the saturated groundwater zone may be carried laterally by the local hydraulic gradient (slope of the water table), or move more deeply into the aquifer, and then laterally, as it moves toward a discharge zone, such as a stream or lake, ocean, or pumped well.

Groundwater can flow to streams in a watershed discharging to them through the stream bed. A watershed is an area of land, often referred to as a "catchment basin" (because it "catches" the precipitation that falls on it), within which the surface water and the shallow groundwater discharging to the streams have a common outflow point to a larger stream or to an ocean. During storms, the water levels can rise in the streams and allow additional water to be transmitted into the channel banks along them. The water table rises along these streams during the precipitation event and as the stream recedes, this bank storage water is slowly discharged back to the stream.

Groundwater moves from high energy (high "hydraulic head") to lower energy (lower "hydraulic head"). When water accumulates below the ground, it can create pressure from its aggregating mass in the subsurface pore spaces. This pressure provides energy to move the water, transmitting the energy through its subterranean travel to the discharge points (a stream, lake, ocean, spring, or well) that release the accumulated pressure through the flow of water. These circumstances explain the movement of groundwater even through minute pore spaces in the ground.

Additionally, some water is held by leaves, stems, and branches of vegetation, called interception, which may be evaporated. A significant amount of moisture is also returned to the atmosphere by plants through transpiration, which draws water from beneath the land surface through the plants' root system. Literally, the plants can "pump" water from the ground through the processes of root uptake and transpiration.

Impervious surfaces can affect infiltration and recharge. In locations where bedrock is at the ground level creating an impervious surface, overland flow may predominate initially in a precipitation event. In these cases, rain or melting snow can only enter the rock at fractures, often too small to see. Similarly, in urban areas, rain water may runoff from streets, sidewalks, and rooftops, creating stormwater which can be routed to and concentrated in sewer lines or detention ponds. If cracks exist in the sewer lines, then the leakage from these sewers can recharge groundwater with contaminated water. Stormwater detention ponds are often designed to allow much of their detained water to percolate into the ground over longer times than the storm.

In Exhibit 2.3, the upper or shallow aquifer's water table exists typically above the elevation of the stream, indicating groundwater discharge to the stream—flow from high hydraulic head to lower hydraulic head. In the western United States, it is common to find the water table below the elevation of the stream. In this case, water from the stream "recharges" the groundwater, transmitting water into the subsurface. Such circumstances exist in the United States Central Plains, where snowmelt maintains the flow of the Platte River that recharges the upper aquifers over which it crosses. In many locations, streams may recharge groundwater, and in alluvial (sand and gravel) valleys, an exchange between groundwater and stream and back to groundwater may occur many times (USGS, 1999b, p. 10), based on the geology through which the stream flows and in which the aquifer exists.

The U.S. Geological Survey has estimated that 40% of the average annual streamflow (the flow of all the water in streams in an average year) is from the groundwater discharge to streams (GWD) (Wolock, 2005), and may be as much as 90% in some streams (USGS, 1999b, p. 40). Groundwater is also discharged to oceans, and maintains water elevations in most lakes. In the western United States, streamflows may also be maintained by irrigation return flow, where water is pumped from the ground and used for irrigation and then allowed to flow to the stream, either overland or underground. As stream water is used many times, the economic interests of many land owners and managers are vested in insuring that they receive their share of the use of this water.

Exhibit 2.3 highlights several key aspects of groundwater that affect its presence in the ecosystem and its use in the economy. First, the dashed lines below the line labeled "water table" indicate the relative travel times for groundwater in the saturated zone. Groundwater nearest a stream or a pumped well may reach those discharge points in a matter of days. Water further away may take years, even centuries or millennia before finally flowing through a stream bed or a well. Groundwater away from the discharge points generally flows downward and the pressure from the hydraulic head can push it back up to points of discharge.

Second, deeper groundwater may be found in "confined aquifers" often lying hundreds or thousands of meters below the ground surface between two confining beds of less permeable geologic material. Confined aquifers may often be the sources of water penetrated by deep wells. These waters may have been deposited in the prehistoric geologic matrix and may be very old, and are often referred to as "ancient" groundwaters. Very little or no water from recent precipitation ever reaches these deep, confined aquifers in the timeframes of people's lifetimes.

A third point is more subtle, with regard to the direction of groundwater flow in and under a watershed. The exhibit shows the land surface sloping downward to the left from the trees and downward to the right beginning with the trees. Beneath the ground surface is the "water table," which is the groundwater level "high" point, sloping downward to the left and then downward to the right. Usually, the water table slightly mirrors the land surface, but not always. The topographic high of the ground surface separates one watershed from another. Beneath the watershed, the "groundwater-shed" may not have its high at exactly the same vertical transect. This circumstance may exist for a variety of reasons, including the location of points of discharge.

Fourth, sometimes, the subterranean features may catch and hold groundwater in places where we do not anticipate. Such is the case in this exhibit of the clay lense located to the left of the pumped well. In this hypothetical situation, a past geologic event is considered to have left a layer of clay of limited extent that stops the water from percolating to the larger unconfined aquifer below it. This condition is referred to as "perched groundwater" and has its corresponding "perched water table," which is also an unconfined aquifer, albeit a small one. If the pumped well had been installed to the left of its location in the exhibit, it would have drawn groundwater at a much shallower elevation. Perched groundwater is not usually a large, dependable water supply.

Fifth, the pumped well affects the elevation of the water table around it. From the exhibit, it can be observed that the water table dips around the pumped well, and this condition is called the "cone of depression." The cone of depression exists around a pumped well because the pumping pulls the water to the well screen that allows water into the well and keeps out larger material, thereby reducing the pressure in the aquifer at that point and lowering the water table around the well. As the rate and volume of groundwater pumped increases, the cone of depression can grow deeper and outward from the well. For example, many wells pumped groundwater from underground in the area of Chicago, Illinois, for such a long time that the combined cone of depression could be measured north into the state of Wisconsin, a distance of well over 83.3 km from the center of the pumping area. (Further useful references for groundwater in the hydrologic cycle include Driscoll, 1986; USEPA, 1993; USGS, 1999b.)

NATURAL FACTORS AFFECTING GROUNDWATER RESOURCES

Nature is a major factor affecting the quantity and quality of the groundwater resource. The hydrologic cycle interacting with the earth's geology is a vital relationship in the ecosystem that influences the presence and quality of groundwater. These factors and others, not as well understood, affect the economics of groundwater. Several key concepts are important in understanding the presence of groundwater in the ecosystem on which we rely for survival and economic exchange:

Precipitation. An area must receive sufficient precipitation—rain, snow, sleet, and other forms of atmospheric water that fall on the land—to allow water to saturate the soil and infiltrate the subsurface, migrating to the water table.

Aquifer. An aquifer is a water-bearing geologic formation, sequence of formations, or a portion of a formation capable of supplying sufficient water for particular purposes (Driscoll, 1986, p. 19; USEPA, 1993, p. 227). Aquifers exist in a range of geologic matrices from sand or gravel to bedrock, in which water is held in minute fractures. Groundwater also flows through solution channels in carbonate rocks, which have been created by water dissolution along the fractures. An important point to note is that for an unconfined aquifer, the saturated portion will vary based on precipitation, discharge, and use. That is, the water table will fluctuate (rise and fall) depending on the volume of the water available to it. During long precipitation events or floods that cause the volume of the subsurface to be more completely saturated, it is possible for the water table to rise to the ground surface.

Deep ancient aquifers. In many areas of the world, water held in ancient geologic strata far below the earth's surface—thousands of meters deep in some cases—may be reached by wells. These deep aquifers do not receive water infiltrating from the ground surface and percolating through the subsurface. These aquifers may be large in areal extent and the only source of water in some locations. When waters in these aquifers are consumed, they disappear in perpetuity from a human-use perspective.

Evaporation. If the temperature is too warm and the precipitation is too minimal, then evaporation of the water—moisture given up because of the heat—in the soil can preclude the water from reaching the water table. In the arid southwestern United States, evaporation can be as much as 3.7 m or more per year in locations that may not receive more than 15–30 cm of precipitation each year.

Permeability and soil texture. The ability of soil to allow water to penetrate and move through it is called permeability. Soils with higher clay content are more impermeable to infiltrating water. Caliche soils in the southwest United States also tend to cause water to run off, rather than enter the subsurface. Highly compacted soils anywhere encourage runoff. Sandy or loose soils permit water to infiltrate and, thus, are more permeable. Furthermore, clay soils with macropores—holes that worms, insects, and burrowing animals create—and cracks can increase permeability.

Geologic matrix (*or aquifer media*). The geologic matrix or aquifer medium that serves to hold water acts as the "container" for groundwater to exist in it. Groundwater may be contained in minute pore spaces of the geologic matrix. Underground channels for groundwater do exist in carbonate geologic formations, because water may have dissolved the formation along the fractures, creating the channels over time. Groundwater can flow from one geologic "container," or formation, to another, with the rate of flow depending on a range of factors, including the amount of pore space and the pressure under which it exists. The generic hydrogeologic settings found in the United States and elsewhere in the world are listed in Exhibit 2.4. This list of hydrogeologic settings reinforces the concept of highly complex conditions under which groundwater occurs in the subsurface environment. In the United States, based on their inherent characteristics, there are 48 common settings, but the natural variation within them is great so as produce wide ranges of specific settings found in the ecosystem.

The geology also affects the accessibility to groundwater. Clays and sands are relatively easy to drill through or dig. However, sand with large cobbles or boulders can damage drilling equipment and slow down the drilling progress. In some cases, more expensive and sophisticated drilling equipment may be necessary. Drilling in bedrock requires durable equipment that is more costly to operate and maintain, as well as requiring specialized training to use. These factors affect the cost to obtain groundwater.

EXHIBIT 2.4 GENERIC HYDROGEOLOGIC SETTINGS OF THE UNITED STATES (LISTED ALPHABETICALLY)

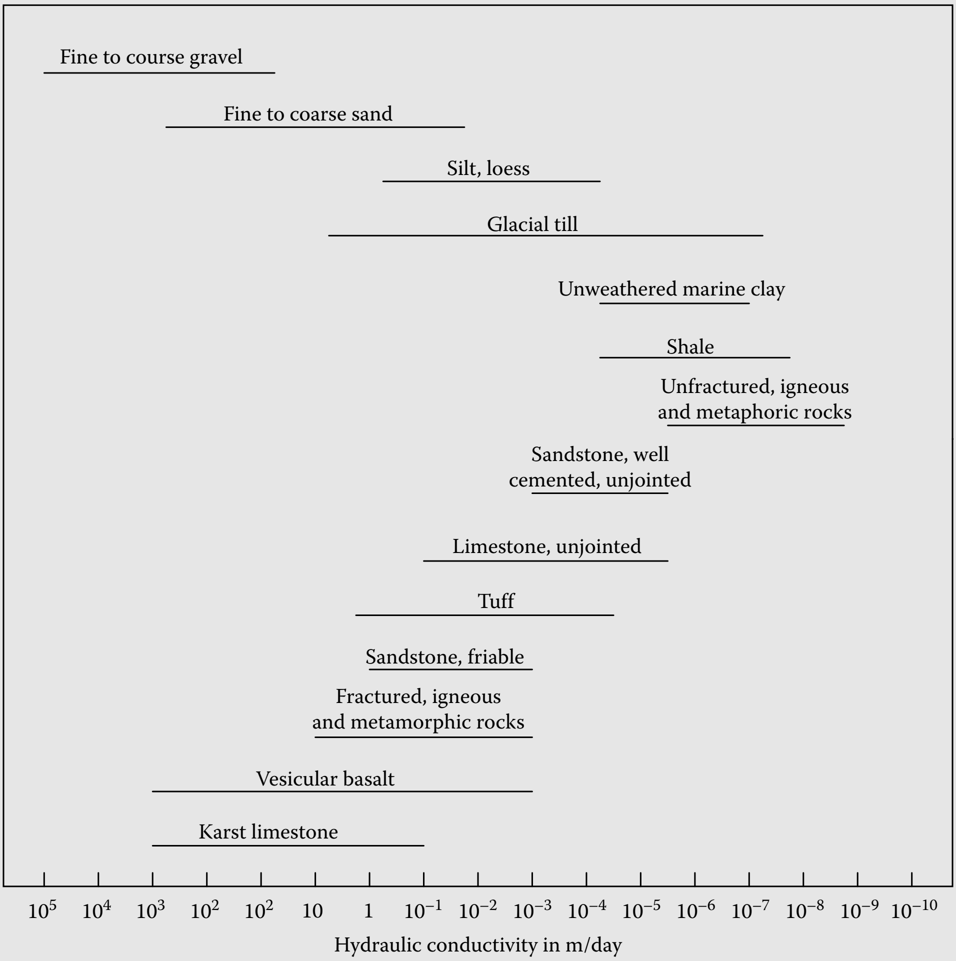
1. Alluvial basins (internal drainage)
2. Alluvial fans
3. Alluvial mountain valleys
4. Alluvium
5. Alluvium and dune sand
6. Alternating sandstone, limestone, shale with deep regolith
7. Alternating sandstone, limestone, shale with thin soil
8. Beaches and bars
9. Beaches, beach ridges, and sand dunes
10. Bedrock of the uplands and mountains
11. Braided river deposits
12. Buried valley
13. Coastal beaches
14. Coastal lowland deposits
15. Confined regional aquifers
16. Consolidated sedimentary rocks
17. Glacial and glaciolacustrine deposits of the interior valleys
18. Glacial lake deposits
19. Glacial till over bedded sedimentary rock
20. Glacial till over crystalline bedrock
21. Glacial till over outwash
22. Glacial till over solution limestone
23. Glacial till over sandstone
24. Glacial till over shale
25. Glaciated mountain valleys
26. Lava flows hydraulically connected
27. Lava flows not hydraulically connected
28. Moraine
29. Mountain crests
30. Mountain flanks
31. Mountain slopes
32. Ogallala
33. Outwash
34. Outwash over bedded sedimentary rock
35. Outwash over solution limestone
36. Playa lakes
37. Resistant ridges
38. River alluvium
39. River alluvium with overbank deposit
40. River alluvium without overbank deposit
41. Sand dunes
42. Solution limestone
43. Swamp
44. Thin till over bedded sedimentary
45. Triassic basins
46. Unconsolidated and semiconsolidated shallow surficial aquifer
47. Wide alluvial valleys (external drainage)
48. Volcanic uplands

Source: United States Environmental Protection Agency (USEPA), *DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeologic Settings*, EPA/600/2-85/018, Washington, DC, 1985, 163.

Subsurface water migration. Once the water moves from the soil to the vadose or unsaturated zone, its rate of migration depends on the size of the particles and pore spaces making up the geologic matrix and the pressure of the water above it, creating a hydraulic head. This is also true for the saturated zones of water called the aquifer, or the groundwater at and below the water table. In clay, groundwater may move as slowly as 0.00000001 m/day (Driscoll, 1986, p. 75) Attempting to pump water from such a strata would be fruitless. On the other hand, sand and gravel aquifers may allow water to travel at rates equivalent to thousands of meters per day. These aquifers are very productive; that is, they can usually provide large quantities of groundwater in relative short timeframes, and can continue to do so as long as drought is not a problem for their recharge. Exhibit 2.5 portrays the typical range of hydraulic conductivity for a range of aquifers, both consolidated and unconsolidated (after Driscoll, 1986, p. 75).

Water traveling in underground rivers is a myth based on fact. In fractured limestone, water, over time, can move along the fractures and dissolve the calcium carbonate that makes up the limestone.

EXHIBIT 2.5 TYPICAL HYDRAULIC CONDUCTIVITY (GROUNDWATER MOVEMENT POTENTIAL) FOR A RANGE OF AQUIFER TYPES



Source: Adapted from Driscoll, F.G., *Groundwater and Wells*, U.S. Filter/Johnson Screens, St. Paul, MN, 1986, 1089. With permission.

As this dissolution occurs over time, large channels develop, called solution channels. In some locations, the dissolution has been so extensive, forming caves and caverns in which people have observed "underground streams." As fractures may intersect, the solution channels may also intersect. Thus, in an area with limestone close to the surface and in which water has been dissolving the calcium carbonate, this underlying geology may have the rough appearance of stormwater collection lines. These areas also typically have "sinkholes," where a cavern or channel has caved in from the above (Figure 2.1). This type of carbonate geology is called "karst." Groundwater movement is very rapid in solution limestone and karst areas, traveling as fast as 3.3 km/day (USEPA, 1985). For comparison water in the Mississippi River at New Orleans, Louisiana, travels at a rate of 5 km/h (USNPS, 2004). Limestone aquifers can be very productive.

Typically, groundwater moves slowly and each particle in the ground becomes an obstacle to movement in a straight line. This is the reason for groundwater contamination typically being localized around the source of contamination, in contrast to traveling tens or hundreds of kilometers in a matter of days or weeks in a river.

Subsurface water migration in an economic context means that groundwater can move from place to place, crossing political or property boundaries, carrying natural or anthropogenic (human-caused) contaminants in the process. Locations in which groundwater moves at faster rates are places where the resource can be produced more easily, minimizing the financial costs of withdrawal, which probably do not include the ecosystem costs of that production.

Recharge zones. Locations that allow water to move with relative ease from the ground surface to the water table are called "recharge zones." Protection of these zones is important in areas of groundwater use because they are the principal locations where water enters the subsurface to supply the aquifer. Rates of recharge are highly dependent on precipitation rates and the geologic matrix. In

FIGURE 2.1 Sinkhole collapse near Ocala, Florida. (*Source:* U.S. Geological Survey)

arid alluvial basins bordered by mountains, recharge rates may be no more than 0.03–30 mm/year. In very humid regions, such as Pacific volcanic islands overlain with alluvium, recharge rates may be as high as 1000 mm/year (USEPA, 1985).

Discharge zones. Areas through which groundwater moves from the subsurface environment to the surface are referred to as "discharge zones." These discharge zones can be stream channels, lake and ocean beds, springs, and wetlands. In some cases, groundwater discharge to a stream may constitute most of its flow (USGS, 1999b).

Productivity or yield. The rate at which groundwater can be pumped from an aquifer or discharged through a spring on a continuing basis is the yield of an aquifer. Bedrock aquifers have varying productivities or yields depending on the grain size, space between the grains, and fractures (also referred to as secondary porosity). For example, granite with minimal fracturing and little pore space may provide almost no water. Highly fractured sandstone with pore space between sand grains is very likely to be a good source of water if it is saturated. Sand and gravel aquifers that may have porosities of 20% or more are highly productive. These may exist along stream valleys, glacial outwash areas, and the base of mountainous regions. Groundwater can easily move through these geologic materials, providing reliable, economical water supply. Yields may range from 0.01 to 0.02 m^3/min in the shale aquifers of Ohio to 4–76 m^3/min in the limestone and dolomite aquifers of Florida (USGS, 1984).

Depth. Depth of the water table, the surface of the saturated zone at the top of an aquifer, is an important element in determining the accessibility of an aquifer for groundwater use. Depth of the water table determines a portion of the cost of drilling and installing a well. Depth also affects the amount and therefore, the cost of energy to lift the water out of the ground by pump. Depths may range from 1 m to over 2000 m (USGS, 1984).

Surface water and groundwater interaction. In locations where streams flow over sand and gravel or fractured bedrock, water from the streams may move into the saturated zone of the ground, recharging the aquifer and later back to the stream depending on the water table levels and hydraulic gradients from place to place along the stream. The nearby wells in this same lithology may typically be shallow and may be drawing water that was previously in the stream. In these situations, the stream is the source water for the wells, and the aquifer acts as a conduit, with the stream bed filtering out large sediment particles carried by the stream.

Wetlands. Wetlands are lands in which water saturation is the dominant factor determining the nature of the soil development and the types of plant and animal communities living in the soil and on its surface (USEPA, 2005b). Groundwater can facilitate the movement of nutrients in wetlands and influence the local microclimate by supporting plant transpiration, thereby sustaining unique flora and fauna (Harvey et al., 2007b). "Wetlands can receive groundwater inflow, recharge groundwater, or do both" (USGS, 1999b). Many wetlands are places of groundwater discharge that maintains the wetlands when no rainfall occurs, and consequently, no overland flow and runoff are generated.

Safe yield and sustainability. The concept of "safe yield" of an aquifer is important in the supply of groundwater and applies to unconfined aquifers, typically, the first aquifer below the ground surface. This term applies to situations in which the rate of pumping and groundwater withdrawal is equal to the rate of aquifer replenishment from precipitation and other sources or recharge. "Safe yield" indicates that the average water table level in the aquifer does not decline and has reached an equilibrium. If pumping and groundwater withdrawal exceeds the safe yield of an aquifer, then groundwater is being "mined," exploited beyond its normal recharge rate, and the water table in the aquifer will drop. In the Central Plains and southwest United States, pumping for irrigated agriculture has mined large aquifers resulting in a decline in the water table of nearly 3 m/year and a total water table drop of 152 m in some locations (USGS, 1985). In the northern part of the state of Gujarat, India, groundwater tables are falling at a rate of 6 m/year (Brown, 2004, pp. 103–104). To sustain irrigated agriculture in these areas, typically new wells must be drilled and installed to greater depths, anticipating future drops in the water table. In locations with declining water tables, groundwater production may not be at levels of "safe yield" and may be unsustainable in the long term. Mining of groundwater reduces the habitat of the subsurface portion of the ecosystem that may also be closely connected to the water supply of streams and lakes.

Even confined aquifers can suffer declines in water level. While confined aquifers are typically under pressure and can naturally push groundwater up a well (partially or completely, depending on the hydraulic head), confined aquifers in the New Jersey Coastal Plain Aquifer System have experienced declines of 60 m or more in some places (USGS, 1995).

OTHER FACTORS AFFECTING GROUNDWATER SUPPLY

Several other factors make groundwater supply a complex issue. While wells can be costly to install in many lithologies, harder bedrock and boulders in sediments and glacial drift make drilling difficult and more expensive. Larger diameter, higher capacity wells are more expensive to drill and install. Larger pumps are more expensive. If water is to be supplied for human consumption, it may need treatment if the well supplies a public water system. Even water from private wells may need treatment for iron, calcium, or other minerals and compounds in groundwater. Water softeners can remove minerals, while carbon filters can remove other chemical constituents, either natural or man-made, in the water. These factors are covered in subsequent chapters.

GROUNDWATER AVAILABILITY

In terms of extent, the groundwater resource is vast, the largest source of freshwater, but less than 1% of all the water in the ecosystem. In the coterminous United States, about 223,300 m^3 of groundwater is within 800 m of the ground surface (USWRC, 1978, p. IV-18). In most of the world, groundwater is a ubiquitous resource, but access to it may be limited by depth or property rights (and technical and legal factors). In most locations, groundwater is accessible through wells. The cost to install a well takes into account the type of geology—for example, sand and gravel, fractured bedrock, or other geologic setting—and the depth to the water table and the diameter of the well, considering the volume of water needed at a site.

In more humid areas, groundwater typically may be easily accessible by shallower wells, because precipitation fills much of the pore space up closer to the ground surface. In drier climates, groundwater may only be available from deeper wells. However, this is not universally true and depends on the regional geology (USGS, 1984).

The use of groundwater has affected its availability. Importantly, the amount of groundwater in the world is reasonably fixed and with depletion of aquifers on all the continents (Danielopol, 2003, p. 111), less groundwater is available now. In the midwestern United States, the water table of the vast Ogallala Aquifer has dropped over 30 m in some locations owing to irrigation pumping; in the northcentral United States around Chicago by 274 m owing to pumping for water supply; and in the southwestern United States in many locations from 15 to over 30 m, primarily because so much water has been pumped out for irrigation, reducing the nearby streamflows where they are linked to groundwater (USGS, 2003b). While some of the irrigated water might return to the aquifer through subsurface infiltration, most is used by plants and then transpired or evaporated from the soil zone. All these factors affect where and how groundwater is used. Subsequently, groundwater becomes more of a "stock" resource, with real limits to its use in the indefinite future.

Impermeable area, that is, surfaces which do not allow water from precipitation to infiltrate the ground surface and ultimately percolate to the water table, affects groundwater availability in the ecosystem. As much of the world's population live in rural areas that produce crops for food and the expansion of urban areas is typically into the rural areas; much of the expanding impermeable area is encroaching into former agricultural zones. In the United States, an estimated 16 million hectares have been converted to roads and parking areas, at the rate of 0.07 ha/vehicle. Elsewhere in the world where the population density is higher, such as in Europe and Asia, the rate is less, 0.2 ha/vehicle, but the conversion is taking place (Brown, 2003). Additionally, the area in buildings, houses, and other structures is also impermeable. These areas cause water to runoff faster, resulting in less groundwater recharge, and, therefore, reduce groundwater availability in the ecosystem.

Relative to the groundwater discharge being available to support streams and other surface waters, groundwater migration and travel through the subsurface affect the delivery of water to streams. Soil infiltration of precipitation and percolation to the water table delays the effect of water transmission to streams. The result of subsurface movement of this water on streamflow is to defer and extend the delivery of this water to the stream, over time (Jha et al., 2003, p. 17). This soil infiltration and percolation of water to aquifers reduces runoff and flooding potential.

The availability of groundwater for the nonhuman part of the ecosystem is of increasing interest. As groundwater is a significant source of water for rivers and wetlands, wildlife depends on it extensively. As noted previously, groundwater is the habitat for fauna that requires this environment. Furthermore, many of these fauna migrate to surface waters for a part of their lives (Gibert et al., 1994a). Thus, availability and access to groundwater is essential for these species. However, the full relationship of this biota to the larger ecosystem is not well understood (Gibert et al., 1994a, p. 22).

GROUNDWATER QUALITY

Groundwater quality also has a significant effect on where and how groundwater is potentially used. Aquifers that contain only slightly mineralized water will readily be tapped for domestic and municipal uses. In some areas, where groundwater is from ancient deposits, brines and even radioactivity may be observed in it. Increasing depth in a geologic formation is observed to increase the temperature of the subsurface [0.6°C] per 30 m. Subsequently, with greater depth, the solubility of many minerals rises, resulting in more mineralized groundwater (Driscoll, 1986, p. 89). In these cases, the groundwater may not be useable, or at least may require treatment. If more recent freshwater is situated over such brines and production is increased to remove (or mine) the newer water, then the brines or other mineralized water may move toward the wells, reducing its quality for certain uses over time. These changed conditions may demand treatment of the water or finding a new water source, both of which have costs associated with them. Similarly, human-caused contamination can also have the same result in affecting a well that supplies drinking water. Interestingly, brines can have beneficial uses. For example, subsurface brines provide the basis for a chemical industry and are still produced for that purpose (also see next chapter).

Natural groundwater quality is a major factor in the supply of groundwater. Exhibit 2.6 identifies the common dissolved inorganic minerals in groundwater, but their presence depends on the chemical composition of the rock with which the groundwater is associated. Groundwater low in dissolved solids, mineral content, and nitrate and without harmful concentrations of other chemicals may be deemed safe for use as a drinking water source. In the western United States and now increasingly in the eastern United States, groundwater is used for irrigation, which cannot support agricultural productivity if too brackish. Groundwaters with high dissolved-solids concentration may be too brackish for irrigation; however, where higher quality is scarce, it may be used for cattle watering. Extremely brackish water (total dissolved solids in excess of 10,000 ppm) has very few uses. Brackish groundwater is also found in association with oil and in areas of excessive pumping of groundwater along the coasts, allowing intrusion of ocean's salt water into what was previously a freshwater aquifer.

EXHIBIT 2.6 PRINCIPAL NATURALLY OCCURRING DISSOLVED INORGANIC CONSTITUENTS IN GROUNDWATER (CATEGORIZED BY "TYPICAL" CONCENTRATIONS)

Major Constituents (Greater than 5 mg/L)

Bicarbonate
Calcium
Chloride
Magnesium
Silicon
Sodium
Sulfate

Minor Constituents (0.01–10.0 mg/L)

Boron
Carbonate
Fluoride
Iron
Nitrate
Potassium
Strontium

Trace Constituents (Less than 0.1 mg/L)

Aluminum
Antimony
Arsenic
Barium
Beryllium
Bismuth
Bromide
Cadmium
Cerium
Cesium
Chromium
Cobalt
Copper
Gallium
Germanium
Gold
Indium
Iodide
Lanthanum
Lead
Lithium
Manganese
Molybdenum
Nickel
Niobium
Phosphate
Platinum
Radium
Rubidium
Ruthenium
Scandium
Selenium
Silver
Thallium
Thorium
Tin
Titanium
Tungsten
Uranium
Vanadium
Ytterbium
Yttrium
Zinc

Source: Driscoll, F.G., *Groundwater and Wells*, U.S. Filter/Johnson Screens, St. Paul, MN, 1986, 97.

In major coastal cities that have relied on groundwater for water supply, groundwater production has been so substantial that saltwater intrusion has occurred (Driscoll, 1986, p. 773). This is a worldwide problem (Bear et al., 1999, cited in USGS, 2005a). "Saltwater is defined as water having a total dissolved-solids concentration greater than 1000 milligrams per L (mg/L). Seawater has a total dissolved-solids concentration of about 35,000 mg/L, of which dissolved chloride is the largest component (about 19,000 mg/L). Concentrations of chloride in fresh groundwater along the Atlantic coast [of the United States] are typically less than about 20 mg/L [the drinking water standard], so there is a large contrast in chloride concentrations between freshwater and saltwater" (USGS, 2005a). In situations of high levels of saltwater in groundwater, cities need to seek alternative water sources, including other wells outside the zone of saltwater intrusion.

The United States Geological Survey documented the background concentrations of certain naturally occurring minerals in groundwater across the United States. Some of these minerals have human health effects of concern when they are consumed at higher concentrations. These groundwaters require treatment for safe human consumption. This subject is addressed further in Chapter 6. The USGS found that natural background levels of nitrate, ammonium, and phosphorus in groundwater were less than 2 mg/L, less than 0.1 mg/L, and 0.1 mg/L, respectively. Exhibit 2.7 gives a perspective of nitrate concentrations in different settings.

Other natural minerals listed in Exhibit 2.6 that occur in groundwater and may be harmful to human health include arsenic, asbestos, barium, cadmium, chromium, copper, fluoride, lead, mercury, nitrate, radium, selenium, and uranium (USGS, 1998a,b, 2000; WHO, 2004; USEPA, 2005a). As noted previously, these elements are found in the earth's crust and dissolved by water (USEPA, 2000, 2005a; WHO, 2004). Considering minerals of recent concern, higher levels of arsenic tend to be found in groundwater than in surface water (USEPA, 2005a). The health-based standard for arsenic set by the

EXHIBIT 2.7 RELATIVE OCCURRENCE OF NITRATE IN DIFFERENT SETTINGS

Settings with Higher NO_3 Concentrations	Settings with Lower NO_3 Concentrations
High rainfall, snowmelt, and/or excessive irrigation	Low rainfall, snowmelt, and/or irrigation
Well-drained and permeable soils underlain by sand and gravel or karst	Poorly drained soils
Areas where crop management practices slow runoff and allow more time for water to infiltrate into the ground	Cemented sandstones and crystalline rock
Low organic matter content and high dissolved oxygen that minimize NO_3 transformation to other forms	Urban, forest, and range lands

Sources:

1. United States Geological Survey (USGS), Nutrients in the Nation's Waters, Too Much of a Good Thing? Circular 1136, 1996, 16.
2. United States Geological Survey (USGS), The Quality of Our Nation's Waters—Nutrients and Pesticides, Circular 1225, Reston, VA, 1999a, 13.

World Health Organization (WHO, 2005), the European Union, and the United States is 0.010 mg/L. In the United States, locations in western states and parts of the midwestern and northeastern states have arsenic concentrations higher than the health-based standard, but the majority of the locations have concentrations below the standard in their water (USEPA, 2005a). However, locations in India, Bangladesh, Vietnam, Taiwan, and Argentina have arsenic concentrations in groundwater up to 50 times the standard (EU, 2005). Health effects of high arsenic levels include skin damage or problems with circulatory systems and increased risk of cancer (USEPA, 2005c). Health-based standards for radium and uranium are 5 pCi/L and 0.030 mg/L, respectively, and health effects of high levels include increased risk of cancer.

Increasingly, the presence of man-made chemicals is observed in the ecosystem. As the U.S. Geological Survey notes, "for nearly every type of water use, … water has increased concentrations of dissolved constituents…" (USGS, 1999a, p. 77). As discussed in the following paragraph, with groundwater in the first or shallow aquifers vulnerable to chemical or microbial residuals applied on the ground surface or under it, the application of nutrients and pesticides has been widespread and has resulted in their presence in groundwaters around the United States (USGS, 1999a,b) and worldwide (Sampat, 2000; UNESCO, 2003). The U.S. Geological Survey conducted 36 studies in 21 large river/aquifer systems in the United States during the 1990s and found nutrients and pesticides in shallow and deep groundwater, as described in Exhibit 2.8 (USGS, 1999a). One conclusion based on current standards is that aquatic life may be at a greater risk from pesticides than human health.

Fuel and heating oil stored in above- and underground tanks, and the use and disposal of household products disposed in septic systems that are or contain volatile organic compounds (VOC) are additional sources of human-produced contaminants in the ecosystem. The U.S. Geological Survey evaluated for 55 VOC in nearly 1926 domestic wells in 39 states from 1986 to 1999 (USGS, 2002). It found at least one VOC in 12% of the samples. The solvents were detected most frequently in 4.6% of the samples. Mixtures of VOCs (more than one) were found in half of the samples tested. Only 1.4% of the samples exceeded drinking water standards or health criteria.

Generally, groundwater quality in the ecosystem is affected by the geologic conditions in which groundwater resides, by human withdrawal—particularly, along coastal zones, and by residuals from wastes and products.

EXHIBIT 2.8 FINDINGS OF NUTRIENTS AND PESTICIDES IN GROUNDWATERS OF THE UNITED STATES

Main findings of a study of groundwater quality related to nutrients and pesticides in 21 river basins in the United States include:

- 53% of the shallow groundwater studies in agricultural and urban areas had moderate nitrate concentrations above background levels.
- 3 of 33 major, generally deeper, aquifers—often a source of drinking water—had elevated nitrate concentrations.
- Nutrient concentrations vary seasonally because of precipitation and chemical application patterns.
- More than 50% of the wells in the agricultural areas had detectable herbicides above the drinking water standards, with only one well in the more than 1000 tested. Atrazine, its breakdown product diethylatrazine, metochlor, prometon, and simazine were the main herbicides detected.
- Insecticides were detected in less than 10% of the wells, but more wells had insecticides exceeding the health standard. Dieldrin and diazinon were the principal insecticides found.
- Deeper wells in major aquifers had substantially lower frequencies of herbicides and none exceeded the health standards.
- Contaminants in major aquifers are more likely to occur in vulnerable settings that allow rapid migration of groundwater from the shallow to the deeper aquifer.
- Groundwater can be a major nonpoint source of nutrients and pesticides to the streams.
- Aquatic life may be at a greater risk from pesticides than human health. While no United States criteria existed at the time from studies on major herbicides, 17 out of 40 streams exceeded the Canadian guidelines in the farming areas studied. Similarly, insecticides exceeded aquatic life guidelines in 18 of 40 streams examined in agricultural lands.

Source: United States Geological Survey (USGS), The Quality of our Nation’s Waters—Nutrients and Pesticides, Circular 1225, Reston, VA, 1999a, 82.

GROUNDWATER FLOW

LOCAL/ON-SITE FLOW

Water in the ground must first flow through the soil zone and unsaturated zone (also called the “vadose zone” with the space between the subsurface particles being occupied by both water and air) below it. The type of soil—sandy or clayey—will affect the extent of precipitation—which may be more or less, respectively—that enters the ground, as well as its rate of travel through the soil zone. The water can carry nutrients and contaminants at or near the land surface into the ground as it successively fills lower pore spaces between the soil particles and migrates downward toward the water table. In coarse soils made up of sand and silt, the larger pore spaces between the sand grains may also contain silt which can slow the water movement, depending on the percent of silt.

Water in the saturated zone may flow at very different rates depending on the type of aquifer material it is being transmitted through. These conditions are described for selected aquifer types in Exhibit 2.5. The important point of focusing on groundwater flow is that beyond the local flow system, groundwater can travel great distances, first in the watershed and then beyond the watershed within the larger region.

WATERSHED FLOW

Groundwater moves within a watershed, a typical management unit for water. A watershed is the area within a ridge of high land that drains into a stream or other water body at a particular point, usually at the intersection with a larger stream or the ocean. Watersheds vary in size depending on the scale of interest. Within a watershed, groundwater typically moves toward the points of discharge, which are streams and wetlands as well as springs and wells. If the elevation of the groundwater table is above the stream or other surface discharge point, then the hydraulic head of the groundwater will "push" it to a location of lower hydraulic head, such as the stream. A stream receiving groundwater as part of its baseflow (i.e., the ongoing movement of groundwater through a streambed to the stream, an important source of water for streams between precipitation events) is said to be a "gaining stream." If the level of groundwater is below a stream or other water body, the stream will recharge the groundwater within the watershed. The stream is then referred to as a "losing stream." In a watershed, the interaction between groundwater and surface water may be such that some portions of the stream are "gaining" and others are "losing." Watershed flow may be measured in months, years, or decades, depending on the hydraulic head and the geologic matrix.

REGIONAL FLOW

As the subsurface geology can be highly variable and does not necessarily match the other surficial features, groundwater can actually flow from one watershed to another. This condition is typical of deeper groundwater flow. Thus, the quantity and quality of groundwater at a site tens of kilometers away may influence the flow of a stream or its chemical constituents in an adjacent watershed. Regional groundwater flow from one watershed to another may take place over centuries, owing to the distance and complexities of the subsurface (USGS, 1999a,b, p. 5).

NATURAL SENSITIVITY AND VULNERABILITY

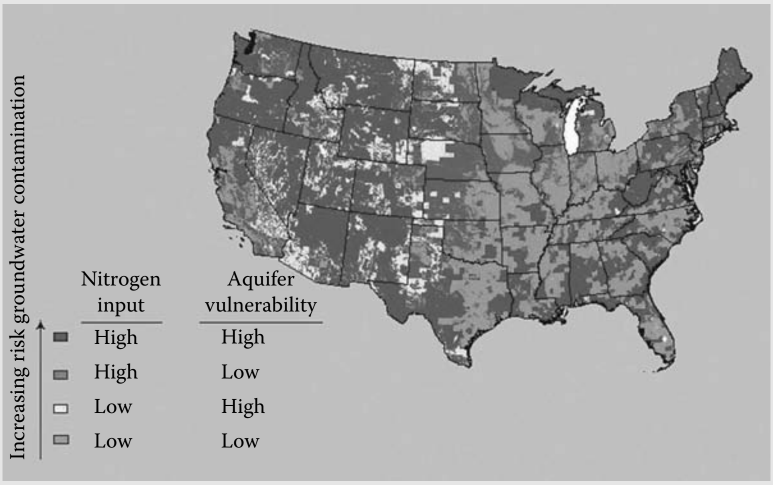
Hydrogeologists have developed systematic approaches to identify the natural sensitivity of areas relative to their potential to allow contamination. Factors include thickness of the unsaturated zone, the existence of a confining unit (or "aquitard"), permeability of an aquifer's geologic matrix, recharge rate of the aquifer, and location within the flow system (proximity to recharge and discharge zones) (NRC, 1993). Groundwater sensitivity is defined as "the relative ease with which a contaminant applied on or near the land surface can migrate to an aquifer" and is a function of the intrinsic characteristics of an aquifer (USEPA, 1993, p. 128). Many locations around the United States and around the world are naturally sensitive to contamination.

REGIONAL SENSITIVITY

Groundwater is known to exist in many types of geologic environments: unconsolidated sand and gravel and fractured bedrock, shallow or deep, with thin or thick soil layers above it, as well as confined and unconfined. All these and other factors can contribute to the sensitivity of groundwater to contamination. A study of aquifer vulnerability to disposal of liquid wastes at or just below the ground surface found that 42% of the continental United States (exclusive of Alaska, Hawaii, and territories) has groundwaters that exist in a geologic environment that is highly susceptible to contamination and another 16% that are moderately vulnerable. Exhibit 2.9 indicates the locations of increasing risk of groundwater contamination across the United States relative to nitrogen input to land typically with well-drained soils and less-extensive woodland (USGS, 1988). About 40% of the European Union area (in 2001) have "highly sensitive soils" relative to nitrate leaching (Notenboom, 2001, p. 253). The implication is that users of chemicals and fertilizers, and disposers of waste on or in the ground, must be very careful about chemical and waste management. The costs of carelessness are high. The costs to ensure that the proper steps are taken in areas of sensitivity are much less than those to remediate the contamination later, especially if it has spread, as will be discussed later.

EXHIBIT 2.9 INCREASING RISK OF CONTAMINATION

Areas on the map below have the highest risk of nitrate contamination of surficial aquifers that receive high nitrogen input, have well-drained soils, and have less-extensive woodland.



Source: USGS, 1988. A National Look at Nitrate Contamination of Groundwater. Reston, VA.

LOCAL SENSITIVITY AND VULNERABILITY

The sensitivity of groundwater in a particular area, such as the immediate vicinity of a wellfield, is influenced by many factors. Conditions of large areas cannot always be generalized to specific locations, as circumstances change over time and space. Furthermore, specific human activities related to chemical use increase the risk of contamination, making a particular location more vulnerable. Groundwater vulnerability is defined as "the relative ease with which a contaminant applied at or near the land surface can migrate to the aquifer or wellhead of interest under a given set of contaminant source management practices, well construction characteristics, and groundwater sensitivity conditions" (Wireman and Job, 1997). These factors include the sensitivity of the ground surface (or soil zone) and subsurface environment (local geology) to contaminant migration, land uses in the area, and the condition of the well(s). These specific factors that affect the local vulnerability can include (Jorgenson et al., 1998):

1. Results of past monitoring—Previous contaminant occurrence may indicate vulnerability of the groundwater resource.
2. Contaminant source risk—The existence (past or present) of a contaminant source may affect the chance of contaminant occurrence in a local groundwater supply. Furthermore, proper management of the potential contaminant sources, such as through a wellhead protection program, can also affect this risk.
3. Groundwater sensitivity—As noted earlier, the ability of the local hydrogeology to prevent the movement of contaminants through the soil or vadose zone is a critical factor in contaminant occurrence and may provide a barrier to or, conversely, a ready pathway for contaminants to reach the aquifer.
4. Well construction and condition—An inadequately constructed or deteriorated well provides pathways for contamination to enter the subsurface and contaminate groundwater.

The economic consequences of past contaminant occurrence, high risk from contaminant sources, high sensitivity to groundwater movement, and poor well construction or deterioration may include lack or loss of a water supply, the need to develop a new water supply, reduction in the development opportunities for otherwise usable land, and destruction of an important habitat.

Notably, the existence of unique habitats and natural sensitivities of groundwater and lands associated with them have resulted in protection of aquifers and their related land areas. In south central Texas, the Edwards Aquifer has been designated as a sole source aquifer by the United States federal government, and the state of Texas established a special administrative authority to oversee the balance of human and endangered species needs for its groundwater, with 14 threatened and endangered species identified. Exhibit 2.10 lists these species in the Edwards Aquifer. Similar findings of

EXHIBIT 2.10 THREATENED AND ENDANGERED SPECIES OF THE EDWARDS AQUIFER, TEXAS

All the forms of life living in the Edwards Aquifer have adapted to this existence by being colorless and eyeless. They often have other senses that are highly developed. These species rely on the water levels in the aquifer being maintained to support discharge to the springs and their substrate or spring runs in which they live. All the information currently available indicates that the subterranean aquatic ecosystem of the aquifer is the most diverse groundwater ecosystem in the world.

The threatened and endangered species of the aquifer are:

1. The Texas Blind Salamander, *Typhlomolge rathbuni*. Listed by both the state of Texas and the federal government as endangered.
2. The Blanco Blind Salamander, *Typhlomolge robusta*. Listed by the state of Texas as endangered.
3. The Cascade Caverns Salamander, *Eurycea latitans*. Listed by the state of Texas as threatened.
4. The Comal Blind Salamander, *Eurycea tridentifera*. Listed by the state of Texas as threatened.
5. The Toothless Blindcatfish, *Trogloglanis pattersoni*. Listed by the state of Texas as threatened.
6. The Widemouth Blindcatfish, *Satan eurystomus*. Listed by the state of Texas as threatened.
7. The Comal Springs Dryopid Beetle, *Stygoparnus comalensisis*. Listed as endangered by the federal government.
8. Peck's Cave Amphipod, *Stygobromus pecki*. Listed by both the state of Texas and the federal government as endangered.
9. The Fountain Darter, *Etheostoma fonticola*. Listed by both the state of Texas and the federal government as endangered.
10. The San Marcos Gambusia, *Gambusia georgei*. Listed by both the state of Texas and the federal government as endangered. It is possibly extinct.
11. San Marcos Salamander, *Eurycea nana*. Listed by both the state of Texas and the federal government as threatened.
12. Texas Wildrice, *Zizania texana*. Listed by both the state of Texas and the federal government as endangered.
13. The Barton Springs Salamander, *Eurycea sosorum*. Listed by the federal government as endangered.
14. The Comal Springs Riffle Beetle, *Heterelmis comalensis*. Listed by the federal government as endangered.

Source: Edwards Aquifer Research and Data Center (EARDC), Threatened and Endangered Species of the Edwards Aquifer System, 2006, URL: www.eardc.txstate.edu/endangered.html (accessed April 28, 2007).

groundwater dependence for endangered species and unique habitats relative to both quantity and quality of groundwater can be found in other studies as well (Harvey et al., 2007a,b). To protect the habitat of the New Jersey pinelands on the sand plain above an extensive sand and gravel aquifer (Kirkwood-Cohansey aquifer), the United States Congress established the Pinelands National Reserve in 1978. This area covers over 404,690 ha of farms, forest, and wetlands, including 56 communities and ecological settings with over a thousand species of plants and animals—almost 100 of which are threatened or endangered (USNPS, 2005).

HUMAN ACTIVITY AND ECOSYSTEM VULNERABILITY

Factors that make groundwater easily accessible and productive as a source of water supply also make it vulnerable to contamination from human activity. Historically, people settled in places that had many natural amenities: fertile soil for crops, easy access for transportation, and a reliable water supply. Shallow depth to groundwater allowed hand-dug wells. Places where water could be produced easily and in large quantities attracted larger populations. Furthermore, locations that allowed groundwater to be replenished readily—usually in sand and/or gravel or river valley alluvium—or large deep aquifers, also attracted industry. Human activity that generates wastes and excess residuals (such as from the use of chemicals that are not entirely used by plants or degraded promptly in the environment) may pose vulnerabilities to groundwater, especially when concentrated on or under the land in application areas or subsurface zones.

Industries use water for cleaning and cooling processes, and to carry wastes away. Liquid wastes may be sent back into the ground via disposal wells or seepage lagoons. Industries also use solvents, petroleum products, and other chemicals. Inadvertently, these chemicals may be spilled. Historically, when waste disposal or spillage occurred, business managers believed that the ground would cleanse whatever went into it. Many of these locations, because of their hydrogeology, allowed contaminants to be carried by groundwater easily in to the subsurface. Until the mid-twentieth century, science did not suggest that this circumstance was problematic. As populations grew and more industries went to locations where the water was available, more waste disposal and chemical spills occurred in densely populated and used areas. Enough time elapsed that past practices that were once acceptable finally started causing serious contamination problems. For example, New Jersey is one of the early industrialized states in the United States with extensively developed industry and substantial waste disposal in areas of sand and gravel aquifers that local populations used for drinking water. New Jersey has more abandoned uncontrolled hazardous waste sites than any other of the United States, while only being 47th in size. While we understand how to control many of the wastes and handle the chemicals today, past practices have shown that we must be careful about considering the location of the industry or any activity (e.g., use of lawn pesticides) in the immediate vicinity of wells and also in the larger subsurface zone that contributes groundwater to the wells.

Another example is the use of nitrate as a fertilizer. Nitrate is soluble in water and is easily transported by groundwater into the subsurface. Nitrate is associated with many human activities, domestic waste disposal and septic systems, manure disposal, and fertilizer applications on farms and residential property, and golf courses. As it easily moves with groundwater and is relatively inexpensive to test its presence, nitrate is often used as an indicator of human activity affecting groundwater quality when its concentration exceeds about 3 mg/L, considered as the natural background concentration in much of the United States. As noted in Exhibit 2.7, the U.S. Geological Survey found higher concentrations of nitrate in the agricultural areas, and lesser concentrations in urban and forested areas (USGS, 1996).

Other chemicals that are now recognized as indicators of impacted groundwater quality include trichloroethane (TCE) and tetrachloroethene (PCE), which are industrial solvents indicating industrial activity and the potential for other industrial chemicals to be present (USEPA, 2005c). The presence of atrazine, the most widely used pesticide, may suggest that other pesticides from past agricultural operations are in the groundwater at a particular location. The occurrence of chlorofluorohydrocarbons (CFCs, such as freon) with other contaminants, such as pesticides, can be used to age-date groundwater, as it was first used in the 1940s and its use steadily increased from that time. The CFC can be used as an indicator of younger water, providing evidence of precipitation infiltrating near the sampling point in recent times (USGS, 2004).

Significantly, the demands of our human population on groundwater, specifically, and the ecosystem, more broadly, are considerable. From 1950 to 2000, significant demands have been placed on the fixed set of resources that can be obtained only from the ecosystem. Specifically, during those 50 years (WI, 2005)

- World population has grown from 2.56 to 6.08 billion, nearly 2½ times
- Life expectancy went up from 46.3 to 64.7 years, an increase of 28%

From 1961 to 2000 (WI, 2005)

- Irrigated land expanded from 139.1 to 272.5 million ha, nearly doubling
- Fertilizer use grew almost 4½ times from 28 to 122 million metric tons

All these and many other factors contribute to the human demands on groundwater in the ecosystem, while this resource has declined because of depletion of aquifers worldwide.

BIODIVERSITY IN GROUNDWATER

As groundwater environments are at least as complex as surface water environments, they may have a similarly complex biological realm. Groundwater ecosystems typically rely on a flow of water and matter. Since the early 1990s, more research has been undertaken to understand the groundwater component of the ecosystem (Stanford and Simons, 1992), which, previously, had been mostly overlooked and disregarded (Gibert et al., 1994b, p. 22), except for concerns about microorganisms that could cause acute illness if they occurred in the groundwater used for drinking. Notably,

> [B]iological distributions and their controls in groundwater are likely to be as diverse and complex as those in surface waters. Just as in surface waters, the biological communities of groundwaters are highly varied, ranging from rich communities with dense populations of bacteria, fungi, protozoans, and hundreds of species of invertebrates to sparse communities of almost inactive bacteria. The distribution of the groundwater biota is certainly controlled by historical factors, physicochemical variables, biological interactions, and interactions among these broad classes of elements … though, we still know little about the extent of biological distributions in groundwater and the specific factors that control these distributions (Strayer, 1994, pp. 287–288).
>
> It has been estimated that the actual number of extant epigean species [*organisms still existing and living on the ground*] in the tropics is 10–20 times greater than the number currently known to science…. There is no denying that tropical epigean organisms are poorly known, but it is likely that on a global scale the groundwater biota is virtually unknown. It appears that groundwater biotopes [*environments*] contain highly diverse faunas with high levels of local and regional endemism [*organisms native to those areas*]…. [M]any truly epigean species colonize, or even depend upon, near-surface hypogean [*underground*] waters, especially when immature, which dramatically increases groundwater biodiversity (Gibert et al., 1994b, p. 22).

We will consider the range of groundwater environments in the ecosystem, but only in limited ways, as so much about them is still unknown, particularly their larger function in the ecosystem. Specifically, the part of the ecosystem that comprises groundwater, covered in this chapter includes (1) shallow, near-surface, (2) karst, (3) first aquifer, (4) littoral zones, and (5) deep aquifer environments. In addition, a note is also included on biodegradation.

GROUND AND NEAR-SURFACE

A vast array of flora and fauna rely on shallow, near-surface groundwater conditions. These locations include wetlands, marshes, and swamps, as well as many riparian areas in which tree and plant roots reach down to the water table. The total number of species and their function in wetlands are still being intensively examined (USGS, 2005b). Wetlands serve to remove nutrients and pollutants, provide spawning areas for fish and other wildlife, are wintering areas for migratory birds, and produce moderate coastal wave action and on-land flooding (USGS, 1997). Groundwater supporting spring-fed streams provides important minerals and nutrients as well as temperature control to promote healthy aquatic life in riverine environments (Born et al., 1997, pp. 42, 75, 115). Groundwater quality and flow to coastal estuaries support highly productive coastal aquatic zones by supplying nutrients needed by phytoplankton and fauna (Bate et al., 1992).

KARST

Karst is a particular landscape created through dissolution of soluble rocks (USGS, 2003a), such as chalk, dolomite, and limestone. Karst environments are characterized by solution channels in the rock with water in the channels and pore space. "In the United States, 20% of the land surface is karst…. Natural features of the landscape such as caves and springs are typical of karst regions" (USGS, 2003a). Bacteria densely populate the water and sediment in caves and carry out various functions, such as oxidation of sulfur compounds, iron, and manganese; nitrification; denitrification; and nitrogen fixation. Karst environments are subjected to quick changes in flow rates at different levels affecting the biota. Shallow karst has simpler assemblages of fauna, whereas deeper water has more diversity (Gibert et al., 1994b). In some locations, organisms existing on the ground actively migrate and colonize a karst aquifer during parts of their lifecycles (Gibert et al., 1994b). Research is being carried out on the ecological relationships and functions in karst (EC, 2001; UMM, 2005).

FIRST AQUIFER

The first aquifer may be an extension of the groundwater in a wetland at the ground surface or near-surface, or may be tens of meters below the surface serving as the habitat for microorganisms that process energy and matter, form minerals, and store biomass—offering the potential to naturally remediate polluted groundwater (Danielopol, 2003, p. 108). These aquifers were originally thought to be biologically homogenous and are now recognized to be heterogeneous (Gibert, 1992, p. 7). Groundwater ecosystems have significant crustacean (animal) species known as stygobites that have adapted to low-energy environments, in addition to bacteria and other microorganisms (Danielopol, 2003, p. 108). The first aquifer may have dissolved oxygen varying from high to low concentrations, "depending on the hydrologic and geologic conditions and the activity of the biota," but sufficient to allow aerobic processes to occur (Strayer, 1994, p. 295). Other factors affecting groundwater biota include supply of organic matter, temperature, sediment texture, salinity, low metabolic rates, long prereproductive periods, small broods, and long intervals between broods; however, predation is poorly understood (Strayer, 1994, pp. 297–304).

In the subsurface zones around the streams extending out under the floodplain where significant groundwater–surface water interaction occurs, referred to as the "hyporheic zone," significant movement of water, energy, and organisms transact to create a highly productive subterranean ecosystem. The hyporheic zone allows important microbial and nutrient interaction between ground and surface waters along the streams. This zone may laterally extend 2 km or more from a stream, as well as 10 m or more below a stream. The macroinvertebrates may spend a part of their lifecycle in groundwater before emerging to the stream. Bacteria provide nutrient cycling (Gibert, 1992, p. 7). The "standing crop biomass in the hyporheic zone could easily exceed benthic biomass in the river" (Gibert, 1992, p. 7). Thus, the significance of this zone for purifying water for streams and wells producing groundwater from it is now being recognized (Danielopol, 2003). Unfortunately, the effects of contaminants, such as pesticides, on hyporheic organisms is not well understood, but is of concern because the higher trophic levels are characterized by longer life spans and low reproductive rates (Notenboom and van Gestel, 1992, p. 316). "The potential for ecological recovery is low in groundwater; small effects might therefore have long-lasting consequences" and the effects may be more severe for microbial processes in anaerobic conditions in deeper groundwater (Notenboom, 2001, p. 257; 259).

Overpumping can change the structure of the groundwater habitat. In one case, a "reduction in the self-purification potential and therefore water quality was observed within the bank filtration area along the Danube [River] at Vienna [Austria] after the major part of the sediment-associated microbial biomass was removed together with the habitat, namely the fine sediment fraction, by overpumping of the water" (Danielopol, 2003, p. 116).

LITTORAL ZONES

As noted earlier, groundwater contributes to the ecological productivity of estuarine wetlands. Groundwater is also discharged along lakes and the coasts of the continents and is subjected to tidal influences (USGS, 2005a). The contribution of high levels of nutrients to littoral environments is a concern because of the extensive nutrient pollution of the near-surface aquifers in these zones (USGS, 1999a,b). Additionally, groundwater and surface-water flux through streambeds and wetlands in riparian zones influence the functioning of the biochemical reactions to affect the exchange of nutrients and organic material between the subsurface and surface components of a watershed system (USEPA, 1996; Tremolieres, 2001), and changes the chemistry of the water as it moves through the sediments (Hoehn, 2001). Furthermore, maintaining vital, hardy wetlands significantly affects the regional biodiversity (USEPA, 1996). Further research is needed on the effects of changes in the chemistry of these lake and ocean waters on the aquatic organisms because of the changes in groundwater quality (Stanford and Simons, 1992; USGS, 2005a).

DEEP AQUIFER ENVIRONMENTS

Deep aquifer environments typically are characterized by microscopic interstitial spaces and anaerobic conditions. Microorganisms—bacteria and archaea—have been found 4 km below the continents and 7.2 km under the ocean floor (Monastersky, 1997). "They use inorganic chemicals, such as hydrogen and hydrogen sulfide, rather than organic matter for their energy and carbon dioxide as their source of carbon. Geothermal, rather than solar, energy catalyzes chemical reactions that generate these life-sustaining chemicals from rocks and … [w]ater … the only absolutely essential ingredient" (Wirsen, 2005). Scientists found a diversity of microorganisms in the groundwater from gold mines in South Africa in fractured bedrock 3 km deep (Wirsen, 2005). Other scientists, who carried out research on a salt deposit 610 m beneath the ground surface in New Mexico, discovered what may be the oldest living microorganism found to date, surviving in a minute pocket of brine within a salt crystal formed over the last 250 million years (Wirsen, 2005). Additionally, discharge of groundwater from below the continental shelves is observed to add minerals to saltwater environments (Church, 1996; Moore, 1996), sustaining their aquatic life. Thus, deep aquifers may hold a vast array of microorganisms, the role of which in the ecosystem and the cycling of nutrients is not well understood.

NOTE ON BIODEGRADATION

With the diversity of the organisms and the geologic matrix in the subsurface and, specifically, in groundwater, there exists a potential for biochemical degradation of contaminants reaching the aquifers. The perspective of approaches to this capability in the United States is to provide natural attenuation; while in Europe, the focus has been to reduce the contaminant mass (Danielpol et al., 2003, p. 120). Danielopol (2003, p. 120) cited various results relying on "indigenous subsurface microorganisms" that "degraded" or "immobilized" a range of contaminants such as "monoaromatic benzol-toluene-ethylene-xylenes (BTEX), polycyclic aromatic compounds (PAHs), solvents and other chlorinated organic compounds (for example TCE, PCE, and vinyl chloride [VC]), nitroaromatic compounds (dyes, explosives, pesticides, and pharmaceuticals), heavy metals like Hg, Pb, Cd, Se, and Cr, and radionuclides." Notenboom (2001, p. 259) cautioned that the use of pesticides may pose risks to the "intrinsic sensitivity of … groundwater organisms," which are problematic because these organisms have low reproduction rates. Furthermore, he noted (1994, p. 487) that organic contamination can destroy subsurface organisms, because it creates an anoxic condition. Thus, human action affecting the subterranean ecosystem may eliminate useful biological production, as well as rely on it for long-term (years, even centuries) remediation if conditions are right.

GROUNDWATER OCCURRENCE AND HUMAN INTERACTION

As indicated earlier, the complex subsurface environment presents many different and unique hydrogeologic settings in which groundwater occurs. Even given the complexity, these subsurface settings usually extend over large areas and are replicated in nature that has allowed systematic development of the resource. The occurrence of groundwater through wells, springs, wetlands, and groundwater–surface water interaction affects our use of it.

WELLS

Typically, groundwater comes from wells installed with human action—hand- or machine-dug holes in the ground to and through the water table into the aquifer. These holes may be a meter to hundreds of meters deep. Once the hole is created, a container can be lowered to withdraw the groundwater, or a pump can be used to lift it to the surface. More details on wells are presented in Chapter 4. As groundwater is nearly ubiquitous, its occurrence allows inhabitation of areas that otherwise would not foster concentrated human activity and economic development.

SPRINGS

Springs are places where groundwater flows out onto the ground surface, down a cliff face, or through a river, lake, or ocean bed. They can be artesian, that is, the groundwater may be under pressure and may flow up to the surface. Springs are usually the result of water flowing along a fracture in the bedrock or along the plane of bedrock strata. Some small towns rely on springs for their source of drinking water without treatment. When springs appear without sources of contamination affecting them and are protected, their waters may be imbibed without treatment and sometimes considered clean enough to be bottled and sold as an alternative drinking water source, although regular testing is important to ensure its safety.

Springs are typically considered as either a "concentrated" or "seepage" spring. A concentrated spring flows from a point in a hillside, at which groundwater is naturally discharged from an opening in the rock. Seepage springs exist where groundwater flows or "seeps" from the ground covering an extensive zone, rather than one site (Jennings, 2005).

WETLANDS

Wetlands are typically lower lying areas in which groundwater maintains a saturated condition in the soil, often times with water from seasonal precipitation occurring in pools and over large areas. These are mainly locations of groundwater discharge (Winter, 1989) and are affected by the quality of the groundwater underlying the larger area around the wetland. Wetlands are considered to be significant locations for aquatic spawning and production (USEPA, 1996). "Many wetlands are among the most productive of natural ecosystems, exceeding the best agricultural lands and rivaling the production of tropical rain forests" (USEPA, 1996, citing NRC, 1991).

Groundwater occurrence in wetlands is critical for the natural balance in the ecosystem, providing water, minerals, and critical temperature variations, as well as a zone of natural decomposition and nutrient recycling (USEPA, 1995):

- Over one-third of the threatened and endangered species in the United States have only wetlands as their habitat.
- Almost half of the species require wetlands during their maturing stage.
- A wide range of other animals and plants rely on wetlands as a source of food, water, and shelter. Additionally, 50% of the endangered animal species inhabit wetlands, and 28% of the endangered plant species require wetland environments in the United States (USEPA, 1996).
- Estuarine and marine fish and shellfish, certain bird species, and some mammals require coastal wetlands for their survival.
- Most of the commercial and game fish reproduce and nurture their offspring in coastal marshes and estuaries.
- Nearly 35% of the rare and endangered species in the United States rely on wetlands habitat (USEPA, 1996).

Wetlands are a manifestation of groundwater occurrence. Exhibit 2.11 provides the hydrologic characterization of wetlands, which suggests that most wetlands are maintained by groundwater or have a significant groundwater component (Gibert et al., 1994a, p. 531, citing Winter, 1989). Consequential ecological interactions exist between groundwater-supplied wetlands and wildlife (Gibert et al., 1994s, p. 387). Wetlands are complex, biologically productive zones in the ecosystem (Cowardin et al., 1979), and groundwater flow to wetlands during drought is critical to their ecological maintenance (Gomez et al., 2001, pp. 318–319).

Loss of wetlands has occurred over time with the development of land-based activities. In the seventeenth century, the coterminous 48 states of the United States are believed to have had over 89 million ha of wetlands. As of 1997, this same area had approximately 42.7 million ha of wetlands. Alaska had an estimated 68.8–80.9 million ha of wetlands in 1980 (about half of the state) (USEPA, 2005d). From 1986 to 1997, the United States lost 23,674 ha of wetlands each year (USEPA, 2005d). A number of wetlands in the United States have been lost or are threatened by groundwater pumping (USEPA, 1996). Wetland loss is also an international concern, with 11 (out of 37) European Union countries reporting in 1999 that of the 420 wetlands, 153 were not endangered, and 11 were endangered from groundwater mining, with 46 endangered owing to other factors (EEA, 1999, p. 102). Loss of wetlands and their functions in the ecosystem are due to a range of natural and human factors, and some major ones are presented in Exhibit 2.12.

GROUNDWATER–SURFACE WATER INTERACTION

Groundwater–surface water interaction is increasingly recognized as an important part of the hydrologic cycle that affects both the quantity and quality of water in either source. As noted earlier, in the hydrologic cycle description, water can flux or move from a surficial aquifer to a stream, lake, or coastal zone, and vice versa. This circumstance is controlled by the geologic material constituting the stream, lake, or ocean bed, and the hydraulic gradient of those bodies of water and surficial aquifer at different times. In humid areas, streams often act as groundwater discharge points. Locations of groundwater discharge and exchange with surface water—fresh and marine—are highly productive ecological zones and are well documented (e.g., see Stanford and Simons, 1992, and Gibert et al., 1994b). In some locations, snowmelt water serves to recharge groundwater, for example, along the Platte River, as it crosses Colorado and Nebraska. Lincoln, Nebraska, gets its drinking water from wells along the Platte River, which draw water from the river through the streambed and into the subsurface. When the concentration of pollutants, such as pesticides is too high in a river, the wells near the river are shut down, so as to reduce

EXHIBIT 2.11 CLASSIFICATION OF WETLANDS AND DEEPWATER HABITATS OF THE UNITED STATES

WATER REGIME MODIFIERS

A precise description of hydrologic characteristics requires detailed knowledge of the duration and timing of the surface inundation, both yearly and long-term, as well as an understanding of groundwater fluctuations. As such information is seldom available, the water regimes that partly determine the characteristic wetland and deepwater plant and animal communities are described here only in general terms.

TIDAL

The water regimes are largely determined by oceanic tides.

Subtidal. The substrate is permanently flooded with tidal water.

Irregularly Exposed. The land surface is exposed by tides less often than daily.

Regularly Flooded. Tidal water alternatively floods and exposes the land surface at least once daily.

Irregularly Flooded. Tidal water floods the land surface less often than daily.

NONTIDAL

Though not influenced by oceanic tides, nontidal water regimes may be affected by wind or seiches in lakes. Water regimes are defined in terms of the growing season, which we equate to the frost-free period (see the U.S. Department of Interior National Atlas 1970: pp. 110–111 for generalized regional delineation). The rest of the year is defined as the dormant season, a time when even extended periods of flooding may have little influence on the development of plant communities.

Permanently Flooded. Water covers the land surface throughout the year in all years. Vegetation is composed of obligate hydrophytes.

Intermittently Exposed. Surface water is present throughout the year, except in years of extreme drought.

Semipermanently Flooded. Surface water persists throughout the growing season in most of the years. When surface water is absent, the water table is usually at or very near the land surface.

Seasonally Flooded. Surface water is present for extended periods, especially early in the growing season, but is absent by the end of the season in most of the years. When surface water is absent, the water table is often near the land surface.

Saturated. The substrate is saturated to the surface for extended periods during the growing season, but surface water is seldom present.

Temporarily Flooded. Surface water is present for brief periods during the growing season, but the water table usually lies well below the soil surface for most of the season. Plants that grow both in uplands and wetlands are characteristic of the temporarily flooded regime.

Intermittently Flooded. The substrate is usually exposed, but the surface water is present for variable periods without detectable seasonal periodicity. Weeks, months, or even years may intervene between the periods of inundation. The dominant plant communities under this regime may change as soil moisture conditions change. Some areas exhibiting this regime do not fall within our definition of wetlands, because they do not have hydric soils or support hydrophytes.

(*continued*)

EXHIBIT 2.11 (continued) CLASSIFICATION OF WETLANDS AND DEEPWATER HABITATS OF THE UNITED STATES

Artificially Flooded. The amount and duration of flooding is controlled by means of pumps or siphons in combination with dikes or dams. The vegetation growing on these areas cannot be considered as a reliable indicator of water regime. Examples of artificially flooded wetlands are some agricultural lands managed under a rice–soybean rotation, and wildlife management areas where forests, crops, or pioneer plants may be flooded or dewatered to attract wetland wildlife. Neither wetlands within or resulting from leakage from man-made impoundments, nor irrigated pasture lands supplied by diversion ditches or artesian wells, are included under this modifier.

Sources:

1. Cowardin, L.M. et al., *Classification of Wetlands and Deepwater Habitats of the United States*, U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC, Northern Prairie Wildlife Research Center Online, Jamestown, ND, 1979, http://www.npwrc.usgs.gov/resource/1998/classwet/classwet.htm (Version 04DEC98).
2. Also see USEPA, 2005b. Wetlands Definitions. Washington, DC.

the possibility of pumping contaminated water from the river through the subsurface during the spring after pesticide application.

As noted previously, groundwater may be discharged to streams and wetlands and maintain their water regime. For example, in a study of a small forested watershed northwest of Baltimore, Maryland, with no source of water other than precipitation, calculations indicated that the baseflow of the stream could be maintained from the groundwater discharge for 25–349 days. Groundwater was observed to sustain the stream for 187 days during a drought in the watershed (Cleaves et al., 1970). "Streamflow during a drought period originates almost entirely from subsurface [groundwater] storage that seeps into the streambed," such as the one that occurred in the Upper Mississippi River Basin, United States, during the drought of 1988–1989 (IDENR, 1994).

Groundwater–surface water interaction also points to another interesting environmental problem: shifting effects in the ecosystem to surface water in time. The control of nonpoint sources of pollution (such as widespread application of fertilizer and pesticides on lawns and in agricultural areas) is usually implemented to reduce overland flow of sediment and contaminants to streams. To reduce this

EXHIBIT 2.12 MAJOR FACTORS CONTRIBUTING TO WETLANDS LOSS

Human Actions

-Drainage
-Dredging and stream channelization
-Deposition of fill material
-Diking and damming
-Tilling for crop production
-Levees
-Logging
-Mining
-Construction
-Runoff
-Air and water pollutants
-Changing nutrient levels
-Releasing toxic chemicals
-Introducing nonnative species
-Grazing by domestic animals

Natural Threats

-Erosion
-Subsidence
-Rise in sea level
-Droughts
-Hurricanes and other storms

Source: United States Environmental Protection Agency (USEPA), Wetlands: Status and Trends, 2005d, URL: http://www.epa.gov/OWOW/wetlands/vital/status.html (accessed August 23, 2005).

flow, tillage practices are changed to allow water to reside on the ground for a longer duration and infiltrate. When this occurs, groundwater and its subsurface environment is the recipient of a substantial portion of the contamination. If those particular groundwaters are closely connected to the surface waters, much of the contamination may eventually reach the stream or lake which the nonpoint source controls are designed to protect. For example, groundwater discharge to the nontidal tributaries to Chesapeake Bay (United States) account for a median value of 54% of their streamflow and a median of 56% of the streams' nitrate loading to the bay (USGS, 1998a,b). Thus, the role of groundwater–surface water interaction in the ecosystem must necessarily address this interaction in the context of the larger hydrologic cycle.

During times of drought and flooding, groundwater–surface water interaction is important for stream recovery. This recovery is relatively quick because of the relationships of the stream, the watershed, and the hyporheic zone, in moving and storing nutrients and interstitial ecological communities (Valett et al., 1992, p. 396). However, the value of this interaction in the ecosystem to the productivity and sustainability of streams requires further research (Valett et al., 1992, p. 402).

THE WATER BUDGET

In its simplest form, the water flow of the hydrologic cycle can be expressed as a water budget. A water budget can exist for a community, a watershed, an aquifer, a region, or a country, as long as the parameters can be reasonably estimated. A water budget is an accounting of the inflow, outflow, and storage changes of water in a hydrologic unit. The equation for a water budget is expressed as inputs and outputs:

$$\text{Inputs} = \text{outputs}. \tag{2.1}$$

In the hydrologic cycle, the input is precipitation (*P*) and the output is equal to evaporation (*E*) and transpiration (*T*) from surface water bodies, land surface and vegetation, total surface water and groundwater flow (SW and GW) to oceans, and consumptive use (CU) of water by human activity in manufacturing products or for processes such as evaporative cooling in houses and power plants. This relationship may be summarized as

$$P = E + T + \text{SW} + \text{GW} + \text{CU}. \tag{2.2}$$

For example, the water budget for the United States is as follows:

- Precipitation, 15.9 billion m^3/day coming to the earth's surface in the coterminous United States
- Consumptive use, 378.5 million m^3/day
- Evaporation and transpiration, 10.6 billion m^3, and
- Total surface water and groundwater flow to oceans, 4.9 billion m^3 (USGS, 1999a,b).

The U.S. Geological Survey has estimated that 40% of the average annual streamflow of the United States is the groundwater discharge (GWD) to streams. From this information, GWD in the United States can be derived: the average annual streamflow is 4.7 billion m^3; if multiplied by 0.4, the calculation results in 1.9 billion m^3. This net GWD is equal, for example, to about 1.25 times the flow of the Mississippi River measured at its mouth below New Orleans, Louisiana. The GWD is greater in the humid eastern United States, where groundwater discharge may maintain as much as 90% of the baseflow of smaller streams. (USGS, 1999a,b, p. 40).

Can a water budget be developed for an aquifer? For a groundwater system budget, it is expressed differently from the one mentioned earlier, as follows (Dunne and Leopold, 1978, p. 219):

$$\text{Inputs} - \text{Outputs} = \text{Change in Storage (of the aquifer).} \tag{2.3}$$

Using some of the information from Exhibit 2.5 and further knowledge of groundwater flow, the following water budget equation can be developed for an aquifer underlying a basin or watershed:

$$\text{GWS} = I + \text{INJ} + \text{EL} + \text{SWR} - \text{SMV} - E - T - \text{CU} - \text{GWD}, \tag{2.4}$$

where
GWS = net groundwater storage in the aquifer
I = infiltration water
INJ = water injected into the subsurface through drains or injection wells
EL = other emplaced liquid wastes (e.g., from landfills) from which the liquid portion has leached to the water table
SWR = surface water recharge to the aquifer
SMV = soil moisture and water in the vadose zone
E = evaporation, which may be important where the groundwater table is close to or at the earth's surface, such as in wetlands
T = transpiration by vegetation
CU = consumptive use from human activity, not returned to the subsurface
GWD = net groundwater discharge to streams

Several other relationships are important to fully understand this water budget equation:

$$I = P - R, \tag{2.5}$$

where
I = infiltration water
P = precipitation
R = runoff or overland flow

Also,

$$\text{PER} = P - R - \text{SMV}, \tag{2.6}$$

where
PER = percolation water transmitted to the water table
P = precipitation
R = runoff or overland flow
SMV = soil moisture and water held in the vadose zone

This equation can also be written as

$$\text{PER} = \text{I} - \text{SMV}. \tag{2.7}$$

Rewriting the aquifer water budget through substitution gives

$$\text{GWS} = \text{PER} + \text{INJ} + \text{EL} + \text{SWR} - E - T - \text{CU} - \text{GWD}. \tag{2.8}$$

This equation shows that the net groundwater storage (GWS) in an aquifer is equal to the inputs of percolation water from precipitation transmitted to the water table, water injected into the subsurface through drains or injection wells, other emplaced liquid wastewater and surface water recharge to the aquifer, minus evaporation, transpiration, consumptive use, and GWD. The equations for

GWS and PER contain parameters important to managing human activities on the land surface that affect the amount of water reaching the aquifer, as well as the quality of that water. The GWS typically refers to the net storage of the first or surficial aquifer, which may leak water to the lower aquifers in complex hydrogeologic settings. Precipitation (*P*) falls over an area above an aquifer and may infiltrate rapidly if the soil zone is very sandy. On the other hand, the precipitation may be on more clayey soil that may allow saturation of only 8 cm before generating overland flow and runoff (*R*). Annual precipitation in the United States, as elsewhere, can vary widely from less than 8 cm in Nevada, to 38 cm in the central United States, to over 254 cm in the rainforests of Hawaii (UI, 2005). Runoff or overland flow is generated after the soil zone is saturated and where impervious surfaces allow rapid runoff without infiltration. Runoff follows the slope of the land surface and is collected in swales that flow into creeks and then into streams. Among other factors, the amount of runoff depends on the rate of precipitation, the soil type (sandy, clayey, or rock), preexisting soil moisture, land use and slope, and vegetation (USGS, 2003a). Large areas of impervious surfaces in watersheds from roads and buildings can increase the runoff, reducing the amount of precipitation that may infiltrate and percolate to the water table and reduce the GWS.

Similarly, the runoff can pick up contaminants from land and road surfaces and be collected in stormwater retention ponds that are designed to seep water slowly into the subsurface. Depending on the ability of the biochemical reactions to breakdown the various types of contaminants, groundwater may become contaminated due to the increasing concentration of these contaminated waters in these retention areas. Storm drains, septic systems, and other unsewered drains from commercial and industrial operations also may collect and inject (INJ) water of varying quality back into the ground. Additionally, landfills and accidental spills may result in emplaced liquid wastes (EL) that leach through the subsurface and reach the water table. Some of these wastes may also be held in the soil and released more slowly to the subsurface over a longer time period.

If a section of a stream flows over sand and gravel channels, such stream segments may allow some of the streamflow to enter the aquifer. This is called groundwater or aquifer recharge from surface water (SWR). Stream channelization can reduce the ability of streams to provide recharge to groundwater, and, conversely, groundwater to discharge to streams (GWD).

Evaporation (*E*) from groundwater may occur when the water table is very shallow or at the ground surface. Such a circumstance exists in wetlands. Wetlands are most often points of groundwater discharge, with the ground being saturated with water at the surface. Evaporation may also occur from the soil zone, reducing soil moisture. Where soil moisture is low, irrigation often is used to grow crops. In the High Plains of the central United States, use of groundwater for irrigation is a fundamental economic necessity for many crops. In this area, evaporation ranges from 127 to 254 cm/year, more in the warmer south and less in the northern plains. Along the Texas–Mexico border, evaporation may be as high as 305 cm/year in some locations. In the upper northcentral and northeastern United States, evaporation can be as low as 76 cm/year (GROW, 2005).

Transpiration (*T*) is a process in which water vapor is given off by plants during photosynthesis. Large plants, such as trees, with deep roots can pull water from a shallow aquifer and transpire it into the atmosphere. A large tree can transpire, depending on its size and temperature, from 378.5 to 3406.9 L/day on a hot summer day (ISU, 1994; FCDB, 2005). Hydrologists have documented diurnal fluctuations in water tables from trees "pumping" large volumes of water for transpiration during the day, temporarily lowering the water table. At night, the water table has been found to rise because of the reduced transpiration (Winter, 1994). Transpiration has an economic importance in places where irrigation is dominant in agriculture. If insufficient water is received by the plants for transpiration, they will die. Thus, sufficient groundwater may need to be pumped to the surface to provide adequate soil moisture for plants to survive the growing season.

Consumptive use (CU) is the human use of groundwater that results in evaporation, incorporation of water into products, or discharge into streams. Examples of these uses include electric power plants using groundwater for cooling, allowing steam to escape from cooling towers. Communities that rely on groundwater for their water supply often treat the resulting wastewater and discharge it to a stream. As a result, these locations may experience long-term lowering of the water table and the need to replace wells with deeper ones.

The GWD occurs where the local water table is at a higher elevation than the stream. Groundwater typically flows from higher hydraulic head to lower head, and this situation is observed in many watersheds and is the reason for such a large percentage of average annual baseflow in streams from GWD.

The model suggests that greater impervious surfaces, allowing more runoff and evaporation of the water held by them, as well as buildings, can reduce water infiltrating in a watershed to an aquifer. If the use of water from the aquifer exceeds infiltration, then the net GWS becomes negative and groundwater is depleted over time. Conversely, recharging the aquifer with recycled and treated water could increase the groundwater in storage in the ecosystem that may become available for use. Recharge of groundwater by untreated stormwater may have mixed results: water quantity is increased, but water quality may be negatively affected, depending on the conditions in the zone of capture of the recharge site and the geochemistry of the geologic formation. This circumstance is highlighted in Exhibit 2.13, which summarizes the results of investigations of stormwater infiltration ponds on groundwater quality.

Scientists are still working to define the biological realm of the subsurface, and more information is emerging about the flux of energy and matter and the biochemistry associated with that living environment. Eventually, the biochemistry budgets can be described to relate to the physical water budget. Consequently, a better understanding of the complex relationships may be possible.

EXHIBIT 2.13 STORMWATER RECHARGE EFFECTS ON GROUNDWATER QUALITY

A 5-year study of three representative stormwater catchment and infiltration ponds in Maryland, assessed the quality of groundwater and the infiltration of stormwater. The findings included:

- Contaminants reached groundwater indirectly because of (1) biochemical reactions in the impoundments that ultimately affected unsaturated-zone and groundwater pH and redox or that caused solubilization of metals from time to time, and (2) dissolution of the rock aggregate used in subsurface impoundments that released trace metals to solution.
- Infiltration rates during dry weather were less than 0.01 m/day and during storm events ranged from 11.7 m/day at one site to 65.8 m/day at another site.
- The trace-element composition of groundwater beneath storm-water impoundments contained heavy metals; storm-water infiltrate was the sole or predominate source. Concentrations were modest and usually did not exceed USEPA drinking water regulations; nevertheless, concentrations of cadmium, chromium, and lead exceeded USEPA [maximum contaminant levels] MCLs in some groundwater samples, and concentrations of barium, copper, nickel, strontium, and zinc commonly were elevated above background concentrations.
- Concentrations of anthropogenic organic compounds were usually below detection limits in stormwater and groundwater.

Source: Abstracted from Maryland Geological Survey (MGS), Geochemistry and Factors Affecting Ground-Water Quality at Three Strom-Water-Management Sites in Maryland, Report of Investigations No. 59 (Authored by Wilde, F.D.), Baltimore, MD, 1994, 201.

GROUNDWATER AND CLIMATE CHANGE

Will climate change affect groundwater quantity or quality? Climate change has a range of effects. An increase in carbon dioxide and/or other greenhouse gases raises temperatures, shifts precipitation patterns, increases evapotranspiration rates, and raises ocean levels, among other things (IPCC, 2001, Chapter 1).

Effects on groundwater can vary from region to region and aquifer to aquifer, but can be noticeable and predictable, particularly on shallow aquifers (IPCC, 2001, Chapters 1 and 4; ECan, 2004). The principal impacts on groundwater are changes in aquifer recharge, groundwater–surface water interaction, and groundwater use (Loaiciga et al., 1998, p. 5; ECan, 2004, Chapter 10). As the result of changing climatic conditions, if an upland region receives less precipitation, then less water will infiltrate and recharge aquifers, which will also affect groundwater quality and reduce GWD and their baseflow (ECan, 2004, Chapter 10). Conversely, if more precipitation is received, a greater amount of recharge will be available. As temperatures rise, more precipitation may be offset by higher evaporation rates. Higher temperatures in areas of already sparse rainfall may create greater soil moisture deficits than those that previously existed. Small changes in precipitation could have large changes in groundwater recharge. Modeling rainfall and groundwater levels for hypothetical climate change in central Tanzania indicated that a 15% decrease in precipitation could lead to a 40%–50% reduction in the recharge to groundwater, at a steady temperature (i.e., no change in evapotranspiration) (IPCC, 2001, Chapter 4). A study in 2008 by the Massachusetts Institute of Technology indicated a similar finding: a 20% rise in precipitation levels might raise aquifer recharge by up to 40% and, conversely, a 20% decline in the precipitation could reduce recharge by as much as 70%, which is of great significance to arid regions (MIT, 2008).

Two factors are considered to be important: timing of recharge and character of the aquifer (ECan, 2004, Chapter 10). The extent of response of aquifers to changes in the precipitation may be slower depending on the location. Fractured bedrock and unconsolidated aquifers nearer the ground surface will be more responsive to changes in precipitation. However, the effects on deeper aquifers may be different: deeper aquifers can probably be relied on to make up for deficiencies that shallow aquifers cannot supply. Thus, deeper aquifers may be depleted in situations where shallow aquifers cannot meet the water demand.

Rising sea levels may also impact the groundwater along the coasts of continents. Higher sea levels may raise the hydraulic head along the coastline. Groundwater tables of surficial aquifers may also rise and saltwater may advance inland, increasing the salinity of groundwater used for drinking water, as well as harming aquatic animals and plants and deeper-rooted vegetation. This change in groundwater quality may also affect coastal wetlands and the use of coastal groundwater for irrigation (USEPA, 1989, pp. 122–123).

SUMMARY: GENERAL OBSERVATIONS ON NATURAL FACTORS AFFECTING GROUNDWATER IN THE ECOSYSTEM

Groundwater has a strong three-dimensional aspect that makes it difficult to observe and sample (ITFM, 1997)—as well as making it expensive to access. As groundwater is out of sight beneath the ground surface, there is a cost to access it, usually by a well. Some general observations about groundwater in the ecosystem and their implications for its economic use include:

Groundwater exists under continental land masses. As groundwater exists in the vast volume of subterranean space nearly everywhere, it is available for supplying water nearly everywhere, can be accessed by people through wells and springs and by deep plant roots, and is the habitat for innumerable microorganisms that live in those places.

Groundwater is a finite resource. Just as the earth has a finite amount of water in its ecosystem, similarly, groundwater, while appearing vast, is also limited. The deeper ancient aquifers that supply irrigation water for many arid regions are being depleted. First, or shallow, aquifers can be replenished if they receive at least as much water from precipitation and recharge, as is being used; however, this is not the case in many places worldwide.

The environment in which groundwater exists is very complex. The range of unconsolidated and consolidated sediment and rock varies, even over short distances and depth. When we think of surface water, our minds focus on pictures of creeks, rivers, lakes, and oceans. Groundwater occurs in shallow sand aquifers, gravel aquifers, and fractured bedrock; in deep sandstone aquifers; in karstic solution channels of carbonate strata; and in deep strata that have "less permeable" or "confining" layers above it that retard the movement of groundwater through them, called "aquitards," such as shale. In fact, USEPA (1985) has identified 48 different typical groundwater environments in the United States, which have analogs on other continents. Each hydrogeologic setting has a chemistry that has been affected by the geologic environment within which it exists. The type of geologic environment influences the cost of producing groundwater from it and its use.

Furthermore, ecologically, the fact that the subsurface is alive with organisms has been given much recognition only since the 1990s, and we still do not understand their function in the ecosystem. The subsurface ecosystem is at least as complex as that of the surface waters. One estimate suggests that the biomass of certain single-cell microorganisms called prokaryotes living in groundwater of unconsolidated geologic formations may equal up to 40% of all the world's microbial biomass—and this is a conservative estimate (Danielopol, 2003, citing Whitman et al., 1998). More research is needed to comprehensively define the many subsurface organisms and their roles in the ecosystem.

Groundwater can be near the ground surface or deep. A shallow water table (e.g., 3–10 m) means that a well may not need to be too deep and may cost less than a deeper well (e.g., 30–150 m). Certainly, in wetlands, groundwater may be at the ground surface. However, if the water table fluctuates substantially, a shallow well may need to be made deeper to ensure a long-term supply of water for drinking or industrial use, and this would increase the installation and operation costs, as water would have to be pumped up to a longer distance. Groundwater is also contained in bedrock aquifers hundreds of meters deep.

Groundwater is more difficult to sample. Typically, the sampler may want a sample that is representative of the aquifer and not the water that may have been standing in the well for an unknown time. To ensure a representative sample, the sampler may pump three or more wellbore volumes of water, and subsequently take the sample. A sample can be taken by putting a tube made of inert plastic into the well down below the water table and using a pump to pull water up the tube and into a sample container. This process may take significant field time and add cost to this labor-intensive activity. The technology for real-time monitoring on a continuous basis is being refined. As microorganisms live in groundwater and could be indicators of its quality, technology for sampling this biota may also receive attention.

Groundwater chemistry and quality are affected by the chemistry of the geologic formation in which it exists, as well as its associated microbiological community, related to land use in the watershed above the aquifer. While groundwater typically moves through the interstitial pore space slowly, it reacts with the geologic formation through which it moves, carrying water-soluble molecules (as ions) with it. For example, a sand and gravel aquifer with significant iron content will result in groundwater with high iron content. Aquifers in fractured limestone or dolomite may have high natural calcium or magnesium concentrations, and if deposited with iron, may also have high iron levels. Other naturally found elements and chemicals occur in groundwater drawn from the rock or unconsolidated deposits, such as arsenic or radium. If a well is too close to or down gradient from a septic system that may release microscopic organisms into the geologic matrix, groundwater can pick up the microbiological contaminants that may have migrated into the subsurface. Removal of any of these elements or contaminants adds cost to making the water drinkable or usable in other applications.

Groundwater moves more slowly than surface water. Typically, groundwater moves in the subsurface in fractions of centimeters to meters per day, depending on the geological matrix in which it resides. Most streams allow water to move tens of kilometers per day.

If groundwater is contaminated, then slowly moving groundwater is likely to ensure that the problem will be localized. However, when the contamination has been in the aquifer for many years, an enormous area may be affected, for example, from 5 km^2 (Berkey and Zachry, 2005) up to 64.7 km^2—in this latter case, from 40 years of hazardous waste disposed on land and leaching into the ground and aquifer (USEPA, 2005e). The areas affected may include adjacent communities that need to be connected to alternative drinking water supplies, as they cannot use their groundwater. Slow movement of groundwater may mean long times for remediation of contamination.

Pollution can fan out in a plume or follow a particular geologic feature, for example, an esker. As noted earlier, pollution may spread slowly—perhaps 180–240 m or more each year—allowing it to cover an enormous area before reaching a well. As it migrates, it may fan out or disperse, creating a plume of contamination. Particular geologic features can facilitate movement in its direction. For example, in fractured bedrock, the contamination will follow the fractures. In an unconsolidated glacial till, an esker, which was formed by an ancient stream under a glacier depositing its load of cobbles and stones, may allow preferential flow along its meandering course. This feature and the contamination being transported along it could potentially be difficult to determine. Large areas of contamination as well as contamination traveling along paths difficult to track may be expensive to remediate, or they may be abandoned as a resource because of that substantial expense.

Areas of more rapid infiltration and recharge of an aquifer are areas which are both highly productive and are easily contaminated. The same characteristics that make certain aquifers very productive (rapid infiltration, faster times of travel, larger hydraulic conductivity) for groundwater also allow contaminants to move more easily into the aquifer. Aquifers near the ground surface (1–15 m) with low percentages of clay or silt in the overlying soil and comprising sand, sand and gravel, fractured carbonates, dolomites, or other bedrock have higher porosity (more open space between grains or rock) which is more openly connected, permitting water to pass through it more easily. Groundwater can travel 30–240 m/year in sand and gravel, and even faster in fractured limestone with solution channels—in kilometers per day. When contaminated, such groundwaters may be associated with high costs of determining the extent of contamination and even higher costs of cleaning it up, especially, if the contamination is extensive, either horizontally or vertically.

It is easier to produce groundwater in some geologic environments than others. The U.S. Geological Survey (1985) has documented the range of yields of major aquifers in each state. Some aquifers can only supply up to 38 L/min from a well. Others are able to produce 7,570–18,930 L/min and are the source of high-production wells used by public water systems and private irrigators. In some locations, groundwater is obtained from a series of aquifers to obtain sufficient volume of flow. In these situations, each aquifer has different characteristics that influence its groundwater flow. The complexity of the aquifer or aquifer system increases the cost of understanding whether these aquifers are good long-term sources of supply or will be difficult and costly to remediate if they become contaminated.

The quality of groundwater and adjacent surface water is related. Groundwater and surface water flow and interact in watersheds as a single resource and component of the hydrologic cycle and ecosystem. While they can be viewed distinctly, they merge and intersect when near-surface, shallow groundwaters discharge to or are recharged by the surface waters. Their biota are related and may have a significant effect on their collective water quality in a watershed.

APPENDIX: HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is a measure of water movement in the ground. It is measured by performing a field pumping test, measuring the elevation of the water table before the recovery of the water table to its initial elevation. This test can also be performed in a laboratory, but the geologic matrix is not under the same temperature and pressure conditions as in the field. This measurement is fundamental to the hydrogeologists' solution to Darcy's law (named after Henry Darcy who established the relationship) for water flow in a porous media:

$$Q = K(\mathrm{d}h/\mathrm{d}l)A$$

where

Q is the quantity of water
K is a constant (hydraulic conductivity) for the media reported as distance/time
$\mathrm{d}h/\mathrm{d}l$ is the change in the hydraulic head over a specified distance
A is the cross-sectional area through which the water moved

$K = Q/A(\mathrm{d}h/\mathrm{d}l)$, which when simplified through units of measure gives:

$$(m^3/t)/(m^2(m/m)) = m/t$$

where

m is distance
t is time

A large hydraulic conductivity, that is, larger distances traveled per unit of time, typically means a more productive aquifer and lower cost in producing large volumes of groundwater where the aquifer is large.

Hydraulic conductivity has been restated to a more general term called "time of travel" (TOT), which describes the travel of groundwater in terms of time alone, and not distance. This concept is important in describing areas around wells for protection or if contaminated, the length of time required to pump the contaminated water out of the ground for treatment. As time is usually a factor in cost, measurements of hydraulic conductivity and TOT are critical.

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3 Groundwater in the Economy

GROUNDWATER'S INFLUENCE IN THE ECONOMY

Water affects every aspect of the economy. Obviously, it is essential for life and we could not live without it. We require water for food production. Water is used in manufacturing processes as a raw material and as a medium for removing wastes. It also influences places where development occurs. If water is not easily available, people may not live in that particular location and industries will not be established there. However, what about groundwater, in particular? A foremost consideration is that, in economic terms, groundwater currently produced at a site is likely to be considered the most economical source of water supply—being available in sufficient quantity and quality for a significant period of time at a location convenient for its intended or primary use at the least cost, when compared with other options for water supply and use. Groundwater has influenced the development of cultures and communities around the world.

Groundwater serves and benefits the economy in five major ways:

1. As a necessity—people and all living things need water to live, for drinking, to satisfy their thirst, and remain healthy (UNESCO, 2003, p. 5; Daly and Farley, 2004, p. 87), and enable people to work in the economy by supplying labor.
2. As a commodity—people derive benefit from groundwater, especially if it is their only water source for drinking as noted earlier, for food preparation, as well as for bathing, laundering, and cleaning; and industries and farms use it as an input to producing manufactured goods and crops for food (UNESCO, 2003, pp. 8, 326; Daly and Farley, 2004, p. 87).
3. For ecological system (or ecosystem) services—water is the fundamental component of the hydrologic cycle which people rely on to provide the balance in nature to transmit nutrients, moisture, and energy; sustain all living organisms, even in ways that we have not yet understood; and provide necessary habitat for water-based food sources, a required input to fish, fowl, and game consumption (UNESCO, 2003, pp. 330–331; Daly and Farley, 2004, p. 87).
4. For residual absorption, that is, a specific and significant ecological system service—water dilutes, decomposes within its natural limits, and transports human wastes and agricultural and industrial residuals elsewhere as a service to the user and disposer (UNESCO, 2003, pp. 81, 86; Daly and Farley, 2004, p. 75).
5. For aesthetic and recreational purposes—people prefer good quality water environments for leisure pursuits, educational interests, and tourist attraction, which, in some respects, appear as a commodity (FAO, 1993; UNESCO, 2003, p. 16), such as hot springs, geysers, and streams, lakes and wetlands maintained through groundwater discharge.

Clearly, some groundwater uses have the "private good" characteristics of a commodity when one use precludes the water for other (rival) purposes. Obversely, groundwater moves, serves as a residual sink and conveyance, and sustains natural wonders, such as hot springs, and one person's use may detract from but not eliminate another's enjoyment of its existence or consumption of its service. In this latter case, groundwater is a "public good," as it would require substantial means to prevent others' use of it (FAO, 1993). As groundwater is mobile, it provides both aerobic and anaerobic contaminant degradation potentials, cycles nutrients, and holds and releases energy while supporting all organisms including human beings; its ecosystem services have a public good characteristic that has no market-based value, but rather is invaluable.

First, we will explore the significance of groundwater availability, use, and quality relative to the economy. Specific examples, such as the extensive use of groundwater for irrigation in the process of food production, will be used to highlight the resource's importance in the economy. Second, we will develop a model to understand the economic role of groundwater more generically.

GROUNDWATER AVAILABILITY

In most locations, groundwater is economically accessible through wells. These wells are long and typically narrow holes in the ground, usually installed by a well driller using a drill rig, but can be put in by hand techniques for shallow groundwaters (The subject of "Groundwater Access" is addressed in greater detail in Chapter 4). Wells usually have a metal casing; however, recent wells have plastic (PVC or polyvinyl chloride) casing, especially in developing countries. Depending on the depth from the ground surface to the water table, wells may be just several meters deep to hundreds of meters deep, even over 1000 m deep (Brown, 2004, p. 104), using oil-well technology. The cost associated with well installation takes into account the type of geology (e.g., sand and gravel, fractured bedrock, or other geologic setting) and the depth to the water table and the diameter of the well, considering the volume of water needed at a site or in a community.

The groundwater resource is extensive, as noted in Chapter 2. Approximately half of the groundwater is shallow (Driscoll, 1986, p. 55) and therefore, potentially accessible for use through wells. About half of this larger resource "is considered extractable if no consideration is given to changes in streamflow, the effect on the environment, and the costs of extraction" (USWRC, 1978, p. IV–18).

Groundwater lies beneath the entire surface of the continents, but the type of geologic formation in which it resides affects its accessibility and its economic production of usable quantities. Formations with a substantial percentage of larger connected open pore space may produce considerable quantities of groundwater. The best example is an aquifer of sand and gravel. Some are commonly capable of producing 1.9–3.8 m^3/min and more. Other formations composed of compacted clay and other rock may hold considerable water, but as the pore spaces are small and not well connected, very little water can be produced, in the range of 0.004–3.8 m^3/min (USGS, 1985). Thus, geology affects resource availability. The geology that allows development to occur away from streams and farms, and to have wells by their houses rather than long pipelines from distant streams with sufficient flow represents an economic advantage for using accessible groundwater: an individual can live almost anywhere. In the western United States, drier range lands can be used for cattle grazing, because wells pumped by windmills make groundwater available where no other water is visible. The irrigated agriculture of the midwestern United States from the Mississippi River to the Rocky Mountains has depended on large volumes of groundwater, with wells in some locations from 3 m to as much as 670 m deep (USGS, 1985).

Economic use of groundwater has affected availability. In the midwestern United States, the water table of the vast Ogallala Aquifer has dropped up to 30 m and more in some locations, such as in areas of Nebraska, because so much water has been pumped for irrigation. While some of the irrigated water might return to the aquifer through subsurface infiltration, most of it is used by the plants and then transpired or evaporated from the soil zone. Similarly, Monmouth County, New Jersey has used the Englishtown Aquifer whose water level has fallen about 30 m as a result of pumping for drinking water supply (USGS, 1985). Because of the fact that groundwater is the only principal water source in the northern region of Jordan, the water table has historically fallen at the rate of 1 m/year, mainly owing to irrigation (Schiffler, 1998, pp. 198–201). Falling water tables have been witnessed in every continent (UNEP, 1999; Sampat, 2000; Narayan et al., 2002; EEA, 2003).

As groundwater tables drop, wells may go dry and costs of operating wells may rise because of increased energy costs to pump the water up a longer column. A liter of water weighs about 1.2 kg. Pumping 1136 L/day to an individual home from a shallow well may not be a major cost. However, pumping tens of thousands of cubic meters, 100–200 m from below the earth's surface is a considerable cost. If a well is older and not deep enough, a new well may need to be installed to a deeper part of the aquifer to obtain adequate supply. Furthermore, if the rock that must be drilled through is harder, then the cost to install the well will be higher. All these factors affect where and how groundwater is used in the economy.

Recognition of conjunctive management of groundwater and surface water together in watersheds holds significant potential to improve water resource availability. As the renewable portion of groundwater (the flow of groundwater that is naturally or artificially recharged) may interact with surface waters (USGS, 1999), incorporating this relationship into utilizing the water resource optimally can facilitate maximum water use for the expanding needs in the economy. Artificial recharge of groundwater (through septic systems, retention ponds, or porous surfaces) keeps water near the points of use (Fields, 1994, p. 24), allowing nature to cycle it within a locality rather than hastening its movement to streams and beyond economic capture.

Groundwater availability also influences land values. For irrigated agriculture, land prices are affected by the amount of irrigation infrastructure in place (Tsur et al., 2004, p. 104). In the drier climatic areas of the western United States, groundwater has been the source for 39% of irrigation water, as indicated in Exhibit 3.1 (USDA, 1997). In the more humid eastern United States,

EXHIBIT 3.1 IRRIGATED FARM LAND IN 17 WESTERN U.S. STATES, 1997

State	Total Farm (km²)	Total Harvested Cropland (km²)	Total Irrigated (km²)	Groundwater Irrigated (km²)	Groundwater Application Rate (m/unit area)	Principal Irrigation Method[a] (%TotIrr)
South Dakota	8,994	3,366	1,203	558	0.20	S/78%
North Dakota	4,354	2,350	667	420	0.23	S/88%
Nebraska	73,438	33,451	23,036	20,514	0.25	S/53%
Texas	55,539	27,820	21,196	18,520	0.41	S/62%
Kansas	38,526	22,543	10,726	10,431	0.41	S/80%
Oklahoma	7,459	3,445	1,828	1,438	0.44	S/77%
Colorado	65,585	12,461	11,906	5,389	0.48	S/54%
Idaho	29,773	12,671	12,903	4,965	0.49	S/65%
Oregon	42,109	5,493	6,212	1,232	0.51	S/53%
Montana	65,825	9,223	7,045	188	0.52	F/71%
Wyoming	51,992	4,772	6,205	367	0.53	F/83%
Washington	13,757	7,585	6,292	1,804	0.57	S/81%
New Mexico	28,958	2,596	2,915	1,722	0.67	F/53%
California	49,986	31,292	32,940	12,431	0.69	F/54%
Utah	27,205	3,884	4,355	565	0.82	F/62%
Nevada	21,777	2,164	2,812	905	0.92	F/70%
Arizona	15,974	3,555	3,535	985	1.13	F/80%
Totals	601,250	188,672	155,779	82,436	0.45	

Source: United States Department of Agriculture (USDA) Economic Research Service, Data: Western Irrigation, 1997, URL: http://www.ers.usda.gov/data/westernirrigation/ShowTables.asp?tabList=1#flag (accessed March 24, 2005).

[a] This column uses a different source of information: USGS (2004).

S = sprinkler system irrigation.

F = surface or flood irrigation.

%TotIrr = Percent of total irrigated land reported by USGS (2004), irrigated by either the sprinkler or the surface (or flood) method; other irrigation methods were also used, but were not a principal method based on application to farm land area.

EXHIBIT 3.2 AVERAGE VALUE PER HECTARE FOR IRRIGATED AND NONIRRIGATED CROPLAND FOR 20 SELECTED U.S. STATES

	1999 Cropland Prices per Hectare (US$)		
State	**Irrigated**	**Nonirrigated**	**Percent Irrigated Greater (Less) than Nonirrigated**
Missouri	4,250	2768	53.5
Kansas	2,520	1539	63.7
Nebraska	3,830	2026	89.0
South Dakota	1,977	1198	64.9
Florida	9,761	3954	146.9
Georgia	3,311	2792	18.6
Arkansas	2,916	2422	20.4
Louisiana	2,372	2669	(11.1)
Mississippi	2,595	2125	22.1
Oklahoma	2,051	1396	46.9
Texas	1,977	1656	19.4
Arizona	9,637	n.a.	n.a.
Colorado	3,954	1001	295.1
Idaho	4,497	1779	152.8
Montana	3,237	853	279.7
Nevada	4,695	n.a.	n.a.
New Mexico	6,301	660	855.1
Utah	6,919	1804	283.6
Wyoming	2,249	593	279.2
California	13,961	4201	232.4
Oregon	5,016	2471	50.7
Washington	8,649	2026	326.8

Source: USDA, 1999. Census of Agriculture, Washington, DC.
n.a. = not available.

groundwater accounts for 72% of irrigation water (USGS, 2004). In particular, water availability affects agricultural land values because of the increased value of production on irrigated lands. In the United States, an average value (unweighted) of agricultural land that is irrigated is nearly 165% greater than that of unirrigated land in the 20 states surveyed, with a range of –11.1%–855.1% (USDA, 1999). Exhibit 3.2 provides details on the agricultural land values in 20 states of the United States. Similar results for India indicate that for 240 villages surveyed in the 16 largest states, the irrigated farm land prices were higher by an average (unweighted) of 63.6% than the nonirrigated land prices, as crop yields were greater in irrigated areas. In addition, farm and nonfarm incomes in those areas also increased with the irrigated land values and yields in India (Foster and Rosenzweig, 2003).

GROUNDWATER QUALITY

Groundwater quality also has a significant effect on where and how groundwater is used. Aquifers from which only slightly mineralized water can be produced will readily be tapped for domestic and municipal uses. In some areas, where groundwater is from ancient deposits that are now lithified (turned to rock) and fractured, allowing water to flow through the fractures, its quality may include higher concentrations of dissolved solids and even radioactivity. In these cases, the groundwater may not be useable, or at least may require treatment. In places where more recent freshwater is situated over brines and where production has increased to remove (or mine) the newer water, the brines or other mineralized water may move toward the wells, reducing its quality for certain uses over time. Significant and increasing withdrawal of groundwater along the United States Atlantic and Gulf coasts, where 65 million people reside and work, has induced saltwater intrusion resulting in closure of private and municipal wells and has resulted in the use of other wells and water sources (USGS, 2003). The consequences of these changed conditions are treatment of the contaminated water or finding a new water source, both of which have costs associated with them. Similarly, human-caused contamination can have the same effect on drinking water supply wells.

Contamination of groundwater has not only caused the resource to be abandoned, but also the land under which it lies to be removed from use in some cases. For example, in Love Canal outside Buffalo, New York, waste chemicals were disposed and buried, and a community was built on it later. After some years, it was discovered that the residents living above the old chemical waste disposal area (canal) were becoming sick because of the chemicals in the groundwater and soil. For over 20 years, the site was abandoned while being remediated. Groundwaters must be intercepted for treatment in such cases rather than being allowed to naturally discharge to the local stream and contaminate it (USEPA, 1987). In other locations, such as Shenyang, China, and Jaipur, India, and other large cities with industries using toxic chemicals and storing solvents in underground tanks, previous groundwater sources could no longer be used and alternate water supplies have been tapped (Sampat, 2000, p. 19). Currently, government and private sector programs all over the world are seeking to redevelop these locations, referred to as “brownfields” (Meyer et al., 1995).

Interestingly, waters that were once considered as nonpotable groundwaters because of higher concentrations of certain naturally occurring chemicals, such as brines (brackish groundwater), can have beneficial uses in the economy. In Michigan and other locations, the subsurface brines, often, but not always, in association with oil and natural gas, have provided the basis for a chemical industry and are still produced for that purpose. The ancient waters held by the subsurface were first used for producing commercial chemicals over 100 years ago. Early products from the brines which were used in the manufacture of other chemicals include bromine for the pharmaceutical and oil markets, chlorine for cleaning and salts, magnesium for the metals industry, and iodine for medical and pesticide applications (Brandt, 1997). More than 400 products have been produced from such brines (Dunbar, 1970, p. 484). Exhibit 3.3 highlights the early development of underground brines as economic deposits with commercial applications.

EXHIBIT 3.3 UNDERGROUND BRINES AS THE RAW MATERIAL FOR A CORPORATION

The Dow Chemical Company was established with the fascination and interest in the chemicals in underground brines by a chemist, Herbert Dow, in the 1880s, who observed them in samples from northeast Ohio natural gas-well operations. The brines were a waste by-product of gas production. Mr. Dow refined the method of using electrolysis for extracting chemicals from brines, producing bromine in the 1890s at a cost lower than other producers of that time. Dow and his associates used wells to produce brine for commercial chemical production in Michigan, Louisiana, and California. One of the first brine wells used by the predecessor to Dow Chemical Company was 914 m deep near Canton, Ohio, in 1889 (Brandt, 1997, p. 14). From these subterranean aqueous sources, the company has grown to one of the largest chemical companies in the world with annual revenues of $20 billion.

Source: Brandt, E.N., *Growth Company: Dow Chemical’s First Century*, Michigan State University Press, East Lansing, MI, 1997, 649.

MAJOR ECONOMIC GROUNDWATER USES IN NATIONAL AND INTERNATIONAL CONTEXTS

INTERNATIONAL

Globally, while difficult to accurately calculate, groundwater provides approximately 50% of potable water supplies, 40% of self-supplied industrial demand, and 20% of irrigated agricultural water use (UNESCO, 2003, p. 78). Worldwide groundwater withdrawals (GWW) are estimated between 600 and 700 km^3 (UNESCO, 2003, p. 78). Most of the world's cities and towns rely on groundwater as a source for municipal water supplies (Shah et al., 2000). By far, the largest use of groundwater is for agriculture, with 44 countries from all the continents using 74% of their GWW for agricultural use (including livestock watering), as reported in a statistics from 1973 to 1996 (WRI, 2005). Furthermore, groundwater is "the world's most extracted raw material … forms the cornerstone of the Asian 'green agricultural revolution,' provides about 70% of piped water supply in the European Union, and supports rural livelihoods across extensive areas of sub-Sahara Africa" (UNESCO, 2003, p. 78).

The uses of groundwater reported earlier have generated real products and benefits for the national economy of the United States, and similar uses around the world contribute similarly to the world economy. Groundwater is a significant economic resource and a basic requirement for 140 million people, nearly half the population, in the United States who rely on it as a source of drinking water and for other household purposes. Thus, it can be stated that groundwater supports about half of the labor supply supporting the economy of the United States. In the European Union, as 75% of the drinking water supply comes from groundwater, this resource similarly maintains a large proportion of the labor supply in the EU economy (Sampat, 2000). Exhibit 3.4 indicates that up to as many as 2 billion people worldwide rely on groundwater as a source of drinking water. Exhibit 3.5 shows the percentages of the drinking water supply in countries of the European Union which are derived from groundwater. In the industrial and power generation sectors, principal water utilization is for the production of food, paper, chemicals, refined petroleum, and primary metals, as well as for cooling (USGS, 2003). Groundwater in the United States accounted for 22% of all freshwater withdrawals, 42% of irrigated agricultural water supplies in 2000 (USGS, 2003), and was the source of water for 25% of irrigated cropland (Brown, 1996). Exhibit 3.6 highlights the key groundwater irrigation costs in the United States, showing the farmers' high capital and energy expenditures. In India, groundwater irrigates lands that produce 60% of the grain production (Shah et al., 2000), doubling yields that occurred solely from

EXHIBIT 3.4 PROPORTION OF DRINKING WATER FROM GROUNDWATER BASED ON WORLD REGION

Region	Proportion of Drinking Water from Groundwater (%)	People Served (millions)
Asia-Pacific	32	1000–1200
Europe	75	200–500
Latin America	29	150
United States	51	135
Australia	15	3
Africa	NA	NA

Source: Reprinted from Sampat, P., Groundwater Shock, *World Watch*, January/February, 12, 2000, www.worldwatch.org. With permission.

EXHIBIT 3.5 PERCENTAGE OF DRINKING WATER SUPPLIED BY GROUNDWATER IN SELECTED EUROPEAN COUNTRIES

Country	Percentage (%)	Country	Percentage (%)	Country	Percentage (%)
Austria	99	Germany	72	Portugal	80
Bulgaria	60	Greece	50	Slovak Republic	80
Czech Republic	43	Hungary	95	Spain	21
Denmark	98	Italy	80	Sweden	49
Finland	57	Netherlands	68	Switzerland	83
France	56	Norway	13	United Kingdom	28

Source:

1. European Environmental Agency (EEA), *Groundwater Quality and Quantity in Europe*, EEA, Copenhagen, Denmark, 1999, 123.

EXHIBIT 3.6 GROUNDWATER IRRIGATION COSTS IN THE UNITED STATES

In 1998, groundwater [in the United States] was the sole water source for 58.1 million hectares and supplied some of the water for an additional 15.6 million hectares of irrigated farm land. Groundwater from an estimated 336,000 irrigation wells served approximately 85,000 farms nationwide (USDA, 1999). Texas had the most wells used for irrigation in 1998 totaling to 65,000, followed by California (49,000), Nebraska (48,000), and Arkansas (37,000).

Groundwater is usually supplied from onfarm wells, with each producer having one or more wells to supply the needs of a single farm. On an average, a groundwater-irrigated farm will have more than 3 wells, with over 9% of the farms reporting 10 or more wells. The Farm and Ranch Irrigation Survey (FRIS) reported on irrigated areas by water source, which excluded certain irrigated farms with about 12.4 million (10%) of the irrigated hectares estimated from the Census of Agriculture. The FRIS is the sole data source for areas irrigated by a source of water, which also collects additional information, such as costs.

The costs associated with groundwater pumping reflect both the variable cost of extraction and the investment cost of access. Variable extraction costs primarily reflect the energy needed to power a pump. A limited number of artesian wells (less than 2%), in which natural aquifer pressure forces water to the surface, are located primarily in California, Arkansas, Kansas, and Colorado. Energy costs vary widely depending on the depth to water, pumping system efficiency, the cost of energy, pressurization needs, and quantity of water applied. In the United States, the total energy expenditures for all onfarm irrigation water pumping were estimated to be more than $1.2 billion in 1998, mostly associated with pumping groundwater. The average energy expenditures were $79 per hectare with a State range from $17 to $171 per hectare. The capital costs of accessing groundwater can be substantial, depending on the local drilling costs, well depth, aquifer conditions, discharge capacity, power source, and pump type. Furthermore, the capital costs for a typical well and pumping plant are widely variable, but usually lie in the range of $20,000–$200,000.

Source: Abstracted from United States Department of Agriculture (USDA), *Agricultural Resources and Environmental Indicators: Water Use and Pricing in Agriculture*, Publication No. AH722 (April) (Authors: Gollehon, N., Quinby, W., and Aillery, M.), Economic Research Service, Washington, DC, 2002.

rainwaters, while farmers' incomes have expanded by 80%–100% (FAO, 1993). Thus, groundwater is very significant to national economies around the world.

UNITED STATES

A wide range of uses of groundwater has been observed in certain regions in the United States, where large surface water supplies are not available or may only be a seasonal resource. These uses are described in Exhibit 3.7 for the year 2000, with percentages based on the total fresh groundwater volume used in the United States (115.1 km^3/year).

The USGS has estimated that fresh groundwater withdrawal in the United States, which was 315 million m^3/day in 2000, was 9% more than that in 1995 and 24% of all the freshwater withdrawals in 2000 (USGS, 2004). During the same time period between 1995 and 2000, fresh surface-water withdrawals declined in the United States by 1% (USGS, 2004). Thus, at the margin, groundwater provides an increasing volume to meet the demands of the economy in the United States. Exhibit 3.8 indicates the United States' national projection from its last in-depth national study of water use. Interestingly, the projection for the year 2000 and the actual population were surprisingly close; however, greater efficiencies were expected with regard to water use than those that occurred during 1975–2000. Young (2005, p. 71) noted the problems in making technology forecasts for water as an input to production. Exhibit 3.9 shows a comparison between groundwater and surface water use in the United States from 1995 to 2000.

Irrigation

Notably, the use of groundwater as a source of irrigation tripled from 1950 to 2000, and has resulted in the reduction in the use of surface water for that purpose. The national factors and costs affecting irrigation use in the United States are highlighted in Exhibit 3.6. Notably, groundwater accounts for slightly more than one-quarter of total irrigation water in the United States (see Exhibit 3.9); more

EXHIBIT 3.7 PERCENT OF GROUNDWATER USE IN THE UNITED STATES DURING THE YEAR 2000

Category	Purpose	Percentage of Fresh Groundwater Use[a]
Public drinking water	Life requirement for humans	19.2%
Domestic water	Private water supplies	4.2%
Commercial and industrial	Washing, processing, and cooling	4.3%
Thermoelectric	Power plant cooling	0.5%
Irrigation	Agricultural plant life requirement	68.3%
Livestock watering	Life requirement for farm animals	1.2%
Aquaculture	Life requirement for farmed fish	1.3%
Mining	Conveying mined materials and wastes and processing	0.9%
Wildlife watering	Life requirement for wildlife	Not measured, not reported
Waste disposal	Sink for residuals and wastes	Not reported
Feedstock (brines)	Raw material for chemicals and processes	0.5% (of 5.5 m^3/day of saline water for industry)[a]

Source: United States Geological Survey (USGS), *Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast* (Author: Barlow, P.M.), USGS Circular 1262, USGS, Reston, VA, 2003.

[a] Except where noted.

EXHIBIT 3.8 PAST PROJECTION OF POPULATION AND WATER USE (WITHDRAWALS) IN THE UNITED STATES

Population (Millions)			Fresh Groundwater Use (Million m^3/day)			Total Freshwater Use (Million m^3/day)		
1975	**2000**		**1975**	**2000**		**1975**	**2000**	
Estimation	**Projection**	**Actual**		**Projection**	**Actual**		**Projection**	**Actual**
216.4	268.0–282.2	281.4	310.4	NE	315.3	1336 (USGS) 1507 (USWRC)	1160 (USWRC)	1307 (USGS)

Sources:

1. United States Water Resources Council (USWRC), *The Nation's Water Resources 1975–2000*, Vol. 2, U.S. Government Printing Office, Washington, DC, 1978.
2. United States Geological Survey (USGS), *Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast* (Author: Barlow, P.M.), USGS Circular 1262, USGS, Reston, VA, 2003.

Note: USWRC reported a 79.1 million m^3 overdraft of fresh groundwater in 1975, which was 25.4% of the total groundwater withdrawn in that year. Most of this overdraft (the respective percentages of overdraft in parentheses) was in the Missouri (24.6%), Arkansas-White-Red (61.7%), Texas-Gulf (77.2%), Lower Colorado (48.2), Great Basin (41.5%), and California (11.5%) water resources regions. Overdraft is defined in the USWRC report as groundwater use exceeding the natural recharge (USWRC, 1978, p. II-11).

NE = not estimated.

arid states that have higher groundwater application rates tend to rely on surface or flood irrigation, than on the more efficient methods, such as sprinkler or microirrigation systems However, arid states have clearly improved water efficiency through the use of sprinkler systems, in particular, in Texas and Colorado. In 2000, groundwater used for irrigation in the 17 western U.S. states with typically drier climates accounted for 75% of all groundwater used nationally for irrigation, 51% of all groundwater used nationally for all uses, and 16% of all water used in the United States (USGS, 2004). Clearly, groundwater used for supplying food is significant.

Drinking Water

Drinking water supply is the second largest use of groundwater in the United States and a primary use in other countries as well (Sampat, 2000), and has a significant role in the economy. In 2000, in the United States, 35,308 community water utility companies used groundwater exclusively for their water supply and 3280 used groundwater as their principal source (totaling 38,508 utilities) out of the 52,186 community water utilities that serve 25 or more people (the largest, serving over 6 million people). However, small water systems that serve transient, nonresidential populations in schools, hospitals, and other facilities, such as roadside rest areas, and have their own water source are not included. At the fundamental level of providing a commodity that is essential to the local economy in the United States, these water utilities operate as an economic monopoly (they are organized to be the only water deliverer in their communities and as such have no significant competition), and supply water that meets health-based standards to domestic, commercial, industrial, and thermoelectric power users that are not self-supplied (USGS, 1998). These water utilities have a large investment in their treatment and distribution systems, and often finance the upgrading and maintenance of these systems, issuing municipal or private bonds, depending on whether they are public- or investor-owned, respectively.

Several trends in water use and infrastructure are evident in groundwater systems in the United States. Exhibit 3.10 gives the population served by and the per capita use of public water suppliers for drinking water and related uses in the United States from 1975 to 1995. The per capita use rose and then

EXHIBIT 3.9 COMPARISON OF GROUNDWATER AND SURFACE WATER USE IN THE UNITED STATES, 1995–2000

	Groundwater				Surface Water			
	1995 (Mm³/d)	2000 (Mm³/d)	Change (Mm³/d)	Percent (%)	1995 (Mm³/d)	2000 (Mm³/d)	Change (Mm³/d)	Percent (%)
Public supply	57.2	60.6	3.4	+5.7	95.0	103.3	8.3	+8.8
Domestic	12.7	13.4	0.7	+5.4	0.1	0.2	0.08	+55.0
Commercial	3.6	RE[a]			7.4	RE[a]		
Irrigation	185.5	215.4	29.9	+16.1	320.6	302.8	(17.8)	–5.5
Livestock[b]	8.6	7.8	(0.7)[c]	–8.4	12.2	12.8	0.6	+4.9
Industrial								
Fresh	15.5	13.5	(2.0)	–12.9	63.2	56.4	(6.8)	–10.8
Saline	0.06	0.02	(0.03)[c]	–56.6	6.2	4.8	(1.4)	–22.0
Mining								
Fresh	4.1	2.9	(1.1)[c]	–28.3	5.6	4.7	(0.9)	–16.8
Saline	3.8	4.8	0.9 [c]	+24.8	0.8	0.9	0.1	+12.9
Thermoelectric								
Fresh	2.1	1.5	(0.6)	–27.6	495.9	511.0	15.1	+3.1
Saline	—	—			219.2	225.2	6.1[c]	+2.8
Total	293.4	319.8	26.5	+9.0	1225.3	1222.7	(2.6)	–0.2
Fresh	289.2	315.3	26.1	+9.0	999.3	991.8	(7.6)[c]	–0.8
Saline	4.2	4.8	0.6	+13.5	226.0	230.9	4.9	+2.2

Sources:

1. United States Geological Survey (USGS), *Estimated Use of Water in the United States in 1995*, USGS Circular 1200, United States Government Printing Office, Washington, DC, 1998, 71.
2. United States Geological Survey (USGS), *Estimated Water Use in the United States in 2000*, USGS Circular 1268, Washington, DC, 2004, URL: http://water.usgs.gov/pubs/circ/2004/circ1268/htdocs/text-do.html (accessed March 25, 2005).

Note: Mm³/d = million cubic meters per day.

[a] RE = recorded elsewhere.

[b] Includes aquaculture.

[c] Difference is in rounding from original units.

declined during this period. Notably, the population relying on groundwater from public water supplies increased by 41%, and public water supply demands rose to 37%. In addition, the population using surface water supplies grew by 22% and the quantity used by this population increased by 32%. This relationship suggests that, at the margin of use, a greater pressure on groundwater sources for public supply existed than for surface water sources that were less efficiently used. Exhibit 3.11 portrays the statistical results and a summary of a review of infrastructure for groundwater-supplied systems in the United States. Significant economies of scale accrue to large water systems, based on the data presented.

Industrial

Industrial use, including manufacturing, thermoelectric cooling, and mining, constitutes 5.7% of all groundwater use in the United States. Fresh groundwater use declined from 1995 to 2000 by 17%, to 18 million m^3/day, while saline groundwater use increased by 23.6% to 4.8 million m^3/day over the same time, primarily because of increased mining demands. The total industrial groundwater use was 2.8% of the total industrial water demand in 2000.

EXHIBIT 3.10 DRINKING WATER USE FROM PUBLIC WATER SUPPLIERS IN THE UNITED STATES, 1975–1995

	Public Water Supply From				Per Capita Use of		
	Groundwater		Surface Water				
Year	Population (in 1000s)	Supplied (Mm^3/d)	Population (in 1000s)	Supplied (Mm^3/d)	Groundwater (L/day)	Surface Water (L/day)	Total (L/day)
1975	64,700	41.6	110,000	71.9	644	655	647
1980	73,700	45.4	112,000	83.3	617	742	693
1985	84,800	55.3	115,000	82.9	651	719	693
1990	88,000	57.2	122,000	89.0	651	731	693
1995	91,200	57.2	137,000	95.0	628	708	678

Sources:

1. United States Geological Survey (USGS), *Estimated Use of Water in the United States in 1975*, USGS Circular 765, United States Government Printing Office, Washington, DC, 1977, 39.
2. United States Geological Survey (USGS), *Estimated Use of Water in the United States in 1980*, USGS Circular 1001, United States Government Printing Office, Washington, DC, 1983, 56.
3. United States Geological Survey (USGS), *Estimated Use of Water in the United States in 1985*, USGS Circular 1004, United States Government Printing Office, Washington, DC, 1988, 82.
4. United States Geological Survey (USGS), *Estimated Use of Water in the United States in 1990*, USGS Circular 1081, United States Government Printing Office, Washington, DC, 1993, 76.
5. United States Geological Survey (USGS), *Estimated Use of Water in the United States in 1995*, USGS Circular 1200, United States Government Printing Office, Washington, DC, 1998, 71.

Note: Mm^3/d = million cubic meters per day.

Per Capita Use

Considering all types of water use withdrawals from both the fresh groundwater and surface water sources, the per capita use in the United States has changed over time. Exhibit 3.12 documents the changes in the water use per person in the United States from 1900 to 2000. In this period reported, the per capita use peaked around 1970. Since that time, the per capita use has declined, most probably owing to the increased demand from a larger population that made the relatively fixed total freshwater resource scarcer. During the 1970s and 1980s, sources of groundwater were found to be contaminated at some municipal well fields, requiring new sources to be found and stream habitat for wildlife were recognized as a required allocation for surface waters, and these were the factors that potentially caused increased costs of supply and actions to conserve water.

All Groundwater Uses

Considering all groundwater uses, the resource supports a significant portion of the water-use economy of the United States. On the other hand, 24% of the direct freshwater uses were supported by groundwater, as identified in Exhibit 3.9 for the year 2000. If the calculation of groundwater use also includes the maintenance of 40% of the baseflow of streams, then the proportion becomes 52% of all the freshwater uses.

Groundwater Services Sector

Groundwater contributes considerably to the economies of the world's nations, underlying that its support is a substantial service sector of which a portion focuses on groundwater and its use. This sector provides groundwater assessments and surveys; installs wells; manufactures drill rigs, hand drills, well casing, and pumps; gives technical consultation; remediates groundwater contamination;

EXHIBIT 3.11 CHARACTERISTICS OF GROUNDWATER-SUPPLIED COMMUNITY WATER SYSTEMS IN THE UNITED STATES, 2000

	Groundwater-Supplied[a] Community Water System Service Population Ranges								
Category	**100 or Less**	**101–500**	**501–3300**	**3301–10,000**	**10,001–50,000**	**50,001–100,000**	**100,001–500,000**	**Over 500,000**	**All Sizes**
Primarily groundwater systems									
100% Groundwater	10,358	12,521	8687	2576	971	80	108	7	35,308
Mostly Groundwater	1398	624	283	495	368	56	53	3	3280
Ownership type									
Public	489	3556	6694	2560	1080	124	143	9	14,655
Private	11,267	9590	2276	511	259	12	17	1	23,933
Average number of wells	1.4	1.9	2.6	4.1	7.8	18.1	20.5	132.2	2.5[b]
Avg. kilometers of pipe in place[c]	1.6	6.4	45.1	136.8	373.4	635.7	931.8	3885	62.8
Average daily production (m^3/day)									
100% groundwater	41.6	128.7	598.1	3986.0	9948.1	45016.1	66740.6	475606.7	1184.8
Mostly groundwater	11.4	71.9	1983.6	3300.9	14074.2	42491.2	112722.0	548744.7	13578.3
Avg. total revenue ($ in 1000s)	5	23	146	622	2179	7878	14,013	75,183	286
Avg. % not charging directly for water	43	32	4	5	6	0	0	0	25
Avg. total expenses ($ in 1000s)	7	25	133	568	2147	6779	18,175	62,201	253
Avg. total expenses per cubic meter produced ($)	1.10	0.67	0.78	0.52	0.53	0.45	0.53	0.36	0.80
Avg. number of employees	1.3	1.6	2.8	5.7	15.2	42.1	64.6	374.7	4.6
Avg. annual labor costs ($ in 1000s)	5	12	38	190	636	1755	2616	17,669	115
Avg. total capital investment in the past 5 years ($ in 1000s)	35	97	309	923	3392	7001	17,656	160,507	624

EXHIBIT 3.11 (continued) CHARACTERISTICS OF GROUNDWATER-SUPPLIED COMMUNITY WATER SYSTEMS IN THE UNITED STATES

	Groundwater-Supplied[a] Community Water System Service Population Ranges								
Category	**100 or Less**	**101–500**	**501–3300**	**3301–10,000**	**10,001–50,000**	**50,001–100,000**	**100,001–500,000**	**Over 500,000**	**All Sizes**
Type of capital expenses in the past 5 years (% of systems reporting each type of expense)									
Land	1.1	2.5	5.0	26.5	27.7	13.6	28.9	34.0	7.0
Water source	30.6	48.7	31.0	49.6	47.8	64.6	47.6	83.0	40.0
Distribution and transmission	40.7	61.7	73.2	70.6	84.9	96.4	100.0	100.0	61.5
Treatment	27.6	32.3	34.0	39.5	59.7	61.9	42.0	66.0	34.0
Storage	30.4	35.1	40.0	43.1	47.9	60.1	80.2	49.1	37.0
Other	11.9	19.8	17.5	28.7	41.7	65.6	45.9	83.0	19.8

Sources:

1. United States Environmental Protection Agency (USEPA), *Community Water System Survey 2000*, EPA 815-R-02–005B, December 2002, 180.
2. Job, C.A., *Natl. Ground Water Assoc*., 24, 48, 50, 52, 2004.

[a] Except where indicated by footnote.

[b] Systems that are primarily surface-water supplied have an average of 5.4 wells per system, and those that primarily purchase water from other systems have an average of 3.9 wells per system.

[c] Includes all groundwater- and surface water-supplied community water systems surveyed.

The selected characteristics of groundwater-supplied community water utilities (or "groundwater systems") provided earlier are derived from a statistical study, and the analysis of these utilities in the United States, completed in 2000, included

Ownership. Sixty-two percent of the groundwater systems in the United States are privately owned, with 87% of these serving populations of 500 or fewer persons.

Average Daily Production. Average daily production ranges from 41.6 m^3/day for systems serving 100 or fewer persons to 475,606.7 m^3/day for the largest groundwater systems.

Average Number of Wells. Small systems serving 100 or fewer persons have an average of 1.4 wells per system. The largest systems serving more than 500,000 persons have an average of 132.2 wells per system. Overall, the average wells per system is 2.5, but the systems that are primarily surface water supplied (and tend to be larger) have an average of 5.4 wells per system and systems that primarily purchase water from other systems have an average of 3.9 wells.

Treatment. Because groundwater is typically considered as a cleaner water source, many systems do not treat it before delivering it to the consumers, to save cost. Thirty-five percent of systems surveyed, serving 100 or fewer persons did not treat groundwater before its use by the consumers. However, the largest systems in the survey provided treatment.

Pipeline in Place. The smallest systems averaged 1.6 km of pipeline to deliver groundwater. The largest systems utilized 3885 km of pipeline. The average distance of the pipeline in place was 62.8 km per system, with a mean of 21.3 connections per kilometer. While the largest systems replaced an average of 165.8 km per system in the prior 5 years, the smallest systems in the survey did not replace any pipeline during that time. The average annual pipeline replacement cost for the smallest systems ranged from $27,962 per km over the 5 years prior to 2000, to $1,068,137 per km for systems serving more than 500,000 persons. Most pipes were less than 40 years old for all the system sizes.

(*continued*)

EXHIBIT 3.11 (continued) CHARACTERISTICS OF GROUNDWATER-SUPPLIED COMMUNITY WATER SYSTEMS IN THE UNITED STATES

Revenues. The average annual revenue for the smallest systems was $5000, while the largest systems had an average revenue over $75 million. Most of the systems (including groundwater and surface water systems) used a uniform rate or declining block-rate residential charge structure. Increasing block rates are used by some (25%–31%) of the larger systems. Nearly 24% of the systems on an average relied on a flat fee for water charges.

Expenses. The survey found that expenses for groundwater systems ranged on an average from $7000 per year for the smallest to over $62 million for the largest. Examining expenses on a water-unit basis indicated significant economies of scale for groundwater systems: $1.10/m^3 produced for systems serving 100 or fewer people down to $0.36 for systems serving more than 500,000 people, a factor of just over 3.

Capital Investment. Capital investment in groundwater systems appears to exhibit a significant economy of scale. Dividing the average total capital investment in the past 5 years (1995–1999 in the case of this survey) by the average daily production indicates that the smallest systems invested approximately $793–$3170/m^3/day, whereas the largest groundwater systems invested from $0.29 to $0.34/m^3/day. The four major types of capital expenses across most system size categories were distribution and transmission systems, water source, treatment, and storage (Job, 2004).

EXHIBIT 3.12 PER CAPITA WATER USE IN THE UNITED STATES, ALL USES, 1900–2000

Year	Population	Total Freshwater Use[a] (Million m^3/day)	Per Capita Use (L/day)
1900	76,212,168	151.4	1987.3
1910	92,228,496	249.8	2710.4
1920	106,021,537	348.3	3285.7
1930	123,202,624	416.4	3380.4
1940	132,164,569	514.8	3895.2
1950	151,325,798	772.2	5102.7
1960	179,323,175	1029.6	5742.5
1970	203,302,031	1404.4	6908.4
1980	226,542,199	1430.9	6317.8
1990	248,709,873	1279.5	5144.4
2000	281,421,906	1306.0	4640.9

Sources:

1. USCB, 2008. Census of Population and Housing, Washington, DC.
2. United States Water Resources Council (USWRC), *The Nation's Water Resources 1975–2000*, Vol. 2, U.S. Government Printing Office, Washington, DC, 1978.
3. United States Geological Survey (USGS), *Ground Water in Freshwater-Saltwater Environments of the Atlantic Coast* (Author: Barlow, P.M.), USGS Circular 1262, USGS, Reston, VA, 2003.

[a] Includes all fresh water uses of both groundwater and surface water sources: public supply, domestic supply, irrigation, livestock, aquaculture, commercial, industrial, mining, and thermoelectric power.

and provides groundwater for use. Exhibits 3.13 and 3.14 provide a perspective on the groundwater services sector in the United States and China. The groundwater services sector in the United States has many companies that deal with large and small wells as well as simple and complex conditions. This sector that is briefly described for China (People's Republic) is focused on extensive small-scale farm irrigation equipment and support.

In Asia, expanding groundwater use for irrigation as well as other purposes has caused a proliferation in the local manufacture of less expensive, but durable water pumps. In India, this industry has increased at a 20% annual rate since 1982. This pump production is a competitive business and

EXHIBIT 3.13 THE GROUNDWATER PRODUCTS AND SERVICES SECTOR IN THE UNITED STATES: A PARTIAL OVERVIEW

Portable Drilling Machines Produced

	1990	**1995**	**2000**
Number	365	463	413
Total value	$75,323,000	$84,473,000	$116,537,000
Note: Exported in	1991	1995	2001
Number	166	164	92

Pumps Manufactured

	1990	**1995**	**2000**
	1,624,379	1,880,778	2,546,528
Note: Exported in	1991	1995	2001
Number	67,013	81,052	75,323

Domestic Wells in Place (Previously Installed) by Type, 1997

Public Supply	**Household**	**Households on Septic Systems 1990, Estimated**
282,828	15,123,730	23,550,800

Annual Private Household Well Construction, by Year (No. of States Reported in Parentheses)

1980 (24)	**1985 (26)**	**1990 (39)**	**1995 (29)**	**1999 (28)**
126,721	142,128	181,983	143,595	121,782

Annual New Private Household Water Well Installation Sales (Estimated)

	1989	**1990**	**1991**	**1992**
Well construction sales	$2.0 billion	$2.3 billion	$2.1 billion	$2.3 billion
Avg. wells/firm (8563 firms)	83	96	83	90
Avg. well depth (m)	61.0	61.2	64.6	64.9
Avg. price/meter drilled	$46.42	$45.93	$45.11	$44.39
Avg. well cost	$2830	$2814	$2915	$2936
Pump sales (9752 firms)	$1.3 billion	$1.4 billion	$1.5 billion	$1.6 billion
Avg. number/firm	113	119	129	132

Annual Borehole Construction of all Types, by Year (no. of States Reported in Parentheses)

1980 (37)	**1985 (45)**	**1990 (49)**	**1995 (37)**	**1999 (34)**
222,126	254,836	357,360	288,454	265,759

(*continued*)

EXHIBIT 3.13 (continued) THE GROUNDWATER PRODUCTS AND SERVICES SECTOR IN THE UNITED STATES: A PARTIAL OVERVIEW

Irrigation Wells in Place

	1988	1994
Capable of use	373,572	363,237
With backflow control	146,181	205,083
Average depth	68.9 m	72.8 m
Average pump depth	40.8 m	43.6 m
Average pump capacity	2.9 m^3/min	3.1 m^3/min

Annual Irrigation and Livestock Well Construction, by Year (No. of States Reported in Parentheses)

1995 (25)	1996 (28)	1997 (24)	1998 (24)	1999 (27)
14,118	12,079	13,250	15,704	17,498

Farm and Ranch Pumps in Use, 1998		Irrigation Well Pump Types in Percent, 2000			
No. of Pumps	Avg. Capacity Range	Vertical Line Shaft	Submersible	Centrifugal	Axial Flow
330,837	0.2–8.2 m^3/min	65%	22%	37%	5%

Municipal Supply Well Construction, by Year (No. of States Reported in Parentheses)

1980 (13)	1985 (25)	1990 (28)	1995 (28)	1999 (27)
7426	2297	2995	2868	1706

Municipal Water Supply Treatment at Groundwater-Supplied Systems in Percent of Systems, 1997

Disinfection/Oxidation	Filtration	Corrosion Control	Fe and Mn Removal	Flocculation/ Coagulation	Organics Removal
92%	39%	36%	34%	33%	27%

Geothermal Heat Pump Installations, 1997 (Estimated)

Ground Source	Groundwater
23,500	5000

Industry Overview, 1998

	Drilling and Pump Firms	Hazardous Waste Firms	Remediation and Industrial Firms	Environmental and Engineering Firms
Number	9517	1824	1240	28,263
Employees	52,248	53,333	100,000	162,766
Sales	\$5.5 billion	\$6.4 billion	\$8.6 billion	\$15.3 billion

Source: Reprinted from National Ground Water Association, U.S. Ground Water Industry Market Backgrounder, Columbus, OH, 2001. With permission.

has significant economies of scale, with the advantage of pumps selling at low cost for the poor rural populace (Shah et al., 2000). Exhibit 3.14 (China) documents the intensely developed groundwater irrigation business sector in China.

UNINTENDED EFFECTS OF GROUNDWATER USE IN AN ECONOMY

As noted earlier, the use of the subsurface as a chemical waste sink and groundwater as a conveyance to move it away, neglecting the public good aspect of groundwater, ignores the significant cost on the

EXHIBIT 3.14 THE GROUNDWATER PRODUCTS AND SERVICES SECTOR IN CHINA: A PARTIAL OVERVIEW OF THE SMALL FARM IRRIGATION MARKET IN 1995

- China's population, 1995: 1.2 billion people with 80% living in rural areas
- Irrigated area of China: 53,790,000 ha with 24.8% irrigated by groundwater
- Irrigation equipment enterprises, 1995, included 166 irrigation equipment enterprises employing 65,000 workers with output of 2620 million RMB yuan (US$310.2 million)
- Domestic market for irrigation and drainage equipment annual sales income in 1995, of 2384 million RMB yuan (US$282.3 million)
- Production of total units of 2,605,316 (an increase of over 40% from the previous year) included
  - Sprinklers
  - Farm water well drills
  - Large pumps
  - Small and medium
  - Mini-pumps
  - Deep-well pumps (long-spindle)
  - Submersible pumps
  - Small submersible pumps
  - Water-turbine pumps

Source: Weiping, Z., Irrigation technology transfer in support of food security, (Water Reports-14) *Proceedings of a Subregional Workshop*, Harare, Zimbabwe, April 14–17, Food and Agriculture Organization of the United Nations, Rome, Italy, 1997.

economy of degrading its benefits. Releasing wastes instead of treating them produces costs and/or damage upon people—and the ecosystem that they rely on—in the future and potentially at other locations, considering the mobile nature of the resource (Young, 2005, p. 278). The company that caused the contamination problem of Love Canal, New York, had to pay an enormous sum, $129 million, in 1995, to compensate the government and others for the site cleanup—monies that could have been used for other productive activities and services, not including the costs to the lives of the families who lived and suffered there (USDOJ, 1995). Elsewhere, groundwaters applied for irrigation to feed many more people than before are being used up faster than replenished naturally, resulting in falling water tables, increased pumping and maintenance costs, and dry wells. This condition was observed in the Great Plains of the United States, Saudi Arabia, Libya, and northeastern China (including Beijing) (Brown, 1996) The effects on the local and national economies can be itemized, but in all cases, they are still not fully recognized in an economic sense, as in the following examples:

- Reduction in the area farmed and the potential return to dryland farming in parts of the Great Plains of the United States because of extensive aquifer depletion (USWRC, 1978).
- Urban infrastructure damage from land subsidence in and around Mandan, China (Brown, 1996) and disrupted land use in Arizona, United States (Gelt, 1992).
- In Saudi Arabia, 75% of water used in the economy is from nonrenewable groundwater resources, stemming in part from significant subsidies and aids for groundwater-irrigated agriculture, resulting in aquifer depletion, water quality degradation, and falling agricultural productivity (Darghouth, 2002).
- A quarter of India's harvest may be at risk from inadequate irrigated water supply because of groundwater depletion (Shah et al., 2000).

- About 300 densely populated large and medium cities in China which rely on groundwater are in danger of severe water shortages (Shah et al., 2000).
- In the South Korean island of Cheju, groundwater overdrafting of the coastal aquifer resulted in saltwater intrusion (Kim et al., 2003).
- About 11 of 37 European countries reported over exploitation of aquifers, including 33 cases of endangered wetlands and 53 situations with saltwater intrusion (EEA, 1999).
- Small island nation-states in the Caribbean Sea have experienced seawater intrusion because of overpumping their aquifers (IPCC, 2001).

ECOLOGICAL AND AESTHETIC USES OF GROUNDWATER

A less obvious, but significant natural use of groundwater is to maintain stream baseflow (USWRC, 1978; USGS, 1999), equivalent to about 54% of all measured groundwater uses in 1990 in the United States, or 1862.4 million m^3/day (EPA, 1998, p. 7). Groundwater discharges through stream channels allow additional water uses downstream. This condition is more obvious during the drier times of the year and in irrigated areas in the western United States, and elsewhere in the world with groundwater return-flow to streams. As indicated in the *National Water Quality Inventory, 1994 Report to the United States Congress*

> The importance of groundwater flow into streams and other surface waters cannot be underestimated. Groundwater can transport contaminants to streams and affect surface water quality and quantity, which may impact drinking water supplies drawn from surface waters, fish and wildlife habitats, swimming, boating, fishing, and commercial navigation. Modifications to the quantity or quality of groundwater discharged into surface water ecosystems can also have major economic repercussions as a result of adverse impacts on recreation, public health, fisheries, tourism, and general ecosystem integrity (EPA, 1996).

An example is instructive. In a more humid area, such as central Wisconsin, the Little Plover River baseflow is maintained by groundwater discharge to the stream. The Central Wisconsin Groundwater Center has predicted that due to the irrigation pumping near the Little Plover River, at maximum pumping rates, some sections of the river would dry up and eliminate its trout fishery (Anderson, 1998). This latter groundwater use to maintain a fishery is typically not quantified and not valued as a product or service of groundwater.

The groundwater in the subsurface environment plays a significant role supporting surface waters, such as wetlands, ponds, lakes, and streams, as well as estuaries and near coastal zones, thereby enriching these water bodies with nutrients for flora and fauna that inhabit them. More animals and plants per unit area exist in a wetland than in any other kind of habitat (USEPA, 2004b). These waters may be used for recreation, sports, research, and instruction. Importantly, we have not fully incorporated these processes, as well as other processes that we still do not fully understand, into the economic exchange of goods and services from which we benefit everyday. Research in subsurface processes including groundwater may lead to many other discoveries about their values, even though they are typically out of sight below our homes and cities. The costs of disrupting or replacing these subterranean services are difficult to estimate, but should not be ignored in evaluating any economic activity affecting groundwater entering the subsurface and moving through it or residing in it, as these costs could be incurred onsite or by adjacent property owners or groundwater users and significantly affect their livelihood.

RESIDUAL ABSORPTION AS A USE OF GROUNDWATER

CHEMICAL WASTES

One use of groundwater typically ignored in most analyses and transactions is its value as a conveyance and treatment mechanism for wastes as well as chemical and biological residuals. The value of this mechanism should be determined, at a minimum, as the cost of the alternative piping and treatment technologies that would need to be applied to obtain a comparable level of service. While using groundwater and the subsurface to transport and dispose residuals might be considered efficient, as it is done at no apparent cost to the disposer, the actual cost may be high and unknown, as was found with abandoned waste sites that included groundwater contamination, with average remedial costs of $3 million per site in the United States. Furthermore, underground injection and landfilling of chemical wastes is the disposal method of choice for nearly one-fourth, about 531.7 million kg, of these wastes in the United States (USEPA, 2006). The subsurface environment is expected to hold these wastes so that they do not migrate, as groundwater is increasingly relied on for water supply. Significant volumes of hazardous or toxic substances, about 102.6 million kg, disposed by industries are required to be injected deep below groundwaters used, and separated by a confining zone from water supply. Another 0.136 million kg are disposed in shallower injection wells. Ecosystem damage and costs to the economy beyond those evaluated as alternative disposal mechanisms require further research.

Pesticides

In 1995, the United States users of pesticides purchased 544.3 million kg for application, most of which was land applied. These pesticides were sold for approximately $10.3 billion at that time. The extent to which these chemicals leached to groundwater is still not known, but their presence in groundwater has been well documented (Barbash and Resek, 1996).

COMPETITION FOR THE SUBSURFACE ENVIRONMENT

Approximately 15 million wells produce groundwater in the United States for public and private use (Westwater Resources, 2006). In the future, disposers of carbon dioxide (carbon sequestration) in response to climate change and wastes from desalinization of ocean-water and inland brackish water may use the subsurface environment for sinks to hold these residuals. For the economy to work, to ensure that there is no failure to consider hidden or unidentified costs, actions in the subsurface which appear to have no costs and benefits that are difficult to quantify, should be reevaluated for their full scope and be assigned appropriate values, so that later users do not bear the costs of the needed remedies. Research into the nature and magnitude of these benefits and costs will become a priority with greater competition for the subsurface environment.

HEALTH AND ECONOMIC PRODUCTIVITY

Economic productivity is related to the health of the populace and water can affect that health (UNESCO, 2003, pp. 101–125). Chapter 4 will address the issues of health and groundwater; however, it is important to note that significant analyses have been conducted which address health as well as clean and safe water. The economic benefits of good health from safe water directly stem from greater productivity in the home and at the workplace, due to reduced illness and death (Hutton, 2001). Furthermore, macroeconomic effects (e.g., employment, exports, tourism) of poor drinking water can be significant (Hutton, 2001).

OTHER SOCIOECONOMIC FACTORS IN OVERVIEW

"The earnings, incomes, and lifestyles of the people significantly affect priorities on use of the Nation's [and world's] water resources. For example, a major change in population growth, a shift in its geographical location, or a change in the composition (age, family size, occupation, etc.) will affect the level, distribution, and mix of water requirements both nationally and regionally. Increasing real incomes and leisure time tend to place higher priorities on instream [surface] water uses—recreation, fish and wildlife, natural areas—rather than on the traditional offstream uses. Many traditional economic and water-use relationships change substantially as prices, incomes, asset values, and productivities adjust to changing energy and trade relationships" (USWRC, 1978, p. III-9). In 1950, three of the largest water-using sectors—agriculture, mining, and manufacturing—contributed 40% of the total earnings in the United States (USWRC, 1978, III-13), while using 70% (490.6 million m^3) of the fresh groundwater and surface water withdrawn (696.5 million m^3) (USGS, 2003). Earnings in these industries were predicted to be 25% of the total earnings in 2000 (USWRC, 1978, p. III-13), with 41% (640.9 million m^3) of the freshwater withdrawals (1544.4 million m^3) (USGS, 2003). Agricultural and economic policies, including import tariffs, subsidies, access to credit and exchange rates, affect GWW in irrigated farming and raising livestock (Schiffler, 1998, pp. 148–152). Clearly, water use plays a significant role in the overall economy—increasingly in nonproduction and service sectors.

ECONOMIC MANAGEMENT CHARACTERISTICS OF GROUNDWATER

Economic management characteristics of groundwater comprise a mix of physical and socioeconomic attributes affecting the market and open access public use of the resource. The purpose of markets is to efficiently allocate resources through prices resulting from the balancing of supply and demand for labor and capital on the supply side, as well as products and services on the demand side by human beings and the ecosystem supporting us. Groundwater has features that make it both a capital (fixed) and variable input in supply (Young, 2005, pp. 51–52), as well as product and service in response to demand. As groundwater can move in the subsurface interstitial space, but may also be contained in deep reservoirs, the results on the ecosystem of its use in the economy, and, therefore, its value, vary from place to place (Young, 2005, p. 37). To provide an economic understanding that can link its natural occurrence to economic use, several concepts have evolved to better portray a range of important characteristics of natural resources, described in Exhibit 3.15 (following Daly

EXHIBIT 3.15 NATURAL RESOURCE CHARACTERISTICS

Resource Characteristic	Characteristic Description
Stock-flow	Material of the resource is incorporated into products and used at any rate (subject to natural limits of availability); it can be stored and consumed
Fund-service	The resource is not incorporated into a product, but is used at rate limited by natural processes; it cannot be stored, but becomes “worn out” rather than consumed
Excludable	Ownership of the resource precludes others from using the resource, usually the result of institutional legal rights or technical features of the resource. This characteristic can be equated to property rights
Nonexcludable	A resource that cannot be precluded from use by anyone through institutional or technical factors
Rival	The physical aspect of a resource that allows it to be used by only one person. All stock-flow and some fund-service resources are rival resources
Nonrival	One person’s use of this resource does not limit other people’s use of it. Any nonrival resource is a fund-service resource
Rival between generations	Resources that can only be used by one generation
Renewable	Resources that reproduce or are replenished naturally and sustainably
Nonrenewable	Resources that are sources of materials that are consumed or used up
Congestible	Nonrival resources that have so many users at particular times or over time, that they appear to become rival resources and their quality declines
Substitutable	One resource can replace another but is not typically a perfect replacement
Complementary	Use of one resource causes other resources to be used

Source: Daly, H.E. and Farley, J., *Ecological Economics*, Island Press, Washington, DC, 2004, 454.

and Farley, 2004). These characteristics provide a basis for considering policies that might best be applied to groundwater for its range of uses over time.

Given the characteristics of natural resources, how do they apply to groundwater? Because of the range of physical conditions of groundwater, it takes on seemingly contradictory characteristics. These characteristics are displayed in Exhibit 3.16. This exhibit shows that the economic management characterization of groundwater and its major uses is complex. Importantly, there exists no substitutes for water for its uses of greatest significance (Daly and Farley, 2004, p. 88), and where it is the only source, no substitutes for groundwater may exist in many locations (McCabe et al., 1997). Groundwater may be found as "renewable" in situations where it is only used at rates of replacement, referred to as "safe yield," or "nonrenewable" where groundwater is contained in fossil aquifers or used at rates in excess of safe yield. Where groundwater is nonrenewable, the resource may be facing "congestion" because of the large scale in the number of users demanding such a collectively large volume of water. Even where groundwater is renewable, if the scale of use is large, this congestion may be evident. In both these cases of fossil aquifers with no renewability

EXHIBIT 3.16 CHARACTERISTICS OF GROUNDWATER BY MAJOR USE CATEGORIES

Major Use	Stock-Flow or Fund-Service	Excludable	Rival	Between Generations	Substitutable
Drinking water (for people and livestock)	Depends on rate of use	Yes	Yes	Depends on ground surface management (infiltration/ percolation potential), recycling, and rate of use	No, except if surface water is available
Irrigation	Depends on rate of use and residual absorption	Yes	Yes	Depends on rate of use	No, except if surface water is available
Industrial	Depends on rate of use	Yes	Yes	Depends on ground surface management, recycling, and rate of use	No, except if surface water is available
Mining	Depends on rate of use	Yes	Yes	Typically yes	No, except if surface water is available
Thermoelectric cooling	Depends on rate of use	Yes	Yes	Typically yes	No, except if surface water is available
Residual absorption	Funds-service	Depends on access	Yes	Yes	Moderate at margin, otherwise, no
Aesthetic/ recreation	Funds-service	Depends on access	No	No	No
Surface Water Supply Support					
Streams/wetland	Stock-flow	No	No	No	No
Aesthetic/ recreation	Fund-service	Depends on access	No[a]	No	No

Source: Based on Daly, H.E. and Farley, J., *Ecological Economics*, Island Press, Washington, DC, 2004, 91, Table 1.

[a] Except if access allows congestion to occur.

and congested "potentially renewable" surficial aquifers used beyond safe yield, the groundwater resource is a rival resource between generations. In those situations, the groundwater consumed is lost for use to the next generation.

The finite stocks of groundwater set a limit on the amount of its economic production, with the constraints not obvious until the resource is significantly depleted; a condition from which it may not recover (Daly and Farley, 2004, p. 91). In this regard, it shares characteristics with a range of other resource types, including petroleum, mineral resources, fisheries, and wetlands. Notably, through the application of technology, water-use efficiency can increase (Schiffler, 1998, pp. 28–31). However, even with improved efficiency and because water is not substitutable and is essential for life, distribution of water to all people and livestock represents a significant ethical issue for market allocations of water (Daly and Farley, 2004, p. 196).

Based on these characterizations, scale of use significantly affects other people's use of groundwater. If large volumes are used for many or multiple purposes in a location (reflecting stock-flow, nonexcludable, and rival characteristics), then an aquifer may become depleted because of massive water consumption. Likewise, extensive or concentrated residual or waste disposal can preclude groundwater from being used from a qualitative standpoint, being "worn-out" from this use (reflecting fund-service, nonexcludable, nonrival characterization). It may take decades, even generations, before natural processes can breakdown residuals and wastes to "renew" the aquifer. These circumstances—stress on groundwater because of demands on quantity and quality—point to problems in the market for this good.

ECONOMIC CHALLENGES AND MARKET FAILURE

Before developing a model of groundwater in the economy, it is important to ask about the circumstances in which the market has failed to address the economic needs relative to groundwater. Identifying market failure along with a specific model of groundwater in the economy will serve as a guide for policies that could respond to real challenges in water allocation and use in the future. Clearly, groundwater policy should not be developed in isolation. However, both groundwater existence and water demand are sufficiently ubiquitous to allow a focus on these elements of the resource together.

Market failure for groundwater relates to several problems associated with excludable and rival resources:

1. Distribution of water at an affordable price for all who need it is a serious problem (Schiffler, 1998; UNESCO, 2003; Daly and Farley, 2004, p. 197). Groundwater is in limited supply and being depleted on every continent. Over 1 billion people are not served by adequate water supply worldwide (UNESCO, 2003, p. 109). In the United States, the government has established plans to provide safe water supply to at least 50% of the people on the tribal lands who are underserved, by 2008 (USEPA, 2003, p. 34). These people are primarily served by groundwater. Affordability of water supplies for economically disadvantaged populations is a factor around the world, with poorer people paying twice to nearly 500 times the price paid by water users with household connections to a water supply (UNESCO, 2003, p. 341).
2. The market for water is not efficient (Daly and Farley, 2004, p. 198). Supplying water is typically carried out by a provider that has a natural monopoly for this commodity, whether publicly or privately owned. Monopolies have little incentive to control costs and do not deal with market share, since they have most, if not, all of it. With no competition, and unless economically regulated, private water suppliers may be less efficient than public suppliers (Daly and Farley, 2004, p. 198). The opportunity cost—the value in the best alternative use—must be accounted for to provide efficient allocation (Schiffler, 1998, p. 40), but may not be considered in a monoply supply situation.

3. Intergenerational fairness should be a factor, as water is essential and groundwater can be mined like petroleum or other minerals, even when it may be renewable. When a resource like groundwater is a rival resource between the generations, the market will not operate efficiently to allocate it across generations (Daly and Farley, 2004, p. 192). This also relates to maximizing annual net profit, as opposed to the net present value of the resource.
4. For renewable resources such as groundwater in more humid climates, the ecosystem services that they provide are nonexcludable and do not have institutions to make them excludable (Daly and Farley, 2004, p. 211). These services may include groundwater supply to wetlands and maintenance of streamflow for drinking water, wildlife, and the web of natural connections, which are not clearly understood but are necessary. Such values are difficult to determine (Schiffler, 1998, p. 40). Therefore, the economy will not invest in these services. Degradation of these services is an "externality," that is, an incidental and unplanned loss of welfare to other people who will not receive reparation for their altered welfare condition (Daly and Farley, 2004, p. 175). Furthermore, pollution itself introduced into this natural capital is a negative externality or "public bad," being nonrival, nonexcludable, and not in demand. Pollution actually diminishes the natural capital available for ecosystem services that support life (Daly and Farley, 2004, p. 215). These services include residual absorption, cycling of nutrients, flood storage, and local and even global climate regulation. As we do not know all the nonmarket services that groundwater may provide, we cannot price them appropriately. Many investments are only profitable because they do not account for all costs; in some cases, for depleting or destroyed ecosystem services, substitutes may not exist (Daly and Farley, 2004, p. 212). These market failures will be addressed further in Chapters 11 and 12 on policy. Their significance is that the individual transactions that support the overall economy do not adequately address these factors in pricing products and services.

A MODEL OF GROUNDWATER IN THE ECONOMY

To this point, we have observed that groundwater is significant to the economy and our survival, which means that it is a critical raw material for our existence and our economic exchanges as social beings. Exhibit 3.9 shows the major uses of groundwater in the economy. Daly and Farley (2004, p. 229) indicated that under current accounting practice, the sum of all goods and services multiplied by their price equals the "country-level" economic measure, its gross national product. For groundwater, this is the value added in terms of labor and capital to produce it. This measure does not take into account "noneconomic welfare," such as a depleted or polluted resource or associated effects. Nor does it account for unmeasured services, such as flood and climate control and the natural productivity of wetlands. Groundwater is an essential substance for the ecosystem to function, a necessity for life, and a critical raw material for industrial activity. Following from the first law of thermodynamics (neither matter nor energy can be created or destroyed) inputs to the economy must equal the outputs. This condition for groundwater is described by the equation

$$\mathrm{GWW} + \mathrm{NME} = \mathrm{R}_p^c + \mathrm{R}_p^d + \mathrm{R}_i^d + \mathrm{ET} \tag{3.1}$$

This equation shows that GWW by the economy along with other natural materials carried by groundwater, extracted and transformed to products (NME) are equal to the groundwater commodities produced (R_p^c) plus the residuals from groundwater producers (R_p^d), discharges back to the environment by domestic and industrial (R_i^d) users, groundwater lost or wasted (L) and evapotranspiration (ET) resulting from domestic and agricultural/industrial uses of groundwater. The residuals from groundwater producers as well as domestic and industrial users, often are returned to the ground or subsurface, either through use (such as for pesticides) or disposal (such as liquid or hazardous waste). These residuals have a potential to contaminate and damage groundwater resources, possibly removing a portion of groundwaters from future economic withdrawal and use. This model will be further refined after the concepts of groundwater function and service have been developed. This depiction is a neoclassical environmental economic model of groundwater in the economy, focusing on the residuals produced and required to be reduced to mitigate damages to health, people, or property.

Scale of withdrawal or residual release into groundwater is a minor, if not nonexistent, problem when the population density of water users is very low. As a result, the factors in the equation presented earlier for any particular location may be small. However, with population growth and high density, demands on resources, generally, and groundwater, particularly, are overwhelming its sustainability (Daly and Farley, 2004, p. 12). The depletion of aquifers and the closing of wells from groundwater contamination are cases in point.

GROUNDWATER FUNCTION AND SERVICE

As discussed previously in Chapter 2, groundwater is both a stock and a flow resource. Stock resource indicates that in some locations, groundwater is of some known extent, is used or managed as a discrete reservoir, cannot be easily replaced or replenished, and is therefore, nonrenewable (USWRC, 1978, p. IV-18). A flow resource is renewed regularly, and moves through the environment, with its use incorporating this movement or flow function, which may result in offsite services. Locations exist where groundwater may be identified with both of these categorizations. As a stock resource, groundwater provides many services in the economy that can be identified and valued. These are described in Exhibit 3.17. These services range from provision of drinking water and irrigation water, to provision of a medium for wastes and support of living organisms. Our valuing of the services provided by the ecosystem functions of groundwater is less than perfect because of our ignorance of their inherent importance and connections in nature that support us, except at a basic level (if we fully understood their significance, we would be able to design and implement solutions to completely resolve the ecosystems issues now). These services generate effects on or for people, such as a change in welfare from an increase or decrease in the availability of drinking water or a change in human health or health risks attributable to a change in water quality. These effects can be evaluated in monetary and nonmonetary terms. Approaches to attempt to value them in economic terms are described in Bergstrom et al. (1996).

Groundwater is also a flow resource that, in many cases, has a movement that may be almost imperceptible, and, in other situations, very obvious, such as in springs from the ground. While many of the services that groundwater provides may be the same for both its stock and flow characteristics, the flow component offers several services that do not exist when considering it only as a stock resource. Specifically, groundwater may provide transport and treatment of wastes, and discharge to surface waters. This discharge to surface waters is significant, because it incorporates services of groundwater that were heretofore rarely considered and certainly not evaluated in an economic context, such as support of recreational swimming, boating, fishing, hunting, trapping, and plant gathering when groundwater serves to maintain surface water (i.e., baseflow of streams year-round and critically in dry seasons), including wetlands. Exhibit 3.17 describes the functions and services that groundwater provides to the economy.

Some of the services that groundwater provides to the economy might be considered as "ecosystem services" (Daley and Farley, 2004), as previously noted, and are not well understood and not monetizable, at least easily. These services are taken for free, and may be used up irreplaceably. These services include natural provision of

- Habitat support for flora and fauna in wetlands, estuarine, and coastal systems through nutrient cycling by groundwater discharge in the hydrologic cycle.
- Erosion and flood control through percolation of precipitation not becoming surface runoff, but transported to groundwater (stock) in the aquifer.

EXHIBIT 3.17 GROUNDWATER FUNCTIONS AND SERVICES

A. Function—Storage of Water Reserve (Stock): Groundwater stored in an aquifer provides a reserve (stock) of water which can be directly used to generate services, including

1. Provision of water for drinking water
2. Provision of water for crop irrigation
3. Provision of water for livestock
4. Provision of water for food product processing
5. Provision of water for other manufacturing processes
6. Provision of heated water for geothermal power plants
7. Provision of water for medium of heat exchange for cooling water of power plants and for heat pumps
8. Provision of water/soil support system for preventing land subsidence
9. Provision of erosion and flood control through percolated water increasing groundwater accumulation (stock) in aquifer
10. Provision of medium of storage and treatment (degradation) for wastes and other by-products of human economic activity
11. Provision of clean water for support of living organisms
12. Provision of passive or nonuse services (e.g., Existence or Bequest Motivations)
13. Provision of unknown ecosystem services, critically important to the balance of life to enable economic activity

B. Function—Discharge to Streams, Lakes, and Wetlands (Flow): Groundwater contributes to the flow or stock of water in streams, lakes, and wetlands. A portion of surface water and wetlands services are therefore attributable to the groundwater resource from its flow, including

1. Provision of water for drinking water through surface water supplies
2. Provision of water for crop irrigation through surface water supplies
3. Provision of water for livestock through surface water supplies
4. Provision of water for food product processing through surface water supplies
5. Provision of water for other manufacturing processes through surface water supplies
6. Provision of water for medium of heat exchange for cooling water of power plants
7. Provision of erosion and flood control through percolation of precipitation not becoming surface runoff, but transported to groundwater (stock) in aquifer
8. Provision of transport and treatment (degradation) through storage for wastes and other by-products of human economic activity
9. Support of recreational swimming, boating, fishing, hunting, trapping, and plant gathering
10. Support of commercial fishing, hunting, trapping, and plant gathering
11. Support of onsite observation or study of fish, wildlife, and plants for leisure, educational, or scientific purposes
12. Support of indirect, offsite fish, wildlife, and plants uses (e.g., viewing wildlife photos)
13. Provision of clean air through support of living organisms
14. Passive or nonuse services (e.g., existence or bequest motivations)
15. Provision of clean water through support of living organisms
16. Regulation of climate through support of plants
17. Provision of nonuse services (e.g., existence services) associated with surface water body or wetlands environments or ecosystems supported by groundwater
18. Provision of unknown ecosystem services of critical importance to the balance of life to enable economic activity

Source: Adapted and modified from Bergstrom, J.C. et al., *Water Resour. Bull.*, 32, 279–291, 1996.

- Water/soil support system for preventing land subsidence.
- Transport, treatment (degradation), and storage for wastes and other by-products of human economic activity.
- Clean air and water through support of living organisms.
- Regulation of climate through support of plants.
- Other services that have not yet been identified in the hydrological and terrestrial realms that support important human needs and balance for life sustenance.

Currently, these are considered free services, but as the economy grows and more groundwater is used and/or more wastes and residuals are released to the ecosystem, these services may become threatened and their value to the economy and the well-being of humankind may be more completely recognized as they become scarce. Once identified as significant or essential, the value of these services may be acknowledged through policy or lifestyle changes. Initial recognition of these ecosystem services is being incorporated in a renewed thinking on the function and management of watersheds and the role of groundwater in their water balances and ecological support.

RECYCLING AND REUSE

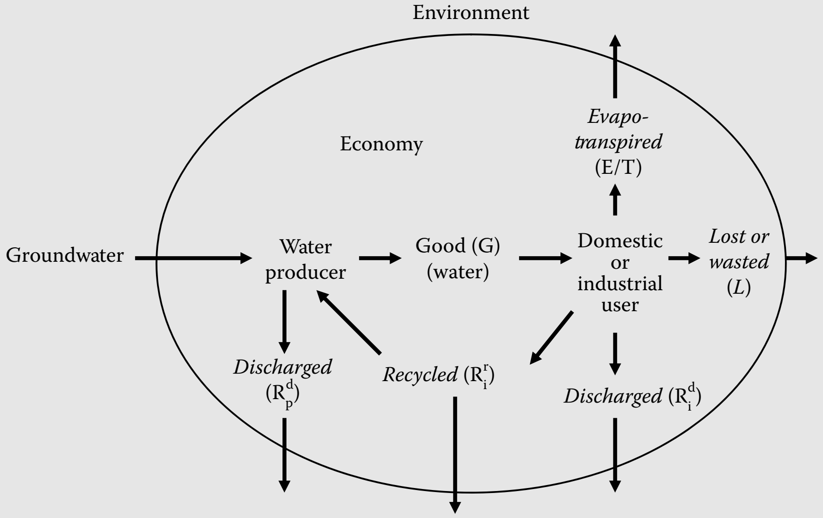
In areas where groundwater and surface waters are limited, recycling and reuse of groundwater may provide the additional supply (WSAA, 2004; Yasmeen, 2006). Recycling water means having a process to collect the water used and then treating the water for human consumption and returning it to drinking water distribution systems, or providing less treatment and redistributing it for nonpotable uses (USEPA, 1994). The water could also be returned to the subsurface environment and aquifer for storage and use at a later time, or to maintain important ecosystem functions (USEPA, 1994). A system for collecting the water is typically the sewer line already supplying the local wastewater treatment plant. In locations having industries connected to the sewer system, these companies are usually required to treat their processing water before releasing it to the sewer. The local wastewater treatment plant will remove pollutants to the level of the environmental standard set previously for the discharge point.

The water could be directly used after treatment in some applications, such as lawn watering and other kinds of outdoor or industrial washing and cleaning. However, for human consumption it would need to be chlorinated and meet the other maximum contaminant levels described in Chapter 6. In some locations, after treatment at the wastewater plant, it could be returned to the aquifer in areas called recharge zones that may be cisterns in the ground, wells to reinject the recycled water back into the ground or retention, and infiltration ponds that allow water to percolate through the soil and ground. This action would permit microbes in the ground to remove any remaining bacteria or contaminants that had survived the wastewater treatment process. Obviously, such a system would require separate sanitary and storm sewers, or a separate retention basin for stormwaters to allow treatment overtime. Groundwater use, treatment, recharge, and recycling are the principal features of a septic system that relies on natural cycling of wastewater after septic treatment.

A SIMPLE MODEL

From both business and public policy standpoints, groundwater can be viewed in a simplified model as a part of the natural environment–economy relationship (modified from Fields, 1994), as presented in Exhibit 3.18, a residual-based model. While groundwater can supply many functions and services that can be valued in the economy, groundwater and the geologic matrix in which it exists have characteristics that make groundwater a commodity, a medium for residuals and waste conveyance, and a residuals and waste sink.

EXHIBIT 3.18 A RESIDUALS-BASED MODEL OF GROUNDWATER IN THE ECONOMY



Source: Adapted from Field, B.C., *Environmental Economics: An Introduction,* McGraw-Hill, New York, 1994, 24.

This model has the economy as a dynamic part of the environment, drawing resources—in this case, groundwater—from the larger environment. A water producer extracts groundwater from the environment and supplies domestic consumers and industrial or agricultural users with the good (water), G. Both domestic consumer and industrial user may recycle and discharge water. The water producer also discharges a residual, R_p^d, back to the environment. The water producer's residual may be a sludge from the treatment process, containing metals, for example, which may be landfilled.

The domestic consumer recycles residuals, R_i^r, which might represent water after septic system treatment that is subsequently cycled back to the water table. Or, the residual, R_i^r, might be water treated in a wastewater treatment plant and returned to use through the water producer after further treatment. The domestic consumer also discharges residuals, R_i^d, which might be water with solids to be removed from domestically consumed groundwater by wastewater treatment and must be landfilled or land applied, and treated wastewater discharged to a stream.

Likewise, the industrial or agricultural water consumer may recycle residuals, R_i^r, which might be process water not consumed in production which is treated onsite for certain pollutants from production. Such pollutants could be reused, depending on the production process, or disposed and returned to the environment. The R_i^d can also represent the industrial water consumer's residual discharge to the environment. This discharge could be water containing waste, which is released to the sewer system connected to the local wastewater treatment plant, land applied if the waste is appropriate to that use, transmitted to the subsurface by injection well, or irrigation waters percolating down below the root zone and carrying unused nutrients and pesticides. In all the industrial situations, the water consumer should have the applicable permit from the government authority to release the residual water with its pollutants. In the agricultural settings, central authorities may take steps to control or reduce applications of fertilizers and pesticides.

In the model, L signifies water lost or wasted. This water that does not reach the domestic or industrial consumer may be substantial. Schiffler (1998, p. 37) indicated that unaccounted-for water may be in excess of 50% of water produced in developing countries, but often may be between 20% and 30% in those countries, and 10% and 20% in developed countries. Interestingly, this is a loss to the economy, but is not a loss to the ecosystem, as it may be "recycled" back to an aquifer from a leaking pipe. However, in such a circumstance, the water quality may have changed significantly because of treatment, or lack of treatment and hence, it may not be as it was originally.

EXPANDED ECOSYSTEMS SERVICES MODEL

Considering the total function of groundwater providing an array of services, which may include known and unknown services from which we benefit everyday, a different equation and model has evolved. The equation might incorporate earth structure, flood water mitigation, wetlands maintenance, nutrient cycling, streamflow maintenance, climate balance, estuary and fisheries support, and wildlife sustenance, among many other possible features. Furthermore, the model may have a natural, and perhaps unknowable, inherent, constraint—carrying capacity for human interactions—beyond which the groundwater environment could not sustain those interactions. Thus, the model requires uses for groundwater withdrawn for human purposes, net recharge of residual liquids, and the earth structure to be less than the groundwater carrying capacity constraint. This relates to the scale of the economy and human uses of groundwater. If they are smaller than the carrying capacity, then the inherent sustainability is preserved. If it is exceeded, then sustainability is not possible, even though all flows and residual quantities may be balanced in the equation. An equation that would recognize the ecosystem aspects of groundwater might conceptually be given as

$$\mathrm{NBGWQQ} = \mathrm{GWR} - \mathrm{GWD} \pm \mathrm{NBAC} - \mathrm{GWWH} + \mathrm{RRH} + (\mathrm{E/T})\mathrm{H} + (\mathrm{E/T})\mathrm{N} + \mathrm{ES} + \mathrm{OES} \qquad (3.2)$$

where the net balance of ambient groundwater quantity and quality (NBGWQQ) equals

GWR = groundwater recharge from precipitation, streams, lakes, wetlands, and oceans, including erosion and flood control
GWD = groundwater discharge to streams, lakes, wetlands, and oceans, for estuary and fisheries support and wildlife sustenance
NBAC = net natural biotic and chemical process substances
GWWH = groundwater withdrawn for human activities
RRH = $\mathrm{R}_\mathrm{p}^\mathrm{c} + \mathrm{R}_\mathrm{p}^\mathrm{d} + \mathrm{R}_\mathrm{d}^\mathrm{d} + \mathrm{R}_\mathrm{i}^\mathrm{d}$, recharge of residual liquids from human activities, including nutrients, contaminants, and substances injected into the subsurface
(E/T)H = (E/T)D + (E/T)I, evapotranspiration from human activities
(E/T)N = evapotranspiration from nature's activities (other than from human activities)
ES = earth structure (maintenance of ground surface rather than land subsidence)
NHS = net habitat support
OES = other ecosystem service flows of and support for groundwater

Subject to GWCC ≥ Net (GWWH + RRH + ES)
where GWCC is the carrying capacity of groundwater in an aquifer.

The carrying capacity of groundwater may be defined in several ways. The term could mean the quantitative use of groundwater such that only water that is replaced is consumed—the concept of "safe yield." It could also be defined in terms of an aquifer's ability to degrade only a limited volume or concentration of a contaminant or mix of contaminants. A third notion of carrying capacity might include a combination of quantity and quality factors, a range of water use that still allows the aquifer to absorb a certain amount of chemical or biological residual.

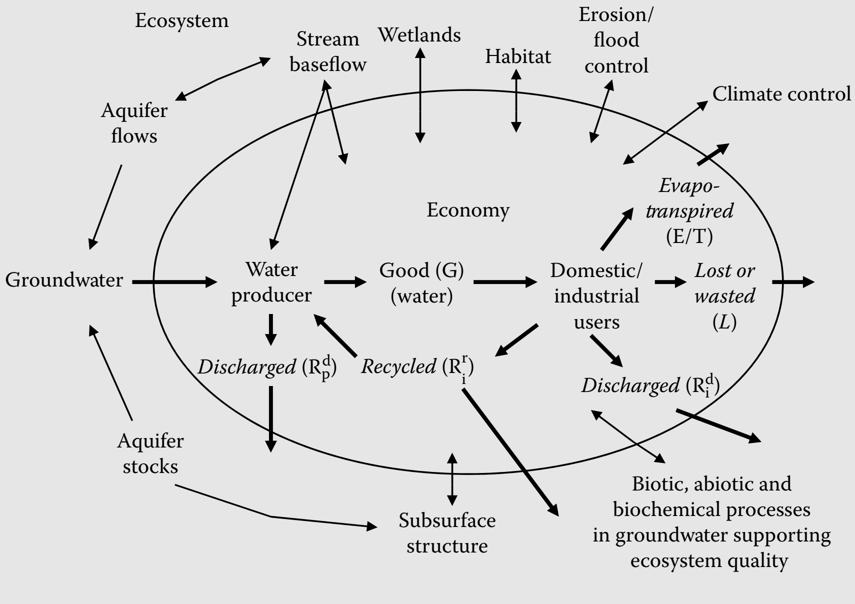
While it may seem odd to include groundwater quantity and quality in the same equation, at a conceptual level and in ambient conditions, they are considered or taken into account together in a particular location or for an aquifer. The services that groundwater provides, whether to human activities or through other ecosystem services, usually factors them together both in terms of available supply and preferred demand.

This model is depicted in Exhibit 3.19, portraying the complex and little understood interplay of groundwater ecosystem services with the economy. In the economy, each of these services would have a price associated with it, reflecting its value in the market. Typically, this value is actually the cost (including a profit to the producer) of producing the service and not the inherent value of the inputs, such as a value for the groundwater itself. Prices may probably be location-specific or dependent, based on the relative availability and quality of groundwater there and the interaction of that location or local market with other locations and their markets. It must be noted that the prices could be assigned to both "goods," such as groundwater used in wheat production, and "bads," such as pollution of groundwater. In neither of these examples is groundwater actually priced in the market directly. Groundwater pricing will be addressed in the later chapters on micro- and macroeconomics. "Ecosystem prices" may be much different than the "prices in a market economy," as the economy would price the value added for the throughput of groundwater, whereas with regard to groundwater mining (groundwater use greater than safe yield), an ecosystem price may be actually negative, that is, a cost to the ecosystem. The model with prices associated with it might look like the following function:

$$\begin{aligned}(\mathrm{a})\mathrm{NBGWQQ} = f[&(\mathrm{b})\mathrm{GWR} - (\mathrm{c})\mathrm{GWD} \pm (\mathrm{d})\mathrm{NBAC} - (\mathrm{e})\mathrm{GWWH} + (\mathrm{f})\mathrm{RRH} \\ &+ (\mathrm{g})(\mathrm{E/T})\mathrm{H} + (\mathrm{h})(\mathrm{E/T})\mathrm{N} + (\mathrm{i})\mathrm{ES} + (\mathrm{j})\mathrm{OES}]\end{aligned} \tag{3.3}$$

where a, b, c, d, e, f, g, h, i, and j are the prices of the factor in the equation, reflecting its value to the ecosystem within which the economy exists. Considerable research would be needed to derive these

EXHIBIT 3.19



Source: Adapted from Field, B.C., *Environmental Economics: An Introduction,* McGraw-Hill, New York, 1994, 24.

values, if they could be determined at all, reflecting our fundamental lack of knowledge of these relationships. If incorporated into the economy from a neoclassical economics perspective, they may most probably only reflect some value added that could be recognized by the market in reflecting its scarcity and not its true worth in the natural balance. Our inability to price these factors owes to the high level of uncertainty associated with their true function which gives evidence of our real ignorance of nature and its value to all our economic processes and throughput.

ECONOMIC EFFECTS ON GROUNDWATER FROM CLIMATE CHANGE

Reduced aquifer recharge, deteriorated quality, and increased pumping are the major anticipated effects of climate change on groundwater resources. Future drought may accentuate the competition between human and ecological uses of water (Loaiciga et al., 2004), in particular, with regard to drawing deeper groundwater resources. This circumstance may focus greater attention on human uses of groundwater for drinking water supply and irrigation, even encouraging more efficient water use. Other effects that are beginning to be recognized may result from carbon (dioxide) sequestration and desalinization waste disposal. As concern grows for taking action to reduce carbon dioxide (CO_2) emissions from economic activities that involve combustion of carbon-based fuels, one disposal sink being actively considered is deep porous rock capped by nonporous rock to reduce the potential for upward migration of these wastes. This option offers environmental benefits of reducing CO_2 emissions to the atmosphere. However, the costs to capture and store CO_2 are significant, but technological research is indicating a downward trend (USDOE, 2005a,b). Another concern is the potential environmental damages from injection not addressed by technology, including acidification and loss of integrity of rock structures, accidental leakage back to the atmosphere, and rapid, catastrophic "blowouts" of stored CO_2 (Smekens and van der Zwaan, 2004, pp. 4–6).

The other key concern related to groundwater directly is sea-level rise that may threaten the advance of saltwater intrusion into coastal aquifers. Water supply wells relied on by people and their local economies may have to be abandoned. Search for new fresh sources of water may include drawing on groundwater further inland or using other sources. Another option is desalination of seawater, which then involves disposal of wastes with high salt content that could include injection into deep geological strata with expectation of remaining in place and not migrating to drinking water sources. Saltwater intrusion, CO_2 sequestration, and desalination waste disposal on larger scales should be factors in modeling pressures on groundwater and demands on the economy.

IMPLICATIONS FOR SUSTAINABLE GROUNDWATER IN THE ECONOMY

Sustainable resource policy for groundwater has multiple economic dimensions. Using up groundwaters that cannot be easily replaced and the natural unrestricted flow of groundwater transfers economic effects to other actual or potential users. Some of these users will have reduced or increased supply, while others will receive a resource of changed quality. Still others may not recognize that their groundwater use has influenced others' use of a surface water resource, whether a stream, lake, or wetland. These transfers of effects could be accounted for in the economy if costs of use are not ignored but incorporated as fully as possible in transactions involving groundwater, and tracked separately in terms of macroeconomic transactions. This will be addressed further in later chapters.

From an ecological standpoint, as water is central to the very function of societies and as groundwater use is expanding as the next most viable and economic source following exhaustive use of surface waters, economic policy development must consider groundwater's role in both the hydrologic cycles of watersheds and as a conveyance and sink for wastes and residuals in the economic processes that occur in those watersheds. By extension, these hydrologic and economic processes must subsequently be incorporated into state, national, and international policy more proactively (UNESCO, 2003).

This simple ecosystem model will be the central concept from which solutions will evolve to address the critical issue of groundwater management. The model represents the integration of the natural environment and the socioeconomic realm through which we must make choices in the future. A point of significant attention for future policy is the sustainability of groundwater as a private commodity to meet the daily human needs of water and food as well as a public good to maintain habitat, geologic structure under places prone to subsidence, and baseflow of streams and other ecosystem processes, including mitigation of effects of wastes and residuals. Sustainability of groundwater requires this integration to meet the high objective of the Brundtland Commission to "meet [] the needs of the present without compromising the ability of future generations to meet their own needs" (UNWCED, 1987). Clearly, groundwater is such a resource which is nearly consumed in both physical and economic terms in some locations in less than a generation, and yet is so relied on at the margin of expanding water demands that it is the future resource of necessity in many lands. Accordingly, we must find ways to manage the physical and economic resources for the future.

SUMMARY

Groundwater provides many water uses, some of which are not obvious. This is because it has the characteristics of both stock and flow resources. It is a resource that is vital to the economies of many countries and localities. Groundwater as a raw material of the environment which is captured and used in the economy has long been recognized. The underlying policy implications of groundwater's movement or storage in the environment could be accounted for in transactions that affect the economy and even more essentially, the ecosystem about which we have incomplete information to address the market transactions. The simple models reflect different world views, one of groundwater use and residuals management in an economy that does not recognized other groundwater values, and the other incorporating ecosystem services difficult to measure, monetize, and price in the market but essential to the economy. As a result of the challenge to recognize the ecosystem services in the economy, market failures include distribution inequity, inefficient allocation, intergenerational fairness, and inability to price ecosystem services. Relating these issues to the economic management characteristics of groundwater indicate that the resource is difficult to own, challenging to control access, and easily depleted or contaminated.

The scale of use affects the extent of depletion and contamination of groundwater, even considering its renewability in many situations. Groundwater affects the economy at the individual level, for example, water for a particular consumer, as well as on large scale, watershed or national level, such as widespread depletion of an aquifer or as an input to national production of crops. As we do not understand all the ways in which groundwater supports the economy because of the inherent relations of the ecosystem, it is difficult to value groundwater in the economy other than through the market, which sets prices based on the value added for the throughput of groundwater, even though this may have negative results for the ecosystem. Prices for the factors that we can define in the ecosystem could not be determined, because we are too ignorant of the intricacies of the balance of nature. The models can be used as a guide to the development of sustainable groundwater policies, taking into account issues such as distributional and intergenerational equity. Future models may need to consider saltwater intrusion and disposal of CO_2 and desalination wastes on a larger scale.

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4

Groundwater Access and Supply: Wells, Springs, and Green Management

ACCESS IS FUNDAMENTAL TO USE

Access to groundwater is the first condition to bring it into human use and value. Since water is essential to all life, water and access to it have an inherent value. The cost of creating properly installed access to groundwater (i.e., a well) affects the groundwater producer's supply cost for water. Access to groundwater may determine habitability of an area: consider the oasis in the desert, the Biblical Jacob's well, or the high-capacity High Plains irrigation well. Gaining admission to the land overlying the groundwater of interest is a basic access requirement for groundwater. The factors that influence access to groundwater and its quality affect its supply cost and ultimately its price to consumers. Before obtaining access to groundwater for whatever purpose, it is best to consider available information about the subsurface before conducting field exploration for groundwater and installing one well or many wells. Hydrogeologic conditions of the subsurface, water demand implications for well size, and well type will also factor into well development costs. Access to groundwater may also provide avenues for supply augmentation as well as disposal, using the subsurface as a sink for treated and untreated wastes and water. Furthermore, wells may be used to produce other substances of commercial value other than water. Ecological aspects of groundwater access should receive further examination.

A TYPICAL WELL

Wells typically provide access to groundwater. A well is defined as an artificial excavation, usually a dug, bored, or drilled hole or tunnel, that penetrates a water-yielding underground zone and allows water to flow or to be pumped to the land surface (ITFM, 1997). A typical well has features common to most wells (Driscoll, 1986; USGS, 1997, pp. 18–32):

Annular space	The space between the drill hole and the casing.
Casing	Usually iron, stainless steel, or PVC (polyvinyl chloride) pipe through which the groundwater is pumped to the surface.
Screen	A slotted section of casing that allows water into the well.
Gravel pack	Gravel in the annular space around the screened interval to allow groundwater to move easily to reach the screen.
Backfill	Sometimes native materials drilled up and put back into the annular space above the gravel pack.
Surface seal	Cement is used to seal the upper annular space above the backfill to the ground surface and create a pad around the casing at the wellhead to keep surface runoff from traveling down along the casing and potentially contaminating the well water.
Annular seal	Often, cement fills the annular space above the gravel pack or backfill. Some states require the first 3 m of annular space below the ground

	surface to be grouted with cement to keep surface runoff from carrying contaminants down along the casing to groundwater and screen.
Grout	Another term for cement used to fill the annular space.
Protective well stack casing	A sleeve of steel casing, larger in diameter than the well casing, that is set in concrete at the wellhead and rises above the top of the well casing to protect it.
Packer	Cement or other impermeable material that is placed between the gravel pack and the backfill to isolate the gravel around the screen to prevent water (and contaminant) movement from above and below the screen. A packer may be used in conjunction with backfill.
Pitless adaptor	Device below ground surface and frost line in a well that allows the sanitary transmittal of water from the well through a line to a building.
Pump	Typically, a motorized device that pulls water from the aquifer and pushes it up the well. Some pumps may be at the wellhead, in which case, they would pull water up the casing. Pumps can also be hand and foot powered.
Apron	At ground surface, a concrete pad or apron is installed around the casing to keep surface runoff away from the well casing.
Well/pump house	A building or shelter built around and over the well or pump to keep the wellhead from being accidentally damaged and allow protected access.

Each of the items above affects the cost of an installed well because they require labor and materials. Depending on how they are installed, these items will also significantly affect the cost of operating and maintaining the well. The features for simple monitoring and municipal wells are described in Exhibit 4.1.

GROUNDWATER RESOURCE INVESTIGATION

Elements of an Investigation

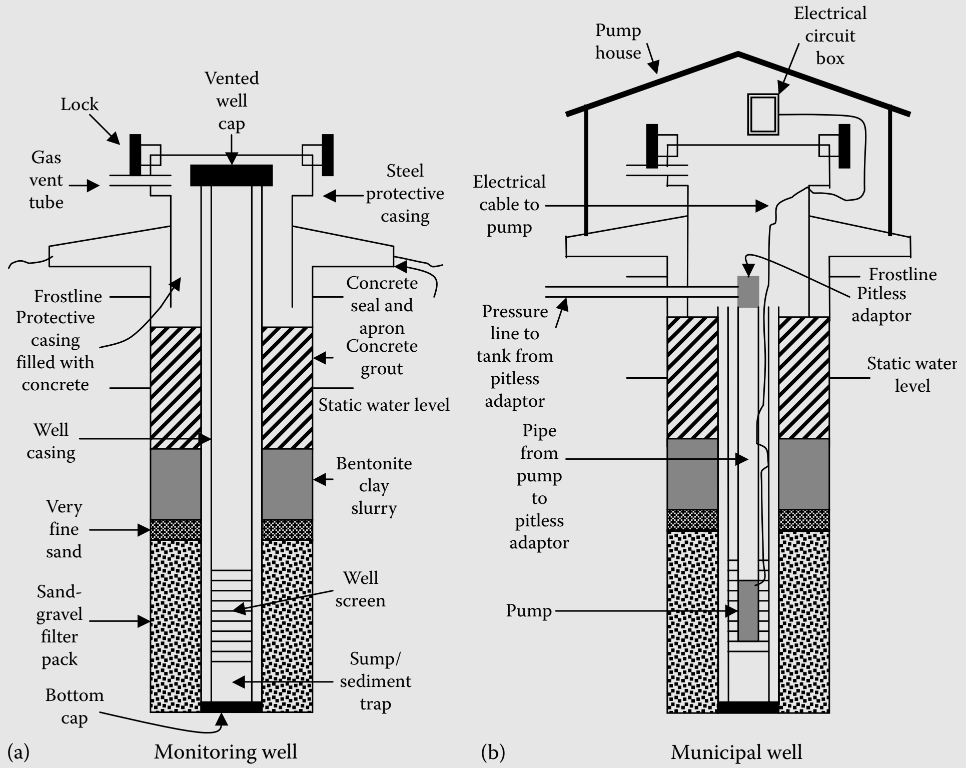
A groundwater resource investigation assesses the volume and quality of the resource that may be produced physically and economically. The investigation of the groundwater resource for water supply is more expensive than that of surface waters, while developing the access to groundwater is less capital intensive than for surface water (Foster, 1989, p. 53). The major steps in exploration and investigation of groundwater are well defined.

Investigation of groundwater occurrence and availability addresses the sources and discharge locations of the resource and the characteristics of the geologic matrix in which it is contained. The principal steps in an investigation program may include (RMC, 1990, pp. 34–35; Driscoll, 1986, pp. 150–204):

- Defining the boundaries of the area to be supported by the water supply or of remedial interest.
- Determining the objectives of the investigation.
- Conducting a preliminary study with available information, including project constraints, such as water rights and laws.
- Establishing an initial hydrologic budget for the area.
- Implementing an investigation program, including testing existing wells for levels and production capability, geophysical surveys, water quality analysis, drilling additional wells to fill information needs, leading to drilling production or dedicated monitoring wells.

EXHIBIT 4.1 TYPICAL WELL DESIGN IN UNCONSOLIDATED AQUIFERS

Generalized monitoring and municipal well diagrams (unconsolidated geological setting)



(a) Monitoring well (b) Municipal well

Groundwater investigation has incorporated the technologies of aerial and satellite remote sensing. An expanded paradigm of groundwater exploration has emerged with modern technologies, referred to as "megawatershed exploration," focusing on groundwater occurrence in deep fractured consolidated rock (Bisson and Lehr, 2004). Subsurface heterogeneity and complexity further add to the investigatory challenge and cost. Other factors affecting the cost of groundwater resource evaluation for large-scale development include acquiring sufficient information on aquifer recharge and storage and on natural and anthropogenic constituents affecting quality. Foster (1989, p. 55) lists the following points as significant in planning and implementing an investigatory program:
Small-scale development factors related to individual rural and residential wells:

1. Location and depth of groundwater producing zones
2. Variabilities of groundwater quality
3. Water table (piezometric level)

Large-scale development factors, in addition to the factors above, affecting large urban, irrigation, and industrial water needs:

1. Water demand
2. Subsurface storage properties

3. Recharge rates
4. Relationships with surface waters (streams, lakes, and wetlands)
5. Intrusion of brackish or saline waters

ANALYSIS OF AVAILABLE INFORMATION

Possibilities for evaluating these factors are enhanced in locations where previous investigation has already occurred and information is available. A first step to obtain access to groundwater is to examine the available information (Foster, 1989). A variety of sources can provide the necessary information on the depth to groundwater, direction of flow, seasonal conditions, geology of the subsurface, previous land use, costs of drilling, water quality, and potential sources of contaminants. Locally, the public health office may have a good idea of conditions relative to depth and quality. Both the state or provincial and national geological surveys of many countries have detailed information on most areas, which is often available on the Internet as well as in hardcopy report format.

In the evaluation stage, project managers can examine the results of important parameters, such as recharge and storage. While this stage may suggest more information is needed, use of modeling and performance of sensitivity analyses can guide the use of further field investment. Further major field investment may not improve the overall results (Foster, 1989, p. 61). Significant effort should be focused on aquifer response, especially in areas of complex hydrogeology. More complete descriptions of steps in the investigation and evaluation process are found in the U.S. Geological Survey (USGS, 1997) and other references (Driscoll, 1986; Brassington, 1988; Schwarz, 1989; RMC, 1990) and will not be detailed here. This resource evaluation will guide the development stage relative to location, number, spacing, size, and depth of wells, and groundwater production.

While individuals think that they may know exactly where they want a well for residential, industrial, municipal, or monitoring purposes, checking available information may make the decision to invest in a well more efficient (i.e., save money) in the long run. For example, knowing the depth to groundwater and seasonal fluctuations of the watertable will help determine how long the screen length should be or how deep to drill the well for a continuing source of supply during dry seasons. Knowing the direction of flow and that an adjacent area was used for other purposes (such as a waste or sludge disposal site) may indicate that the well should be placed more distantly from certain features of the site. Aerial photos combined with property title and environmental permit searches may identify important information on previous land use and potential contaminants on-site or nearby that would affect the quality of groundwater. The cost of obtaining this range of information is minuscule in comparison with the cost of problems that could lie ahead once drilling is underway or the well installed and the water testing over time showing a deterioration of water quality.

Part of the initial site assessment and preliminary plan development in establishing the direction and rate of flow and aquifer recovery from production need to be established from information on watertable levels combined with detailed hydrogeologic data about the aquifer of interest and other pumping in the area. If existing wells cannot be used, then new monitoring wells may be installed to establish these needed data for further groundwater analyses. The groundwater project would enter the investigatory phase at this point.

Investigatory groundwater monitoring wells may be installed to satisfy initial concerns about the suitability of a site for more permanent production wells. Hydrogeologists will also consult available field data from state and national geological surveys, reported well logs, and local drilling companies. On the basis of the data, a hydrogeologist may prepare a map of the area with watertable contours to guide his or her drilling, well installation, and other geophysical investigation.

COST OF INVESTIGATION

Costs of these assessment factors will influence investigation and development. Early groundwater investigation may be funded by government to provide the basis for future groundwater development, considering such information as a public good. In the private development case, economic return on groundwater use will be a constraint on expenditures for groundwater resource evaluation. Public sector projects will likely focus on least-cost assessment of options having similar results. In any case, success of the investigation is driven significantly by costs and associated expenditures.

Foster (1989) offers a framework to evaluate investigation costs. First, a comparison of subsurface investigation method cost to drilling savings is done. If *m* and *n* are two different methods with costs of C_m and C_n and their average cost of a successful borehole can be described as d/P, d being average drilling cost and P the probability of success, then the method selected has a cost differential less than the saving in drilling costs, defined as:

$$(C_n - C_m) < \left([d_n/P_n] - [d_m/P_m]\right). \tag{4.1}$$

We would choose method *n* if this relationship held for that method's costs. *P*, the probability of success, will be strongly affected by subsurface factors as well as aquifer yield-drawdown relationships and the groundwater quality acceptability (Foster, 1989, p. 56).

Second, the maximum expenditure that would be warranted for groundwater investigation could be estimated by

$$C_{\max} = \left(d[1 - P_n]/P_n\right), \tag{4.2}$$

where

d is the drilling cost
P_n is the probability of success for method *n*

P_n will typically be less than 1.0 (or 100%) for any method, since success does not just consider groundwater occurrence, but also yield-drawdown and water quality, and may include other factors specific to a location of potential water use. Curves for Equation 4.2 relating $C_{\max}$ to P_n can be developed (Foster, 1989, p. 57).

While the probability of success cannot be known in advance, a minimum accepted probability of success could be calculated by

$$P_{\min} = (dP_n)/(d - \mathrm{C}_n P_n), \tag{4.3}$$

where the symbols are as previously used.

Equation 4.3 gives the fraction of boreholes that meet the success factors to allow a particular method to be considered for use in field investigation.

Several approaches to improve the cost-effectiveness of groundwater investigations may be considered. Typically, groundwater development activities evolve in stages: investigation, evaluation, and development. Investigation involves risk capital investment. At this stage, integrating available data to identify high-cost aspects of the project, considering alternatives, and examining possible drilling sites based on hydrogeologic assessment can provide information supportive of flexible decision-making. Geophysical exploration may include, but not be limited to (along with relative cost indication) (1) electrical resistivity measuring the slope of the watertable and the concentration of ions in groundwater through transmitting current through the ground and recording voltage loss (low cost), (2) seismic refraction (medium cost)/reflection (high cost), which measure compression waves traveling through the subsurface and reflecting off different densities of rock, (3) gravimetric surveys measure differences in densities of rock, saturation, and faults (high cost), (4) electromagnetic surveys record the time for electromagnetic waves to reach different densities and reflect back (low cost), (5) ground penetrating radar (low cost), and (6) borehole methods recording electrical resistivity, gamma radiation, neutron energy loss, temperature changes, acoustic patterns, and fluid flow movement of the stratigraphic sequence in a borehole (high cost) (Driscoll, 1986, pp. 168–202;

Sanner and Abbas, undated). Remote sensing and gravity measurements by satellites also provide further techniques of identifying the presence and elevation of groundwater (O'Hanlon, 2003).

Options for dealing with high cost factors can be considered before major investment is made. One course of action is to address one area at a time, concentrating on geophysical exploration and drilling equipment and coordinating results through a chief field hydrogeologist who can make immediate decisions on well depth, completion, and screening of appropriate intervals for production and water quality acceptability.

Documentation of costs for groundwater resource investigation is not extensively and readily available. Foster (1989, p. 59) found that in the United Kingdom costs per production borehole for low-yield rural water supply wells were \$2000 (\$3050 in 2007 \$US) compared with \$50,000 (\$76,260 in 2007 \$US) for high-yield irrigation or municipal water wells. For high-yield wells, Foster (1989, p.59) reported costs of \$100–\$1000 (\$153–\$1525 in 2007 \$US) per km^2 and \$100–\$250 (\$153–\$381) per m^3/day for groundwater production. Schwarz (1989, p. 74) identified that in Spain investigation wells cost one-tenth that of production wells. For a two-year exploration of a 10,000 km^2 area, a breakdown of total groundwater investigation costs of \$600,000 (1989 \$US) was experts, 1/2; field labor, 1/6; and equipment, 1/3. For 1989 in comparison, he found that rural water supply studies in Chad and Mali cost \$5 per km^2 and \$25 per km^2, respectively (1989 \$US).

Megawatershed exploration for groundwater is an approach developed based on investigation of groundwater occurrence in fault and fracture zones in bedrock that transcends watershed boundaries and topographic features. Estimates by the principal investigators of this method suggest that accessible groundwater resources may be 10–100 times larger than current calculations for many water-stressed parts of the world (EarthWater Global, 2009). The approach combines investigation using currently available geological data with satellite-based remote sensing of faults and fractures in deep bedrock and geographic information systems to analyze fracture width, density, and connectedness and relate those characteristics to fluid flow (Bisson and Lehr, 2004, p. 136). Use of this approach has led to developing high-volume groundwater supplies (5,000–75,000 m^3/day depending on location) in Trinidad, Tobago, Sudan, Somalia, and New Hampshire. Long-term effects on water tables and on the quality and habitat of connected coastal receiving waters have not been documented.

COSTS AND BENEFITS OF GROUNDWATER INVESTIGATION

Consideration of costs and benefits of a resource investigation guide the determination of proceeding on an investment in groundwater supply. Practically, a groundwater development program, in particular, in an area with no other water source alternative and with scarce economic resources, should proceed by evaluating the benefits to society or the communities served and the costs of developing the groundwater resource. Chapters 9, 12, and 13 will go into greater detail on comparing costs and benefits. Exhibit 4.2, Benefit–Cost Model for Groundwater Investigation, will provide an initial view of cost–benefit analysis applied to groundwater field investigations.

The megawatershed approach to groundwater resource investigation for water supply has benefits that have some elements that have been quantified in the available information (EarthWaterGlobal, 2009):

- Capital cost: low, compared with alternatives of dams and reservoirs and desalination.
- Treatment requirements: low, assuming high-quality water not needing treatment.
- Operating costs: low, assuming principal cost is for operating and maintaining wells and pumps.
- Environmental effects: confined mainly to the subsurface and groundwater fracture flow.
- Land requirements: areas around wellheads, approximately 0.04 hectare/well.
- Water supply reliability: high, assuming continued natural flow sources.
- Time to initial production: 6 months from beginning of project compared with 10 years for dams and 1–5 years for desalination projects.
- Contaminant risk: low, since the sources are deep.

EXHIBIT 4.2 BENEFIT–COST MODEL FOR GROUNDWATER INVESTIGATION

A simplified approach to evaluating benefits and costs of groundwater resource investigation considers success and failure of multiple attempts (subsurface explorations) to find groundwater, drawing on Bayesian analysis. This approach incorporates only two outcomes, water is found (success) with probability P_q and water is not found (failure) with probability $1–P_q$. Success may include factors such as achieving a particular continuous pumping rate, location within a specified distance of the point of use, and finding water within a predetermined depth. These factors may be derived based on local economic conditions. Failure would then be the opposite of these factors. The model description is

Probability of water found capable of providing quantity q (a priori estimate) = P_q
Probability of water not found in sufficient quantity = $1–P_q$
Cost of subsurface exploration providing sufficient information = C_I
Probability of subsurface exploration providing necessary information to determine availability of groundwater (a priori estimate) = P_I
Probability of failing to obtain sufficient information from subsurface exploration = $1–P_\mathrm{I}$
Cost of groundwater development of quantity $q = C_q$
Benefits (discounted to net present value) of groundwater supply of quantity $q = B_q$

Note that incorporation of probabilities for the quantity desired and the success of investigation in the model addresses the notion of planning for "expected" success and benefits.

The entity proposing to develop the groundwater supply may choose among at least three policies after evaluating the available information:

1. Assuming successful investigation, develop resource
2. Attempt to develop resource without investigation, relying solely on the available information
3. Do not develop resource

The three policies' evaluation considers their "net benefits":

1. Investigation followed by development: $(B_q–C_q)P_q – (C_\mathrm{I}/P_\mathrm{I})$
2. No investigation, but proceed with development: $B_q P_q – C_q$
3. No investigation and no development: 0

Schwarz further elaborates the decision rules for proceeding with development using the net benefits framework:

Investigation followed by development is substantiated based on two circumstances applying to the situation:

1. When $(B_q–C_q)P_q–(C_\mathrm{I}/P_\mathrm{I}) > 0$, indicating that the net benefits must be greater than zero, or rearranging the inequality to give $(B_q–C_q)P_q P_\mathrm{I} > C_\mathrm{I}$, noting that the benefits from development must exceed the costs of the investigation
2. When $(B_q–C_q)P_q–(C_\mathrm{I}/P_\mathrm{I}) > B_q P_q–C_q$, that is, the net benefits from investigation are greater than the net benefits from development without an investigation

Development without investigation is warranted when:

$B_q P_q–C_q > 0$, i.e., the net benefits are greater than zero, or rearranging and restating the inequality, $B_q P_q > C_q$, the benefits are greater than the costs.

(continued)

EXHIBIT 4.2 (continued) BENEFIT–COST MODEL FOR GROUNDWATER INVESTIGATION

Schwarz notes the ranking process for groundwater development projects may evaluate:

1. Selecting among investigation approaches for the same project through cost-effectiveness: C_I/P_I
2. Selecting among investigation approaches for several development projects using net benefits criterion for ranking: $(B_q-C_q)P_q-(C_I/P_I)$
3. Depending on the need for the desired quantity of water, an alternative approach could consider ranking by P_q, balancing investigation costs with reduced variance of obtaining the quantity desired.

Source: Schwarz, J., *Groundwater Economics: Selected Papers from a United Nations Symposium Held in Barcelona, Spain,* Elsevier Science Publishers B.V., Amsterdam, the Netherlands, 1989, 67–81. With permission.

LAND OR PROPERTY ENTRY

Fundamentally, access to groundwater means obtaining entry to the land in the vicinity of the aquifer of interest and, if the property does not have a free flowing spring, having the right to install a well and produce groundwater (NGWA, 2003). The conditions for land to be entered for groundwater production involve:

1. Ownership or permission of the owner or trustee to use the land.
2. Ensuring that the property rights allow subsurface intrusion and groundwater production.
3. Permission of the governmental jurisdiction(s) in the area to install a well and produce groundwater.
4. Location and distance from underground features, such as pipelines and cables or distance from drains, septic tanks, and cesspools.
5. Overland access and egress for drilling equipment to enter and leave the property.
6. The capacity of the land to accommodate well-drilling equipment, including sufficient land area and overhead space to enter and position a drill rig.

Costs of land or property entry, equipment positioning, permission for well installation, and groundwater production must be considered in the cost of groundwater access. Otherwise, groundwater access may not be possible. These land and property costs will vary by location and must be evaluated on a site-by-site basis.

FACTORS AFFECTING WELL LOCATION

Many factors affect well location. As will be discussed here, well location has both a horizontal (or areal) and vertical (or depth) component. Some of the major factors include

1. Property ownership and its access to others
2. Water rights
3. Sources or pathways of contamination
4. Geology
5. Depth to desired water-bearing zone
6. Location of other wells
7. Subsurface structures (avoidance of)

8. Overhead access for drill rig
9. Natural water quality
10. Volume of water demanded

Property ownership will be a major determining factor as to the location of wells, either for water supply or for monitoring. Unless access to the wellhead can be controlled, a certain amount of liability is associated with a well. Therefore, any owner agreement to have a well on his/her property is significant. Liability can take several forms: if not properly marked or fenced, the wellhead may not be highly visible and be a physical hazard; if the wellhead casing or surface apron is damaged, contaminants can potentially enter the aquifer affecting the well's water quality and possibly that of other wells; subsurface engineered structures need to be located prior to construction, but even with this precaution taken, well installation can cut or penetrate such structures, disrupting other services and potentially creating a dangerous situation. These situations create additional cost for well installation, especially if not taken into account prior to decisions of location and installation.

Volume of water to be pumped also affects both the vertical location of the well completion and the location across the area being considered for the well. Pumping by its nature draws water from the zone beyond the well and if pumping is excessive, it can affect production at the surrounding wells on neighboring properties. When large volumes of water are needed, it may be necessary to install larger capacity wells in deeper aquifers. This, of course, raises the cost of production. However, one larger, deeper, higher capacity well may be preferable to several shallower wells. Where water tables are dropping at high rates due to water use, deeper high-production wells must be used. The long-term problem with this approach in some locations is that such pumping may draw water from the overlying shallower aquifers, thus impacting the water available in all the useable aquifers. Impermeable geologic strata (also called aquicludes) are never totally impermeable, allowing water to move down to lower aquifers, albeit, at a slower rate, which can be accelerated by deep, high-volume pumping.

Factors influencing well design and installation include (USGS, 1997, p. 20)

- Nature of the subsurface materials that overlie and comprise the aquifer (ranging from unconsolidated sand to fractured bedrock with dissolution channels)
- Well-casing and screen material depending on subsurface conditions
- Screen length and type
- Diameter of casing and screen (or open borehole)
- Depth to static water level
- Depth to the top of the aquifer of interest
- Depth to the zone in the aquifer to be monitored or produced

Local or jurisdictional requirements will also affect the materials and other factors of the well. These requirements may vary from state to state and include well termination at or above ground surface, depth of grout, grout mix specifications, protective casing use, type of casing material, casing dimensions, well capping type, discharge control, disinfection, correction of damage, yield tests, and well sample tests, as well as abandonment procedures (Job and Gabanski, 1987). Exhibit 4.3 demonstrates the differences among U.S. states in well construction requirements. Notably, some states have requirements for well termination 107 cm above the highest known flood elevation and other states do not reference any elevation. Depth of grout in the annular space ranges from no minimum to 9.14 m. Cap requirements to safeguard direct access to the well casing vary from none to welded or locking caps. Thus, in some states, a well may cost significantly more than in adjacent states.

Additional factors for locating high-volume irrigation, industrial, or urban water supply wells may include (Niñerola, 1989, p. 84)

EXHIBIT 4.3 SELECTED WELL CONSTRUCTION REQUIREMENTS IN 12 NORTH CENTRAL U.S. STATES

State[a]/Well Type Affected	Location Requirement	Termination Requirements	Minimum Grouting Depth	Grout Mix Specifications	Casing Type Specifications	Locking Cap Requirements	Disinfection Requirements
Colorado/all	—	30.48 cm above GS[b]	3.05–6.1 m	—	—	—	Yes
Illinois/all	Yes	60.96 cm above HFE[c]	—	Yes	PVC[d] or steel	—	—
Indiana/PWS[e]	—	—	—	—	—	—	—
Iowa/all	Yes/45.72 m from contaminated Source	45.72 cm above GS 106.68 cm above HFE	6.1 m	Yes	Steel	No (welded or threaded steel cap)	Yes
Michigan/all	Yes/Health Officer approval in certain cases[f]	30.48 cm above GS	7.62 m	Yes	PVC; no steel for monitoring wells	Yes	Yes
Minnesota/Mon[g]	Yes/in contaminated Sources	30.48 cm above GS 60.96 cm above HFE	9.14 m	Yes	PVC or steel	Yes	Alternative methods
Nebraska/Mon	Depends on geology	30.48 cm above GS	3.05 m	Yes	PVC or steel	—	Yes
North Dakota/all	Yes/away from contaminated Sources	30.48 cm above GS	6.1 m	Yes	PVC or steel	No (welded plate)	Yes
Ohio/All	Yes/away from contaminated Sources	20.32 cm above GS	Aquifer to GS	—	PVC or steel	—	Yes
South Dakota/ NonPWS	Yes/away from contaminated Sources	30.48 cm above GS 60.96 cm above HFE	6.1 m	Yes	PVC or steel	—	Yes
Wisconsin/Mon	Yes/for groundwater monitoring	30.48 cm above GS	—	Yes	PVC or steel	Yes	—
Wyoming/all		60.96 cm above HFE					
	Yes/away from pollution sources	30.48 cm above GS	3.05 m	Yes	PVC or steel	No (temporary seal)	Yes

Source: Modified from Job, C. and Gabanski, G., Monitoring wells need consistent regulation, *Superfund '87, Proceedings of the 8th National Conference*, Washington, DC, The Hazardous Materials Control Research Institute, Silver Spring, MD, November 1987 (Reprinted in *Waste Age*, 1988, 164–170).

[a] State requirements drawn from the following sources:

Colorado: Rules and regulations governing construction of wells and the installation of pumping equipment.
Illinois: Water well construction code, Chapter III ½.
Indiana: Indiana code 91-11, 13.
Iowa: Iowa Water Supply Facilities Design Standard, Chapter 3.
Michigan: Michigan Act 368, P.A. 1978, Part 127 and Rules; Act 315, P.A. 1969.
Minnesota: Minnesota Rules Chapter 4725.
North Dakota: North Dakota Century Code, Chapters 43–35 and 33–18.
Nebraska: Guidelines for Design and Construction of Water-Quality Monitoring Wells, NRS Chapter 12.
Ohio: ORC-3745-9, ORC-3745-41, ORC 3701-28.
South Dakota: South Dakota Code Chapter 74:02404.
Wisconsin: Guidelines for Monitoring Well Installation; Wisconsin Administrative Code Chapter NR 110, Chapter NR 214.
Wyoming: Part III—Water Well Minimum Construction Standards; Chapters VIII, IX, X, Water Quality Rules and Regulations.

[b] GS means "ground surface."

[c] HFE means "highest-known flood elevation."

[d] PVC means "polyvinyl chloride."

[e] PWS means "public water supply."

[f] Health Officer Approval needed near polluted sources; permission needed for flood areas.

[g] Mon means "monitoring well only."

- Energy costs for pumping water to the ground surface
- Distance from the wellhead or field to the location of use
- Distance for extending energy supply to the site
- Ease of access for machinery and materials

These factors may also affect long-term operation and maintenance of the groundwater production site and its wells.

Job and Gabanski (1987) show that the differences in state well requirements, in particular, for monitoring wells can have a significant result on costs, which can vary from state to state. They found that for two wells in the same hydrogeologic conditions (glacial till of interbedded clay and sand with some boulders) and depth (15.24 m), differences in requirements might cause one well to be twice as expensive as another well for the same purpose (monitoring). Most of the cost difference is in the type of casing used, steel or polyvinyl chloride (PVC) plastic. If the less expensive PVC casing is used with the more protective package at the wellhead, the cost difference is about 25%.

These differences are described in Exhibit 4.4.

EXHIBIT 4.4 COMPARATIVE COSTS FOR MONITORING WELLS UNDER DIFFERENT REGULATION REQUIREMENTS

Well 1[a]	Cost[b] (1987 $US)	Well 2[a]	Cost[b] (1987 $US)
Drilling and casing		*Drilling and casing*	
Depth: 15.24 m		Depth: 15.24 m	
Drilling with truck rig and 8.26 cm hollow stem auger		Drilling with truck rig and 8.26 cm hollow stem auger	
Soil sampling conducted		Soil sampling conducted	
Stainless steel screen (5.08 cm × 3.05 m) and casing		PVC[c] screen (5.08 cm × 3.05 m) and casing, flush grade	
Subtotals	$1400–$1550		$750–$900
Pack/grout/seal		*Pack/grout/seal*	
Sand and gravel pack		Sand and gravel pack	
Cement grout from Seal to GS[d]		Cement grout 3.05 m to GS[d]	
Bentonite seal		Native backfill up to 3.05 m from GS[d]	
Subtotals	$300		$250
Well protection		*Well protection*	
Protective casing		Threaded steel cap	
Three protective posts			
Locking cap			
Subtotals	$250		$10
Totals	$1950–$2100		$1010–$1160

Source: Job, C. and Gabanski, G., Monitoring wells need consistent regulation, *Superfund '87, Proceedings of the 8th National Conference*, Washington, DC, The Hazardous Materials Control Research Institute, Silver Spring, MD, November 1987 (Reprinted in *Waste Age*, 1998, 164–170).

[a] Assumes glacial till of interbedded clay and sand with some boulders.

[b] Costs do not include mobilization or utility clearance costs and will vary for each state.

[c] PVC means "polyvinyl chloride" plastic.

[d] GS means "ground surface."

WELL PERMITS

Installation requirements for wells vary from state to state, as noted, or country to country. Some local jurisdictions even have well installation requirements. These requirements are to protect the well owner and to protect against contamination of the aquifer. The types of well installation requirements are

1. Well installation standards
2. Well installer certification
3. Well permit

Well installation standards: Some jurisdictions have requirements on the depth of the screen below the ground level or the watertable, depth of grout, type of grout, surface (wellhead) completion, type of casing, setbacks, and other requirements, based on the type of well (Job and Gilbanski, 1987).

Well installer certification: Other jurisdictions may have requirements concerning the knowledge, training, and experience of well installers to be met before a well installer is allowed to operate a well installation business in the state. Often, knowledge of specific well standards, such as those set by voluntary standards organizations as ASTM, is required to be tested (Job and Gilbanski, 1987).

Well permit: In some states (e.g., Ohio), a property owner must apply for a well permit. Depending on the water volume to be produced and the water use, the state will decide whether a well permit be issued. A key factor is whether pumping would interfere with other groundwater uses nearby.

All of these jurisdictional requirements are for the protection of the well users or owners. While they add cost, the states having the standards have determined the standards to be of value in protecting the health and welfare of its citizens from inappropriate well installation practices and in minimizing damages to adjacent groundwater users.

WELL DRILLING AND INSTALLATION

The use of the well and conditions of the area and subsurface should guide construction of a well through drilling and installation. Well construction is detailed in other texts (Driscoll, 1986; USGS, 1997). Unconsolidated sand and sand and gravel typically provide easier drilling conditions and are probably the least costly. Exhibit 4.5 describes briefly different well drilling methods.

EXHIBIT 4.5 DRILLING METHODS

Dug wells. Constructed by using simple hand earth-removal tools (shovels, trowels, etc), usually to several meters in depth, with a brick, stone, or concrete wall for casing and open at the bottom.

Drilled wells. Require a motorized drill rig and downhole equipment to loosen and remove unconsolidated material or cuttings from consolidated geologic formations. Several techniques may be used, the principal ones being

- *Cable tool.* This method uses gravity to drive a drill bit on the end of a cable hanging from the tower of a vehicle mounted drill rig into the subsurface. Drill cuttings are removed by pumping water in the borehole to become slurry with the cuttings and then pumping the slurry out of the hole. Wells in unconsolidated material have reached depths of 305 m.

(*continued*)

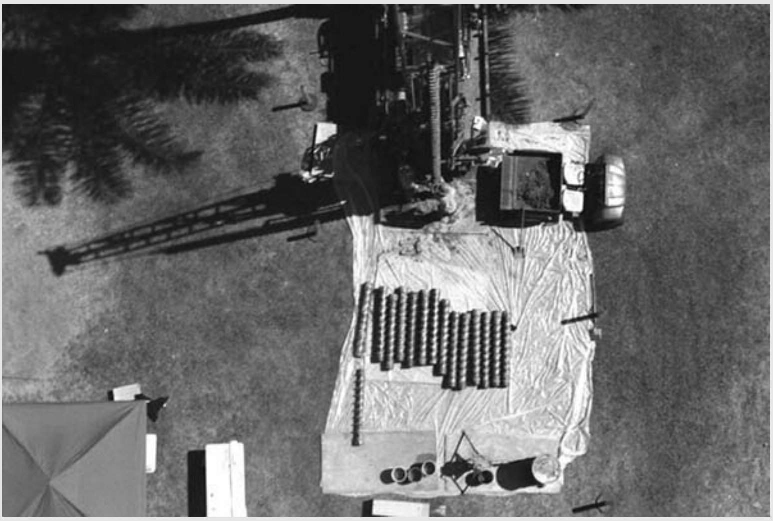
EXHIBIT 4.5 (continued) DRILLING METHODS

- *Rotary drilling*. This technique also uses a drill rig and turns a drill bit into the subsurface to loosen the geologic material. Either water or air is pumped into the borehole to combine with the cuttings and be pumped out. Variations on this technique have achieved depths in excess of 610 m.
- *Air hammer*. A drill pipe of special alloy steel is driven in successive rapid strikes against the rock with the cuttings brought to the surface by the air used for the hammer strokes.
- *Jet percussion*. A high-velocity water stream is used in combination with the percussion drilling to remove cuttings and keep the drill bit clean so it is striking uncut rock. Depths ranging from 61 m to 305 m have been reached with this technique.
- *Hydraulic percussion*. This technique is similar to jet percussion except that a check valve allows the water-cuttings mixture to be captured and drawn up the casing with each stroke.
- *Jetting washbore*. A high-velocity water stream is jetted into a casing to remove unconsolidated earth materials.
- *Earth augur*. The vehicle-mounted augur turns and bores in the subsurface and brings the loosened material to the surface. Depths of 76.2 m for a bucket augur, 36 m for a solid-stem augur, and 91.5 m for a hollow-stem angur have been achieved with this method.
- *Other variations*. Variations of the above drilling methods are described in detail by Driscoll (1986).

Driven wells. This technique can only be used in unconsolidated geologic material that do not contain rocks. Hollow metal casing with a well point can be driven by hand to depths of 9.1 m or machine to 15.2 m or more.

Sources:

1. Driscoll, F.G., *Groundwater and Wells*, Johnson Filtration Systems, Inc., St. Paul, MN, 1986, 268–339.
2. Niñerola, S., *Groundwater Economics: Selected Papers from a United Nations Symposium Held in Barcelona, Spain*, Elsevier Science Publishers B.V., Amsterdam, the Netherlands, 1989, 90–96.
3. Photographs in this exhibit provided through the courtesy of Richard Laton and the National Ground Water Association.



Hollow stem drilling rig

EXHIBIT 4.5 (continued) DRILLING METHODS

Mud rotary drilling rig

Drill bits

(continued)

EXHIBIT 4.5 (continued) DRILLING METHODS

Air rotary drilling rig

More drill bits

Monitoring wells of different types in different hydrogeologic settings used in monitoring well construction are presented in Exhibit 4.6. The table clearly shows that hydrogeologic settings of sand are the least expensive to install a well in, of till are intermediate in cost, and of bedrock are the most expensive. Also, steel-cased wells are more expensive than PVC-cased wells. Deeper wells tend to be steel cased.

EXHIBIT 4.6 COMPARISON OF AVERAGE MONITORING WELL INSTALLATION COSTS[a] BY WELL TYPE AND HYDROGEOLOGIC SETTING IN THE UNITED STATES

Installed Well Costs per Monitoring Well

	Well Depth		Hydrogeologic Setting (1995 $US)		
Well Type	**(m)**	**Well Casing**	**Sand[b]**	**Till[c]**	**Bedrock[d]**
1	15.24	PVC[e]	1,577	2,005	2,771
2	30.48	PVC[f]	3,170	4,253	4,646
3	30.48	Steel[g]	4,964	6,015	6,279
4	60.96	Steel[h]	12,757	14,865	13,448

Unit (per m) Costs for Monitoring Wells

	Well Depth		Hydrogeologic Setting (1995 $US)		
Well Type	**(m)**	**Well Casing**	**Sand[b]**	**Till[c]**	**Bedrock[d]**
1	15.24	PVC[e]	31.54	40.10	55.42
2	30.48	PVC[f]	31.70	42.53	46.46
3	30.48	Steel[g]	49.64	60.15	62.79
4	60.96	Steel[h]	63.78	74.33	67.24

Source: U.S. Environmental Protection Agency (EPA), Office of Water, *Ambient Ground Water Quality Monitoring Cost Analysis*, EPA 816-R-97–013, 1997, pp. C-1 and C-2.

[a] Costs assume Auger Methods for Sand and Glacial Till for Well Types 1, 2, and 3, and Air Rotary Methods for Bedrock Wells and for Well Type 4, and do not include stratigraphic core sampling or decontamination.

[b] Sand means that the predominant material in the unsaturated zone and below the water table of the aquifer into which the well is installed is unconsolidated sand.

[c] Till means that the predominant material in the unsaturated zone and below the water table of the aquifer into which the well is installed is unconsolidated glacial till.

[d] Bedrock means that the predominant material in the unsaturated zone and below the water table of the aquifer into which the well is installed is bedrock.

[e] Representative Well Type 1 is 15.24 m deep, 5.08 cm PVC casing and screen, sand and gravel pack, bentonite seal, complete grouting, locking cap, and no protective devices.

[f] Representative well Type 2 is 30.48 m deep, 5.08 cm PVC casing and screen, bentonite seal, complete grouting, locking cap, and protective steel well stack casing.

[g] Representative well Type 3 is 30.48 m deep, 5.08 cm stainless steel casing and screen, bentonite seal, complete grouting, locking cap, and protective steel well stack casing.

[h] Representative well Type 4 is 60.96 m deep, 10.16 cm stainless steel casing and screen, bentonite seal, complete grouting, locking cap, and protective steel well stack casing.

Exhibit 4.6 also shows that for a particular hydrogeologic setting, stainless steel casing is more expensive to install than PVC casing by 57% for a 15.2 m well and 41% for 30.5 m well. Generally, costs increase with depth and more complicated hydrogeologic setting. This increase is because of the increased cost of stainless steel, and the time and labor it takes to add more drilling flights and generally complete repetitive tasks over longer distances in the borehole with each meter of depth.

Installation costs for some production wells are provided in Exhibit 4.7. Deeper wells and more complex hydrogeologic settings have higher costs. Bedrock presents the greatest difficulty in drilling and typically is most expensive for well installation. Care must be taken in well installation that conditions are not created that could cause aquifer contamination (USGS, 1997, p. 47).

Additionally, Navarro (1989, p. 50) evaluated costs of irrigation wells in Spain as a percentage of total production cost, exclusive of externalities costs, and found the following cost distribution:

- Drilling: 9.7%
- Pump installation: 15.4%
- Operation and maintenance: 41.1%
- Water distribution: 29.6%.

EXHIBIT 4.7 DRILLING AND INSTALLATION COSTS FOR PRODUCTION WELLS

Various (anonymous by request) water well installers in the United States provided information in 1989 and 1995 on the costs of installing municipal wells. Locations relying on aquifers in deeper bedrock formations have higher costs, as would be expected.

Municipal Water Supply Wells
Capacity and Price of Average Well Installed from Examples in the United States
($US for year indicated)

	August 1989		September 1995	
Location	**m^3/Day**	**Price**	**m^3/Day**	**Price**
Upper Midwest	2,840	$80,000	2,840	$93,000
Central Midwest	2,840	$75,000	2,840	$100,000
Gulf Coast	4,920	$175,000	4,920	$500,000
Southwest	6,435	$150,000	8,328–16,277	$400,000–$500,000

Price of 5678 m^3/day Well Installed in the United States
($US for year indicated)

Location	August 1989	September 1995
Upper Midwest	$125,000	$145,000
Central Midwest	$150,000	$200,000
Gulf Coast	$200,000	$600,000 [a]
Southwest	$140,000	— [b]

Source: Various industry sources.

[a] Typically deeper wells in excess of 305 m.

[b] Drilling larger, deeper wells at that time than previously installed.

WELL SIZE

Well size depends on its use. A large capacity water supply well may be 30 or more centimeters in diameter and made of iron casing. Its depth may vary from 30 to 460 m or more. Large irrigation wells may also be of this size. The more water that needs to be produced over a given time, the larger the diameter of the casing must be.

A monitoring well used to check water level or quality may be 4 or more cm in diameter and may be made of iron, stainless steel, or PVC, depending on water quality testing requirements. A monitoring well used to determine water level and test physical characteristics of the aquifer is called a piezometer. Piezometers can also be installed underwater in streambanks or shorelines to test the groundwater discharge or recharge relationships and even to collect water samples for water quality tests. In stream piezometers can be quite small.

PRIVATE DOMESTIC WELLS

Most private domestic wells are typically installed to draw water from the first aquifer and are deep enough to provide water during drier seasons when recharge is less and the water table may fall (be lower). Approximately, 40 million people in the United States are served by private domestic wells. An easily installed well may cost from $2,000 to $10,000, depending on depth and geology. Private wells are less costly to install, generally. This installation cost depends on the location and type of geology. Sandy subsurface environments are more easily drilled. However, in rocky subsurfaces, such as glacial till with boulders, or in bedrock, well installation is more difficult and costly. Shallow bedrock wells may often not be reliable. Residences locating in areas of shallow bedrock aquifers may have other serious problems such as wet basements. The location of wells and residential activities should be suited to the hydrologic conditions. Otherwise, additional costs not anticipated in the original investment will be incurred. These costs may include needing to truck water in, inability to use basements because construction has changed underground flow causing wet basements, and wet yards that cannot be used during certain times of the year. The point here is that completing a domestic well may not mean the location is suitable for residential use.

A well in a low-yield formation that produces 568 L/day may be adequate to sustain a family of four. However, this rate of production is probably at the margin, given the water use of today's water using appliances and bathroom fixtures in the United States.

MONITORING WELLS

Monitoring well costs vary by hydrogeologic setting and well type. Exhibit 4.7 summarizes more information from eight well drilling companies across the United States.

WATER SUPPLY WELL

In part because of competitive pricing within the well drilling industry, well drilling and installation costs are not well documented in the literature. Niñerola (1989) provides estimated unit (per meter) costs for municipal and irrigation wells in Spain in 1987 for different types of installation: percussion drilling and reverse rotary drilling. Notably, deeper wells and larger casing show diseconomies of scale for well installation costs with both greater depth and larger casing per meter and diameter, respectively. Niñerola found reverse rotary drilling unit costs to be 71%–90% that of percussion drilling depending on depth and casing diameter.

Water supply well costs vary across a country, based on the factors of well location (noted above), the volume of water needed, and regional labor and equipment rates. Exhibit 4.7 gives a perspective of how variable these well costs may be for public water supply wells in the United States. From the information provided, it appears that for the regions compared, municipal water well prices generally rose faster than the national inflation rate. While these are not a statistically valid result, the data do show some interesting trends. The locations in the eastern half of the United States relied on shallower municipal wells, while the more western locations contracted for deeper and higher capacity wells. This circumstance also correlates with increased precipitation and increased potential for recharge in the more humid east. Larger volumes of water pumped from deeper locations require more energy, thus increasing pumping costs as a part of operation and maintenance costs. When larger volumes of higher quality water are consistently demanded, but are more remote (from deeper aquifers), the costs of water availability are higher to meet those requirements. Costs for a 5678 m^3/day municipal well ranged from \$145,000 to \$600,000 (1995 \$US) depending on the hydrogeologic setting.

In implementing the results of an investigation of groundwater supply using the megawatershed method in Trinidad and Tobago, Bisson worked with the water authority to develop 75,708 m^3 per day supply for the two islands at a capital cost of less than \$40 million (compared to a dam and reservoir proposal estimated to cost \$60 million) with operating costs of \$0.09 per m^3 (Bisson, 2004).

WELL PUMPS

A range of pump types can be applied to bring groundwater to the ground surface. These include electric, diesel-powered, solar, animal-driven, and hand and foot pumps. Clearly, a spectrum of costs are associated with such pumps. Pumps may be installed at the wellhead or down in the well (referred to as "submersible" pumps). Exhibit 4.8 provides a range of prices for different pump types.

The cost of operating a pump to produce groundwater must involve well depth and volume of water withdrawn. Properly operating pumps should have efficiencies of 70% or more. Poorly operating pumps may only have efficiencies of 40% or less and can consume much more energy in operation. The weight of the water that the pump must bring to the surface has to be multiplied by the distance up the well casing that it has to move, the pumping rate (cubic meters per minute), the efficiency, and the power or fuel cost to determine the energy cost. This cost can be substantial and often factors in decisions about whether a well can be economically operated. Exhibit 4.9 provides a hypothetical example of calculations for groundwater pumping energy costs.

EXHIBIT 4.8 COST OF GROUNDWATER PUMPS

Many combinations of pump and motor capability are available. Some examples of costs are

Residential application

1. ½ Horse-power
   - Producing 3.79–37.85 L/min depending on well depth: \$170–\$200 (US\$2005)
2. 1 Horse-power
   - Producing up to 113.57 L/min depending on well depth: \$300–\$400 (US\$2005)

Municipal application

1. 60 Horse-power, 3.785 m^3/min, submersible turbine pump, motor, starter, controls, depending on depth: \$12,000–\$26,000 (US\$2005)
2. 150 Horse-power, 17.03 m^3/min, submersible turbine pump, motor, starter, controls, depending on depth: \$29,000–\$39,000 (US\$2005)

Source: A variety of industry sources.

SOLAR-POWERED PUMPS

Exhibit 4.10 provides information as of 2005 on solar pump costs and two examples of solar applications for livestock watering. This technology may have broader application for small water suppliers as greater attention is placed on reducing energy costs and the "carbon footprint" of energy generated by fossil fuel.

EXHIBIT 4.9 ENERGY COSTS TO PUMP GROUNDWATER

What does it cost to pump groundwater up a well to the ground surface?
Assume:

1. Well depth of 30.48 m
2. Pumping rate of 3.785 m^3/min
3. Municipal well pumping for 12 h

Weight of groundwater to be pumped for 12 h is calculated by

- Using conversion of 3.785 L of water weighing 3.785 kg
- 3.785 m^3 × 1000 kg/m^3 × 60 min/h × 12 h

$$= 2{,}725{,}496.496\,\text{kg of groundwater}$$

Energy required to lift water 30.48 m is calculated by

- Using the equation of

$$\text{Energy required} = \text{weight of water} \times \text{meters of lift}$$

- 2,725,364 kg × 30.48 m = 83,069,094 m-kg of energy

Power required to accomplish the lifting of water

- Using conversion of

$$138{,}254.933\,\text{m-kg} = 0.3766161\,\text{kWh}$$

- 83,069,094 m-kg × 0.3766161 kWh/138,254.933 m-kg = 226.286 kWh

Or

- Using conversion of

$$3.7854\ \text{L of diesel oil} = 14{,}940{,}876.608872\,\text{m-kg}$$

- 83,069,094 m-kg × 3.7854 L of diesel/14,940,876.608872 m-kg = 21.2 L of diesel

Inclusion of pump efficiency

- Using 70% (0.7) efficiency (an acceptable efficiency for either electric or diesel pumps)[a]

$$(226.286\,\text{kWh})\ 0.70 = 323.266\,\text{kWh required to lift groundwater 30.48 m}$$

Or

$$(21.2\,\text{L})\ 0.70 = 30.28\,\text{L of diesel required to lift groundwater 30.48 m}$$

(*continued*)

EXHIBIT 4.9 (continued) ENERGY COSTS TO PUMP GROUNDWATER

Cost of pumping 3785.4118 L/min of groundwater 30.48 m for 12 h

- Assuming energy costs of US$0.05/kWh and US$ 0.53/L diesel in 2005
- 323.266 kWh × $0.05/kWh = $16.16

Or

- 30.28 L of diesel × $ 0.53/L diesel = $16.05

In this hypothetical example, the prices of electricity and diesel fuel are competitive as energy sources for operation. Total costs would need to consider costs of the different pumps and their maintenance. This example does not include transmission costs nor of further pressurizing the water in pipelines or irrigation systems.

Source: The University of California Cooperative Extension, Tulare County, Energy and cost required to lift or pressurize water. Publication No. IG6–96, 2005, URL: http://cetulare.ucdavis.edu/pubgrape/ig696.htm (accessed February 24, 2005).

[a] A properly designed electric water pump should operate at 70% efficiency. *Source*: The University of California Cooperative Extension, Tulare County, Energy and cost required to lift or pressurize water. Publication No. IG6-96, 2005, URL: http://cetulare.ucdavis.edu/pubgrape/ig696.htm (accessed February 24, 2005). An acceptable efficiency for a diesel centrifugal irrigation pump is above 65% and for a diesel turbine pump is above 75%. *Source*: New South Wales (Australia) Department of Primary Industries, Is your diesel pump costing you money? Agfact E5.12 (August), 2004, URL: http://cotton.pi.csiro.au/Assets/PDFFiles/WATERpak/WPAp9_2.pdf (accessed February 24, 2005).

EXHIBIT 4.10 COST OF SOLAR-POWERED PUMPS IN GROUNDWATER APPLICATIONS

Solar-powered pumps have decreased in cost. Industry sources indicate that the cost ranges for example applications as follows (2005 US$):

1. 1.5–2.6 m^3/day, submersible pump, 30 m well: $2300–$2400
2. 23.1–26.5 m^3/day, submersible pump, 30 m well: $7100–$7200
3. Surface pumps, depending on capacity and well depth: $220–$2100

Two specific examples of solar-powered pumps are described here:

Livestock Water Pumping Using Solar Energy

Example 1

A field installation of a photovoltaic (PV) powered livestock water pumping system is described. The system is designed to supply water to two locations; 12.1 m^3/day at 16.8 m lift, or 3.8 m^3/day at 50 m lift, or a combination of these two lifts and flows.

EXHIBIT 4.10 (continued) COST OF SOLAR-POWERED PUMPS IN GROUNDWATER APPLICATIONS

This is sufficient to water 67 beef cattle. The system was originally funded by Energy, Mines, and Resources Canada, together with the B.C. Ministry of Agriculture, Fisheries, and Food, and was located in Cache Creek, B.C. in August 1986. The system was moved to Savona, B.C. in the spring of 1989.

Water is pumped only when solar energy is available. The system was sized to deliver sufficient water on sunny days to allow some excess water to be stored for cloudy days. In this manner, energy is stored as pumped water rather than in batteries. The PV array powers the pump directly through a maximum power point device, a Wardun WD700 DC–DC converter (transformer). This device ensures sufficient motor starting current and maximum operating power throughout the day. The pump is a Mono P32 progressive cavity unit submerged in the water and shaft driven by a 2 HP permanent magnet DC motor mounted above the water level. The Mono pump is well suited for a PV system as it will deliver the full lift over a wide range of speeds. This is important because with a panel-direct design, pump speed varies as sunlight intensity varies on the panels. Both the motor and pump were chosen for their high operating efficiencies.

The array consists of 10 ARCO M-75 panels rated at 50 W (peak) each. They are wired in series for a nominal output of 165 volts, 3 amps. The array is mounted on a rigid frame with provision for manual adjustment to match the seasonal changes of the sun.

The pumping system costs (1989) totaled $8000. This includes 10 panels, the array frame, converter, motor, pump, mounting assembly, and wiring. The delivery pipe and water storage costs will vary between sites; the total cost is approximately $5000 for the Savona site.

Example 2

This example also describes a field installation of a PV-powered livestock water-pumping system. The system is designed to supply an average daily volume of 2 m^3 pumped to a maximum lift of 9.8 m. This is sufficient to water 35 beef cattle. This project was funded by the B.C. Ministry of Agriculture, Fisheries, and Food, the D.A.T.E. program, and the cooperating rancher. It has been operating since 1989. Beef cattle require water ranging from 30 to 57 liters/day.

Energy stored in the form of pumped water was chosen over chemical storage in batteries. With adequate water storage, water need only to be pumped during the hours of bright sunlight simplifying the design. The PV array powers the pump directly through a transformer (a linear current booster) that ensures sufficient motor starting current. This device transforms the panel output in low light conditions (e.g., morning) and is commonly used in PV water pumping systems. The motor/pump is a low-cost unit manufactured by Flojet. A 12 V permanent magnet DC motor drives a diaphragm pump capable of 7.2 liters @ 7031 kg/m^2. The motor draws a maximum of 7.0 amps and has a fan for cooling under continuous operation. The array consists of 2 ARCO M-75 panels rated at 50 W (peak) each. They are wired in parallel with one linear current booster per panel for a 100 W (peak) output. Panels are mounted stationary at approximately 50% (the latitude of the site) with no seasonal angle adjustment.

The pumping systems costs (1989) totaled $1350. This includes two panels, two linear current boosters, motor/pump, suction screen, wiring, switch, and miscellaneous wood and steel materials. The polyethylene delivery pipe and storage tank costs were approximately $1000. The water well development costs were approximately $450. These last two costs are site specific and will vary depending on the water source and the distribution required.

Source: Abstracted from British Columbia Ministry of Agriculture and Food, *Livestock Watering Factsheet: Livestock Water Pumping Using Solar Energy*, Order No. 590.306-4. Agdex: 778 (June), 1994, URL: http://www.agf.gov.bc.ca/resmgmt/publist/500series/590306-4.pdf (accessed February 24, 2005).

WIND-POWERED WELLS

With the reemergence of concern about energy prices and fossil-fuel production with carbon footprints, wind power wells are also getting a renewed interest. In the United States, power from windmills provided many farms with groundwater since the mid-1800s. Use of wind power is being advanced by research in the United States by the Department of Energy (USDOE, 2004a,b). Applications are varied, including individual systems, municipal water supply, groundwater remediation (USEPA, 2004), and irrigation (Vick et al., 2000). Feasibility depends on wind area classification (wind reliability), depth to water and amount of water to be pumped, availability of transmission lines, cost of land, use of land, and cost of alternative power sources. Exhibit 4.11 gives costs for a wind-electric pump system at two locations in Texas, showing economies of scale.

EXHIBIT 4.11 COST OF WIND-POWERED GROUNDWATER PUMPING SYSTEMS IN TEXAS

Windmill Power Output	Location	Pumping Depth	System Specifications	Cost
1.5 kW	Wheeler County, Texas	40 m	Wind turbine 18.5 m Rohn 25G tower poly pipe in well 1.1 kW 3-phase 230 V submersible motor 0.75 kW 15-stage centrifugal pump	$8,000
10 kW	Lubbock County, Texas	45 m	Wind turbine 40 m Rohn 45G tower 60 m of galvanized pipe 5.8 kW 3-phase 230 V submersible motor 3.8 kW 15-stage centrifugal pump	$35,000

Source: Vick, B.D. et al., Wind-powered drip irrigation systems for fruit trees, *Presented to 2000 ASAE Annual International Meeting*, Milwaukee, WI, July 9–12, 2000, 13, URL: http://www.cprl.ars.usda.gov/Drip%20Irrigation/vick_asae2000.pdf (accessed April 24, 2008).

OTHER WELL TYPES

Other types of wells serve other purposes. These other well types include hand-dug wells and injection wells. Hand-dug wells are usually older wells, which may range from a pit a meter deep to deeper wells of several tens of meters with stonewalls in rural settings. These wells are usually for rural domestic use. The water from them is typically untreated.

Injection wells allow for disposal of water, wastewater, and liquid waste into the subsurface. For wastewater disposal, these wells are regulated in the United States under the Safe Drinking Water Act, Section 1414, which prohibits injection of waste into or above an aquifer used, or potentially used, for drinking water purposes. In the European Union, the Water Framework Directive 2000/60/EC, Article 11(3) (j) prohibits injection of regulated pollutants into groundwater, controls the injection of waters containing substances from oil, gas and mining extraction, and construction activities, and authorizes reinjection of waters for geothermal production. The governmental programs designed to protect drinking water from injected wastes are known as "underground injection control" programs. These programs also issue permits for deep injection of wastes below drinking water aquifers that have an impermeable zone below them. Deep injection wells must be specifically designed, often with double casing, and tested for integrity so that no waste would be released from cracks or seams in the casing to drinking water aquifers through which the injection well may pass. Chapter 7 describes the Underground Injection Control Program in the United States in more detail. This program controls the largest volume of waste disposed into land or water in the United States. A similar program exists in the European Union.

Bamboo tubewells are addressed in Chapter 6.

AQUIFER STORAGE AND RECOVERY

Aquifer storage and recovery (ASR) is defined as "the storage of water in a suitable aquifer through a well during times when water is available, and recovery of the water from the same well during times when it is needed" (Pyne, 1995). ASR may utilize injection wells to place water into the subsurface for storage and use at a later time. Also, this technology may employ recharge areas, often artificially created wetlands or ponds (Dillon, 2002).

Many aquifer storage projects are already in place or are being developed in the United States and around the world. As a potential response to drought, variation in water supply, and climate change, benefits of aquifer storage may include (Reichard et al., 2004)

Direct Benefits

- Using the transmission and treatment capacities of the subsurface environment
- Reduced costs for pumped storage
- Management of subsidence and saltwater intrusion

Indirect Benefits

- Buffer and existence values of maintaining aquifers
- Avoided costs of alternative water supply during drought
- Avoided impacts to communities during water shortages
- Conjunctive management of ground and surface waters

Costs of aquifer storage may include (Reichard et al., 2004)

- Direct capital and operating expenses
- Indirect costs for water quality treatment and protection

Aquifer storage has costs ranging in relation to the depth and magnitude of the subsurface zone used. Aquifer storage zones may exist at depths ranging from 75 to 900 m (ASRF, 2003). The piezometric surface of these storage zones can be 10 m over the ground surface to 300 m or more underground (ASRF, 2003). Ambient water quality native to the storage zones varies widely from fresh (potable with no contaminant removal) to brackish with as much as 5000 mg/L of total dissolved solids (ASRF, 2003). ASR systems exist in the United States, United Kingdom, Canada, Australia, and Israel, and the Netherlands, New Zealand, Thailand, Taiwan, and Kuwait are developing them (ASRF, 2003). The United States has 56 operational ASR sites (ASRF, 2003). ASR systems have annual operating costs of \$1,600–\$10,600 per thousand m^3 of recovery capacity, which is typically greater than the operating cost of conventional water treatment and distribution systems (Pyne, 1995). Considering capital costs, ASR systems may be less expensive than alternative conventional water systems with savings of capital costs of 50%–90% (Pyne, 1995). Exhibit 4.12 provides some insights into several applications of this groundwater technology.

Concern has been raised about recharge and subsequent production of groundwater from reclaimed and untreated wastewater (El Sheikh and Hamdan, 2002; Legg and Sagstad, 2002; Tsuchihashi et al., 2002). Contaminants of concern in reclaimed water may include pathogens, metals, and organic compounds (El Sheikh and Hamdan, 2002; Tsuchihashi et al., 2002). Access and use of this groundwater should be evaluated to determine the proper course of action to protect

EXHIBIT 4.12 AQUIFER STORAGE AND RECOVERY IN WISCONSIN: CASE STUDIES

Aquifer Storage and Recovery (ASR) is a proven technology currently in use in 14 states and several countries worldwide. ASR allows a water utility to store water during low demand in underground aquifers for recovery to meet seasonal peak demands, at typically half the cost of other alternatives. One case is Oak Creek, WI, for which initial development had the following results:

ASR was introduced in Wisconsin in 1997 at Oak Creek, Wisconsin. Oak Creek Water and Sewer Utility (OCWSU) converted a standby bedrock well for use as an ASR well. During the low demand winter season OCWSU stores 159,000 cubic m of treated Lake Michigan water in the well and then recovers the water to meet summer peak demands. OCWSU conducted a 2 year pilot study with cofunding from the AWWA Research Foundation. OCWSU has been using the well operationally through annual extensions to its conditional approval permit for the past 3 years. One hundred percent of the volume stored on an annual basis can be recovered into the distribution system and all of the recovered water meets drinking water standards, despite the fact that the native groundwater exceeds the combined radium standard.

Green Bay Water Utility also began evaluating ASR in 1998 as an alternative to expanded Lake Michigan treatment plant capacity, and as a possible cost saving solution to provide for the water needs of the surrounding Central Brown County Water Authority customers. A projected combined savings of about $100 million is expected if ASR can be successfully developed and incorporated into a joint water supply and radium compliance plan between these two entities.

ASR testing began in April 2002 using one of Green Bay's standby bedrock wells. The initial shakedown cycle test entailed recharge of 37,854 m^3 of treated Lake Michigan water and monitoring three different intervals of a monitoring well located about 15 m from the ASR well. The oxygenated recharge water caused the release of arsenic, nickel, and cobalt from sulfide minerals dispersed in the middle interval formations. The water was recovered from the ASR well and discharged to the sanitary sewer until concentrations for these constituents returned to background concentrations below drinking water standards.

Source: Miller, T., Aquifer storage and recovery in Wisconsin: Case studies—The good, the bad, and the ugly, *Presented at the Wisconsin Ground Water Association Conference*, Geneva, WI, April 9, 2003, URL: http://www.wgwa.org/conference/papers/miller.htm (accessed June 21, 2003).

public health. Ecological issues have also been raised that may cause the ASR user to incur costs for ensuring recharge of reclaimed waters. These include clogging of recharge areas and scrapping the bottom of recharge ponds (de los Cobos, 2002; Olsthoorn and Mosch, 2002).

Since ASR projects often involve some level of construction, they have been examined for costs compared with benefits. In certain situations, the benefits far outweigh costs in the decision process employed. Several cost-to-benefit comparisons are presented in Exhibit 4.13.

HEAT PUMP WELLS

A quality of groundwater that is typically forgotten is its temperature, which groundwater heat pumps may use to provide heating and cooling to residences and commercial establishments. Because groundwater is usually fairly constant in temperature—about 12.5°C—efficient heat pumps have been developed to exchange heat in the subsurface with groundwater. The principal concern with groundwater heat pump use was that substances from the exchange process could be released to groundwater. Manufacturers have been cognizant of this circumstance and have been careful to properly design these systems to prevent such release. Most state or local regulatory

EXHIBIT 4.13 SOME BENEFIT–COST COMPARISONS REPORTED FOR AQUIFER STORAGE AND RECOVERY PROJECTS

Country	Benefit/Cost	Reported By (in Source Below)
The Netherlands	Avoid expensive treatment plants and reduce land use intensity in "absorptive" (recharge) areas	Hoogendoorn
The United States	Two seepage trenches 6 m deep, 45 m long (infiltration rate 2.2–2.7 ML/d), cost $15,000 each trench, four spreading basins (infiltration rate 0.6 m/day), cost $30,000 each basin five recharge wells 36–48 m completed, 450 mm diameter, PVC casing, 2.5 mm slot screen, cost $130,000 per well	Legg and Sagstad
India	Percolation tanks with 10–25 mm/d infiltration rate with catchment area of 10–50 sq. km, cost $61,000–$84,000 US 2002, Benefit–cost ratio ranges from 1.3 to 2.0	Limaye
India	Cavity tube well, benefits $3000–$4000 US 2002, benefit–cost ratio = 25	Malik et al.
Australia	Large-scale stormwater treatment/groundwater recharge/ water reuse scheme, cost $9 million AUS 2002, payback period 10 years or more	Chaudhary and Pitman

Source: Dillon, P.J., (ed.) *Management of Aquifer Recharge for Sustainability,* A.A. Balkema Publishers, Lisse, the Netherlands, 2002, 567.

agencies require that groundwater used in heat pumps be injected back into the aquifer from which it was withdrawn (Rafferty, 2003).

HYDRAULIC FRACTURING WELLS

Production of methane gas from extensive deep geologic formations in which it exists in microscopic pores may be stimulated by fracturing those strata, allowing the gas to be released along the fractures. The fracturing takes place when wells are drilled into these formations and liquids are injected under high pressure causing the strata to fracture. Wells are then used to collect and produce the methane to sell commercially. Environmental concerns are that the fluids used must be monitored to ensure that they do not escape and contaminate groundwater that is currently used or could be used in the future as a source of drinking water (Blend, 2002).

BRINE PRODUCTION WELLS

While brine and brackish waters may be a by-product of oil and gas production and often reinjected for disposal in the subsurface, underground brines may be produced by wells for raw materials in manufacturing chemical products. As noted in Chapter 3, brine production provided the basis for the beginning of the chemical industry. The location of the industry in its early stages was dictated by the location of brine production wells (Brandt, 1997; Dunbar, 1970).

SPRINGS

Springs allow groundwater to flow to the ground surface and be easily accessed for human use and other purposes. Notably, the Potomac River North Branch starts as a spring along the Maryland-West Virginia border (Gude, 1984, p. 4). Some springs are used for water supply directly. In the early days of the European settlement of the United States, some springs were diverted to provide waterpower to turn grist mill wheels. Springs are also used to provide drinking water. In these cases, a springhouse is often built to protect the spring and collect water in a cistern, which is then connected to a distribution line. Jurisdictions may regulate the use of spring water just as they regulate groundwater brought to the ground surface.

DEWATERING

In the case of construction in areas with water tables determined to be "high" relative to the subterranean activity, access to groundwater may be for the purpose of dewatering an aquifer—temporarily or indefinitely drawing down the water table—during construction to have a dry work site below the ground surface (Powers, 1992). Depending on the area and volume of water involved, numbers and capacities of wells would need to be determined appropriately. Construction site dewatering may only affect a limited area for a small local project, or, in cases such as mining, could lower the water table in an extensive subsurface zone. For example, a gold mining operation in Nevada (western United States) lowered the water table 503 m to remove the ore, which has in turn reduced the baseflow of the Humboldt River 32.2 km away (Glennon, 2002, pp. 175–176). Use of available information about the groundwater at a site or adjacent sites and for existing nearby wells aid in the planning and design of a dewatering project (Powers, 1992, pp. 190–202) and will help estimate costs. Since groundwater would be removed from the site, it would need to be disposed off-site, typically in a sewer or stream, and not usually back to groundwater. Usually, the local jurisdiction or state requires a permit to discharge this groundwater to sewers or streams, even though it may be clean and uncontaminated. The cost of planning, well installation, and production and disposal of the groundwater from dewatering may be a significant access cost, depending on the volume of groundwater to be disposed. Factors affecting dewatering costs are presented in Exhibit 4.14. Dewatering costs can be highly variable based on volume, depths, and tunneling requirements.

EXHIBIT 4.14 DEWATERING COST FACTORS

Construction site cost estimating factors (exclusive of off-site or external side effects and costs)

Basic data	Wage rates	
	Total cost/Unit time of construction equipment, including drillrigs	
	Cost of fuel or power	
Mobilization	Dewatering equipment	Wellscreen and casing
		Well pump
		Wellhead and fittings
		Discharge lines
	Jetting and developing equipment	Pumps
		High-pressure hoses
		Holepunchers and casings
		Surge blocks
		Air and water jet pipes
	Sumping equipment	Pumps and controls
		Extension cables
		Hoses
		Discharge lines

EXHIBIT 4.14 (continued) DEWATERING COST FACTORS

	Standby equipment	Generators
		Switch gear
		Fuel tanks
		Automatic startup devices
	Utilities (all)	
	Housing for generators and control equipment	
	Electrical substation	Transformers
		High line
		Installation charge
	Engineering expense	System Design
		Field testing
		On-site engineer
Installation and removal		
	Crew cost per day	
	Equipment cost per day	
Operation and maintenance		
	Operating and maintenance labor and supervision	
	Fuel or power	
	Maintenance material	
	Chemicals or removal of encrustration	
	Equipment repair and major overhaul	
Other costs		
	Labor and energy escalation rates for long-term operations	
	Payroll taxes and insurance	
	State and local taxes on materials and gross revenue	
	Contractor margin for overhead and profit	
	Contingency allowance for unknown geological or hydrological circumstances	

Source: Powers, J.P., *Construction Dewatering: New Methods and Applications*, John Wiley & Sons, Inc., New York, 1992, 433–440.

The benefit of dewatering a site is the ability to work in a dry space below the ground surface. This condition has resulted in many important commercial structures being constructed in cities and towns around the world, generating economic returns. Dewatering of a site may also cause unintended, but potentially predictable, effects that may damage the use of the overlying and adjacent land and water, including

- Ground settlement/land subsidence
- Reduced yield of other wells on adjacent lands
- Reduced baseflow of streams in the vicinity
- Water quality effects, such as salt water intrusion or accelerated migration of contaminant plumes
- Timber structures below the original water table being attacked by aerobic organisms as the water table declines

- Wetlands ecology being disturbed by reduced water supply as the water table drops
- Trees and vegetation with roots in the water table may dehydrate

(Powers, 1992, pp. 65–71; Glennon, 2002, pp. 175–176)

These adverse effects may create costs to the overlying and adjacent landowners. The magnitude of these costs will be determined by the purpose and size of the project and the volume, rate, and duration of the groundwater withdrawal.

GEOTHERMAL PRODUCTION

Geothermal production involves accessing hot water and steam from deep below the ground surface in excess of a temperature of 300°C. Total dissolved solid concentrations may be as high as 250,000 ppm, substantially higher than seawater. Drilling procedures are similar for reservoirs. However, once steam conditions are encountered, high-pressure air drilling methods are used (California DOGGR, 2003). Typical well installation parameters and cost are given in Exhibit 4.15. Costs to install injection wells at geothermal power sites may be approximately 20% more than the installation costs for production wells because of alternative drilling methods that must be used (Rafferty, 2007, p. 2). Well materials, usually steel casing and cement in the annular space around the casing, must be able to survive extreme temperatures and corrosive conditions. Wells may be 40%–70% of the cost of the entire geothermal production unit. Other products may be derived from geothermal water such as sulfuric acid, silica (used in concrete), and zinc, which reduce waste disposal costs and enhance revenue from these energy projects. Other costs include well and wastewater discharge permits. Additional special disposal may apply based on the chemical content of the water. Access to geothermal waters for use in energy production reduces environmental costs, which would have been incurred by other sources: geothermal production emits very small amounts of carbon dioxide and sulfur dioxide and none of the nitrogen oxides (U.S. Department of Energy, 2003).

EXHIBIT 4.15 GEOTHERMAL WELLS AND COST

The following parameters generally describe conditions affecting geothermal well access to superheated water and steam, including well cost, in the United States.

Well depth: 91.4–3658 m
Water/Steam temperatures: 180°C–315°C
(180°C is considered minimal for direct electric power generation).
Pressure in well: Steam < 14.061 391 566 kilogram-force/square centimeter
Fluid < 703.069 578 3 kilogram-force/square centimeter
Well diameter: Near surface: 30.48–33.02 cm
At depth: 15.24–30.48 cm
Well cost: $700,000–$3,000,000

Source: U.S. Department of Energy, *Geothermal Energy Program: What Is Geothermal Energy?* 2003, URL: http://www.eere.energy.gov/geothermal/geoimpacts.html (accessed September 6, 2003).

IN SITU AND ON-SITE GROUNDWATER TREATMENT

When groundwater is contaminated by human activities, access to groundwater may be fundamental in remediating the resource. Access for remediation typically involves many of the steps and costs previously identified (USEPA, 1989), including

1. Access to the property
2. Permission from the property owner or trustee and the relevant governmental jurisdictions to install wells and produce the groundwater
3. Permission of the owner/trustee and jurisdictions to treat the groundwater on-site and release the treated groundwater from the property
4. In cases where the groundwater is to be treated in situ (in the subsurface environment without being produced), permission must be given by the owner/trustee and governmental agency having jurisdiction to apply chemical or microbiological substances on the ground or into the subsurface to treat contaminated groundwater.

The third and fourth steps are particularly problematic in many situations. Some states and federal agencies require application for a permit to discharge the treated groundwater to a sewer, if in a sewered area, or a stream or other body of water, including an aquifer. Special application for an underground injection permit may be needed if the treated water is to be injected back into the ground or the aquifer, assuming that the jurisdictional authority allows that practice, which it may not. In situ treatment usually requires further permission. The cost of identifying the information needed to satisfy these permit requirements, preparing the permits, and providing explanation to the regulatory authorities with jurisdiction over these steps must be factored into the cost of access to groundwater for remedial purposes.

BENEFITS OF PROPERLY INSTALLED AND MAINTAINED WELLS

While well permits and construction standards may add costs, the perspective of local governments is that they are for the protection of the well owner and adjacent groundwater users. Having well construction standards provides some assurance to the well owner that the well meets best science and engineering practice, as long as the state or local government keeps the standards current. A properly constructed well can operate for decades without mechanical or contaminant problems, assuming the original well placement has not been encroached on by land uses that could affect its water quality or use. Having a properly constructed well saves the owner from the costs of proper abandonment of an old well (often requiring pulling the casing out of the ground and carefully cementing the hole from the bottom up to the ground surface) and installing a new well, if a replacement well is required.

Properly constructed wells also eliminate pathways for contamination around the wellhead by grading the ground away from the well and installation of a concrete apron. Construction also should provide for grouting (cementing) the annular space around the well casing 1.5 m or more below the surface. This construction keeps surface water runoff away from the wellhead and from going down the well. The apron and the annular grouting also keeps contaminated runoff from moving to the casing and down along the casing to the water table. Should the well water become contaminated, the well user may suffer illness of short or long duration, depending on the contaminant. This illness is a cost to the well owner and may include medical expenses and lost income. Avoiding these costs is a benefit to the well owner. Knowing the construction of the well may give the owner some understanding of the potential risk for contamination and exposure to the contaminants.

Since groundwater moves in the subsurface, reducing the risk of contamination to the well's water supply may also reduce the risk of contaminating the groundwater used by a neighbor. Unfortunately, neighbor has sued neighbor to address nearby contaminant sources that are a cost to the contaminating property owner for correction. While not all wells will be in the contaminant pathway, proper construction can help avoid such costs, thereby benefiting the well owner.

Well permitting is usually related to the density and production of wells. The well permit process considers existing adjacent groundwater production and the use and production of the proposed well. A well permit may not be granted if the area's groundwater production is not sustainable and would result in groundwater mining, lowering water tables, drying up neighboring wells, and causing lost water production at neighboring wells, thereby affecting the use and value of the property. Proper management of the density of wells provides benefits to current and future groundwater users by ensuring sufficient water sources.

(Note that western states using prior appropriation groundwater doctrine do not consider adjacent users groundwater production, since it is already allocated by appropriation. That right allows the owner to produce a specific volume of water despite impacts on junior appropriators nearby. These effects could include groundwater mining, resulting in costs of installing deeper wells and more powerful pumps to lift the water further. These costs may be incurred by all users in the area, not just the large producers. Furthermore, the volume of water available in the future is likely reduced, even with constant or increased demand, since in many western locations, precipitation is low and evaporation rates exceed precipitation rates)

COSTS OF IMPROPERLY INSTALLED OR MAINTAINED WELLS

Wells not properly installed or poorly maintained may result in costs to users. Improper grouting of wells, no or cracked apron at the wellhead or no well house can allow contaminants down along the well casing and annular space and into the aquifer. Cracked well casing can also allow contaminants to enter the well and allow pumped water to escape before reaching ground level. Injection wells with cracked casing can release contaminants to groundwater. At least three injection well sites are locations of remedial actions in the United States (Paque, 2003). Such problems may pose health risks and economic costs to well owners and users and, because groundwater migrates, also could present costs to adjacent groundwater users.

ECOLOGICAL ASPECTS OF ACCESS TO GROUNDWATER AND THE SUBSURFACE

The ecological aspects of access to groundwater and the subsurface are emerging as a preeminent water issue with environmental or total systems implications for water management. Groundwater reinforces the concept that "everything is connected to everything else." Just as groundwater inherently responds to nature's physical, chemical, and biological forces to achieve balance, human action is effecting continued changes influencing the balance in the subsurface and all that is connected with it. It has been estimated that the earth's largest amount of biomass exists under the ground surface. This is also the location of the largest volume of freshwater available for human use: the aquifers of the subsurface environment. The very pathways through intergranular space below ground are also routes for contaminating the resource. Since most groundwater nearer the ground surface moves, aquifers become a transport mechanism for what is released to them. Briefly, we will consider the ecological aspects of access to groundwater and the subsurface. This is a subject that needs more serious documentation through research and evaluation.

UNSATURATED ZONE AND SHALLOW AQUIFERS

Residual chemicals released intentionally or unintentionally to the ground or beneath it can move through the interstitial subsurface space and be degraded or adsorbed to some particles depending on their electrical charge, if they are adapted to do so or move through it. If they move through it, they can reach or access the first groundwater in the saturated zone to be transported to adjacent locations. In some cases, large volumes of chemicals have overwhelmed the subsurface environment and its ability to adsorb or degrade them, ultimately being received in high concentrations that contaminate the groundwater for future users. Past chemical waste disposal practices were based on the belief that this subsurface environment could carry away these wastes, not to be a problem any more. We now know that is not the case. The aquifers can carry these residuals to places that may kill vegetation and other wildlife, contaminate streams, and befoul water supplies.

Additionally, since groundwater exists in the interstitial spaces of the subsurface, we might think of the subsurface as large holder (even as a subterranean "sponge") of water. This capability of the subsurface to allow water to percolate into it and be held evens out the unpredictable sequences of precipitation for ecological purposes and human use. This capability also moderates extreme precipitation events to lessen flood conditions, a benefit to wildlife and human beings.

Shallow aquifers are accessed by plants through their root systems. This groundwater access provides life-sustaining water to the plants and organisms associated with them. These plants also transpire water as vapor back to the atmosphere and maintain their part of the hydrologic cycle. Other shallow groundwater moves through fractures and even caverns in limestone and dolomite and provide habitat for larger forms of wildlife, including fish.

Rivers and Streams

Most rivers and streams are discharge points for groundwater. While rivers can also recharge groundwater, they act to release groundwater stored below ground from past precipitation for gradual release for various purposes that humans have imagined and actually implemented: drinking water supply, wildlife support, waste removal and dilution, navigation and transport, and recreation. Certain fish and other aquatic wildlife depend on the quantity and quality (specific natural chemical concentrations and temperature) of groundwater discharges to the streams (Glennon, 2002, pp. 4–8). Most rivers and even smaller streams flow when there is no precipitation in their watersheds, because groundwater is discharging to them through their streambeds during these times. Rivers can also be dried up from producing so much accessible groundwater that the water table is lowered below the riverbed, no longer able to discharge to it, as happened to the Santa Cruz River in southern Arizona (Glennon, 2002). Other uses of the river are eliminated and wildlife are destroyed.

Wetlands

Many wetlands are discharge points for near-surface groundwater. This relationship allows wildlife to access groundwater for their own existence. Since wetlands are highly productive zones, waters flowing to them with nutrients may be degraded and recycled through the biological actions of the wetlands flora and microscopic organisms. Wetlands, in turn, can provide important habitat for many fauna, including spawning zones for fish.

Access to groundwater is typically viewed from the human perspective. Access to the groundwater and the capabilities of the subsurface should also be considered in the larger context of the ecological system and its myriad of interrelationships. This connection of groundwater to "everything else" indicates that the cumulative actions, while seemingly isolated, in the aggregate affect the larger world in ways we may not consider. We all, humans and wildlife—even microorganisms we forget but depend on to degrade the residuals we want to be rid of—share access to groundwater in ways not always or typically contemplated. How we balance this access with each other can have profound effects on the resource, its future use, and interpersonal, interjurisdictional, and international relations.

GREEN MANAGEMENT

Water Source

Green management of storm runoff to augment groundwater supply typically focuses on on-site factors. Ecologically supportive groundwater supply augmentation techniques include low-impact development (LID) to minimize water runoff and facilitate infiltration (TBS, 2008):

- Bioretention areas to buffer, pond, and hold soil and organic material in runoff
- Permeable and porous pavement allowing precipitation infiltration

- Reduction of paved surfaces to minimize runoff
- Filter strips such as landscape features to collect water flow and allow infiltration
- Cistern collection systems to collect water from large areas and hold it for use during dry periods

With proper planning, these techniques may cost less than conventional runoff control methods (TBS, 2008). Initial costs per 0.1 square meter of permeable and porous pavement are (TBS, 2008)

Porous asphalt: \$0.50–\$1.00
Plastic grid systems
(filled with sand or sand and soil, designed to reduce erosion): \$1.00–\$2.00
Block pavers: \$2.00–\$4.00

Municipalities are still gathering information on operational costs of these techniques.

Artificial recharge using underground injection wells is also practiced. Since these waters go directly into the aquifer, they should be clean before injection. Reclaimed wastewater has been injected to augment groundwater supplies. Aquifer storage allows underground space to be used for holding water for future use and was addressed earlier. Underground injection technology is described previously in this chapter.

WATER QUALITY

Water quality aspects of access include protecting water sources from contamination so that when they are accessed they are safe and suitable for their intended purposes. A wide array of programs at all levels of government address groundwater protection. Topics related to green management are included in chapters on water quality and treatment, groundwater policy, and sustainability, and address wellhead and source water protection. These latter approaches attempt to manage contaminant sources to locate away from wells and groundwater recharge zones.

SUMMARY

Access to the groundwater resource is the key to obtaining an economic groundwater supply. Access is affected by a number of factors, including land entry rights, hydrogeologic setting, and depth of the water table and well. The cost of installing a well affects the user's or producer's cost of supplying groundwater. Developing the approach to groundwater access starts with checking land entry requirements and then proceeds to exploration. Costs of well installation increase with depth and with complexity of the hydrogeologic setting. Costs of groundwater access vary by location, purpose, and requirements for properly producing groundwater in a locality. Jurisdictional well installation requirements, while adding costs up front in the well installation process, are for the protection of the consumer and adjacent property owners who use groundwater. Well installation costs can vary from location to location because of differences in requirements, and sometimes costs in one locality may double those in another. Benefits of properly installed wells for groundwater access include avoided costs of reinstallation, potential illness, and damage to neighboring well users, as well as maintenance of property use and value. Other types of wells include dug, injection, heat pump exchange, hydraulic fracturing, remedial, dewatering, geothermal, and in situ treatment. Shallow wells that allow untreated wastewaters into the subsurface may impose costs on adjacent groundwater users if the subsurface is not able to degrade contaminants from nonpoint sources that flow into stormwater drains. Injection of any substances into the subsurface should meet regulatory requirements and objectives for the use of adjacent groundwater without costs to water users. Disposal of produced waters typically requires a discharge permit and associated costs. Improperly installed and maintained wells can serve as conduits of contamination to groundwater and result in health risks and economic costs to owners and nearby groundwater users. Green management of stormwater to increase infiltration to groundwater for supply augmentation is also useful and can be cost effective. Ecological aspects of groundwater access influence other human and wildlife use of and reliance on the resource, even interpersonal, interjurisdictional, and international relations.

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5 Groundwater Law

A COMPLEX FRAMEWORK

A complex mix of local, state, national, and international laws affects the use of groundwater as a source of water supply and as a sink for contaminants. In the United States, states typically have the leading legal role in controlling the use of groundwater (USEPA, 1991). In Europe, a new groundwater directive identifies the role of national governments in responding to both quantity and quality issues of the resource (EU, 2006). In the United States, law basically treats groundwater as a local or state resource. The U.S. federal law does not recognize the emerging understanding that groundwater can migrate across long distances over time and may be essential to streamflow in many areas of the country. European Union law recognizes explicitly the relation of ground and surface water in watersheds (EU, 2000). Some U.S. state laws have linked ground and surface water legally to provide conjunctive management. International law dealing with transboundary (cross-border) issues embraces the need to consider the effects on neighboring countries. The framework of state, federal, and case law in the United States indicates who has the property rights in groundwater, the process for dealing with damages incurred by adjacent property owners, who can dispose of contaminants in the subsurface and in what concentration or volume, and who must pay for the cost of cleanup of contaminated groundwater. These legal frameworks provide the basis for economic relationships and exchanges among governments, corporations and individuals which result in the need for economic information and analysis applied to groundwater.

Leading legal authorities, Joseph Sax and Robert Abrams, in 1986, said of groundwater law:

> Water law has traditionally separated groundwater and surface water and provided independent rules of allocation and assignment of property rights. Much of the historical reason for the duality is attributable to the lack of knowledge about the movement of water beneath the earth's surface. This separation of legal regimes continues in the law of a majority of American states, even though the science of geohydrology has come of age. It is now possible to trace subterranean water movement and to establish groundwater discharge as a major component of base streamflow in most streams. Legal doctrine has not kept pace… It is a mistake to consider groundwater as only a minimally relevant subset of water law (Sax and Abrams, 1986, p. 786).

SOCIOECONOMIC CONSIDERATIONS

The economics of groundwater resources has, as a principal social basis, law to guide who pays and who benefits from actions taken to or through it. As economics works to bring a balance between-supply and demand and monetize fairness in applying and using the resources of labor and capital, law brings a balance between the ownership of that labor and capital and the associated rights. As exchanges of ownership and rights occur, or as damage to owners of and users with rights to groundwater is incurred, law provides a part of the basis for value, costs, benefits, and prices. The other major element of determining the values of water, is, of course, human desire and need, fashioned by tastes and preferences of individuals and groups (NRC, 1997, p. 157), as well as imperfect information on the availability and quality. Groundwater law, then, affects and is affected by the uses to which groundwater is put (Goldfarb, 1988, p. 6).

RANGE OF USES RECOGNIZED IN LAW

In the United States, nine major uses of water are recognized in law: navigation, irrigation, potable water, waste disposal, industrial process and cooling purposes, hydroelectric power, recreation, fish and wildlife maintenance, and scenic/aesthetic enjoyment (Goldfarb, 1988, p. 6). A similar range of uses of water is recognized by the European Union (EU, 2000) and by international organizations (UN, 2003). Science has expanded our understanding of how surface water and groundwater interact and the significance of groundwater in all these uses is now better understood. In areas or circumstances where surface flows are minimal, groundwater may be relied on to provide all these uses, including maintaining streamflows for fish and wildlife maintenance and scenic/aesthetic enjoyment.

A principal concern for water uses in the past has been an adequate supply of water. Laws affecting the provision of safe drinking water, because of the social preference for healthful uncontaminated water, have caused additional treatment of drinking water, resulting in increased supply costs and value of drinking water. As recognition of groundwater contribution to the other water uses grows (Bergstrom et al., 1996), cost impacts of reduced quantity and quality of groundwater as well as the value of maintaining the quantity and quality of groundwater will increase. As this recognition grows, the law in the United States may eventually incorporate these considerations, as already done by the European Union directives.

Goldfarb (1988, pp. 6–7) notes that one major water use has been neglected: demand-side conservation. As he indicates, "Water is, and will continue to be, scarce in many parts of the United States. Consequently, we are learning to perceive water conservation as an end in itself, a use on a par with other uses of water." Goldfarb projects this conservation use, "intentional nonuse and use reduction," as "one of the most volatile areas of water law for the foreseeable future" (Goldfarb, 1988, pp. 6–7). Schiffler (1998, pp. 334–335 and elsewhere) indicates that investment in water conserving techniques in water-short areas is effectively a way to supply greater needs for water. This issue relates to a topic addressed later: sustainability of the groundwater resource.

A major characteristic of water that has only received much attention in the last half of the twentieth century, and for groundwater, in the last quarter of that century, is quality. In this light, Goldfarb moves away from terms such as "consumptive" and "nonconsumptive" uses to a new terminology of "transformational" and "nontransformational" uses, in line with some current thinking on sustainability (for example, see Daly and Farley, 2004, pp. 62–64). "A transformational use is one which causes a significant change in the existing condition of a waterbody" (Goldfarb, 1988, p. 7). "A 'nontransformational use' leaves a waterbody in a basically unaltered state. This approach has the advantage of placing all water uses on the same plane. Thus, it deals directly with the fundamental value question inherent in water resource management: Are the social and economic gains produced by water use worth the costs of ecosystem change?" (Goldfarb, 1988, p. 7). This subject was examined in Chapter 2.

GROUNDWATER QUANTITY AND QUALITY

Water law in the United States historically has treated quantity and quality in separate statutes. The European Union addresses all major pollutant releases affecting ground and surface water quality in one Directive, whereas the United States divides them into several statutes. When population was not as dense and concentrated, concerns about quality were less. But as the use and the range of uses increased, quality became a significant concern. While quality and quantity as well as groundwater and surface water are inextricably related, they are still usually legislated separately in the United States with potentially important economic consequences. For example, the U.S. Clean Water Act has provided the basis for communities to treat their wastewaters at a central treatment plant with water discharge typically into a stream. The US Safe Drinking Water Act regulates injection of liquids including storm water and wastewater into the subsurface. Communities using groundwater for water supply must evaluate the regulatory, hydrologic, engineering and economic considerations and decide whether, faster release of water to a stream or reclaiming and recycling the water by employing hydrologic or redistribution processes is in their best interests. Such an evaluation can recognize the importance of the hydrologic cycle in maintaining water supplies and not respond only to water quality effects. In areas where the water tables may be falling, causing both municipalities and residential well owners to install deeper wells or causing greater public expenditure on what might have been unnecessary public water systems expansion—an inefficient approach in a systems analysis context.

In such cases, all costs may not be accounted for because the "hydrologic system" was not defined in the enabling legislation. The law simply did not reflect an understanding of groundwater in the hydrologic cycle and its relation to both ground and surface water quality. Similarly, many U.S. state laws address water quantity and allocation issues without relating them to water quality considerations. Some state laws maneuver around this situation with broad legislation for the conservation and protection of all waters of the state but do not acknowledge the significance of the hydrologic cycle in water management.

GROUNDWATER MOBILITY

The dynamic factor that distinguishes water from resources like land is its mobility (Hanemann, 2005, pp. 14–16). Groundwater moves at different rates depending on the geologic matrix in which it occurs. Because it moves and its other characteristics that may be changing over time move with it, groundwater quality and quantity change as well. This condition of groundwater indicates that a collective sharing of right to access, rather than ownership of a predetermined volume of a given quality, is conceptually more commensurate with its natural occurrence. This mobility factor should influence to what extent groundwater can be considered as property.

GROUNDWATER AS PROPERTY

"Property rights are defined as 'a bundle of entitlements, privileges, and limitations defining the owner's rights to use a resource' " (Schiffler, 1998, p. 92; citing Tietenberg, 1994). Groundwater as property to be owned in some form is addressed in the rights: (a) to use a resource—e.g., pump and drink groundwater, (b) to the return flows from the asset—e.g., groundwater flowing across a boundary to a down-gradient property owner, (c) to change the asset's form and substance—e.g., adding pollutants to groundwater even at low concentrations, and (d) to transfer a resource—e.g., selling groundwater, all of which can be held by either a central government (state or nation), a community or a person (Schiffler, 1998, p. 93). However, because groundwater moves, it is difficult to define a groundwater property right. (Schiffler, 1998, p. 95) Depending on where in the world groundwater use is taking place, its consumption or use as a pollutant sink may be governed by property rights (i.e., exclusive use by the owner) or open-access to the resource (i.e., use is not restricted, controlled, or managed and available to anyone for any purpose). National or state laws may control groundwater use in most cases in a legal status between these extremes.

Legal resource distinctions affect consumers' use of groundwater. An open-access resource categorization may apply to groundwater, as it would to air, in cases where drilling and production of the resource are not controlled or limited in any way. Water consumers may actually be denied the use of the resource in circumstances of (a) restricted common property, (b) communal property, and (c) private property (Schiffler, 1998, p. 93; citing Dales, 1968). Thus, rights in groundwater affect who can use it and to which uses it can be put. The three categories of restricted property rights just listed have different implications for groundwater users (Schiffler, 1998, p. 93):

1. Restricted common property might apply to groundwater in a national park or reserve, where the resource is owned by the central government in trust for anyone to use but resource use is controlled.
2. Communal property might apply if a community has exclusive rights to groundwater, such as a spring, and can exclude other users.
3. Private property has direct application in locations such as the western states where rights to groundwater stocks can be managed for exclusive use by the owner.

Whereas private property rights exclude use by others, public goods by their nature do not have restrictions on who uses them and how they are used. Depending on the location and authority over groundwater, the resource may be a private good or a more public good. This distinction affects both its use and its value. However, the more detailed the identification of rights, whether privately or publicly held, the greater the groundwater value since this definition specifies what rights are conferred with control over the resource. In cases where particular use is legally specified, groundwater value may be lower, since market forces are constrained (Schiffler, 1998, pp. 93–94). "(F)ully specified property rights are a powerful incentive to conserve resources, while their absence leads to the overutilization of resources," as would be the case if an aquifer had open access to anyone desiring to install a well and produce groundwater (Schiffler, 1998, pp. 94, 95).

Schiffler (1998, p. 94) notes some conditions under which groundwater might be considered an open-access or a private resource:

- Open access: aquifers of high porosity; no groundwater management
- Private: aquifer not porous; no interference from adjacent wells; access regulated.

Other conditions may be consistent with these categorizations. It is notable that private rights to groundwater do not allow an owner to do anything he or she may desire, since groundwater moves across property boundaries and excessive pumping or large amounts of pollutants reaching an aquifer may damage neighboring users' consumption of groundwater.

Under the legal systems of most countries, governments own the groundwater (Schiffler, 1998, p. 97) and in the United States, most states typically own and manage a water body as "trustee" for its citizens. In these states, an individual can only own the right to use the water, termed "usufructory right." This right of use ownership is private property. This right is not absolute, and the government may determine that its use of the resource for the community is a priority and can take private property with just compensation. A major concern of the legal system is "at what point does a governmental regulation to protect the public health, safety, and welfare become a 'regulatory taking' of private property for which just compensation must be paid?" (Goldfarb, 1988, p. 11). Once this is decided, the legal system must also draw on information from the economic system to determine the appropriate level of compensation, which may vary from place to place.

Both a legal and an economic problem is the law's historical recognition of boundaries of water bodies, which do not exist in the physical environment. For example, surface water courses are not lined pipes. Groundwater of varying quality and quantity can interact with a stream and vice versa. This interaction changes with time and location; groundwater recharge from a stream and discharge to a stream vary with precipitation events and seasons of a year. However, a large body of law exists that governs rights to and use of groundwater, treating it as a "stock" resource with well-defined boundaries.

GROUNDWATER LAWS OF THE UNITED STATES

Groundwater law in the United States has aspects existing at all jurisdictional levels: local, state, and federal. Much of early U.S. groundwater law was derived from English court law and then from U.S. court cases, which used common law to determine outcomes. Later, state law in the 1800s and then federal law in the 1900s, particularly in the latter years, addressed issues significant to groundwater and factors that affected its management, such as hazardous chemicals and wastes that were disposed of on or in the ground without adequate safeguards. The laws at any level were typically developed to address particular economic issues that arose, related to property use, income, health, and environmental degradation, and may not have considered the effect of the issues related to the hydrologic cycle at that time.

STATE GROUNDWATER DOCTRINES, LAW, AND POLICY IN THE UNITED STATES

Currently in the United States, 50 state groundwater doctrines have evolved, although some are quite similar. The doctrine related to groundwater quantity has a local focus, having evolved from English court law and ultimately into state law. These laws and court interpretations typically deal with the effects of one groundwater user on the availability of water to another user. This section reviews those doctrines in the United States as they apply to groundwater and has been summarized primarily from Goldfarb (1988). Legal terms for groundwater categories are important in understanding some of the legal and hydrologic issues associated with these doctrines.

TERMINOLOGY FOR GROUNDWATER CATEGORIES IN CASE LAW

In the hydrologic cycle, one cannot always distinguish between groundwater and surface water. However, because law has not historically always relied on science, some courts continue to distinguish even among artificial categories of groundwater, as well as ground and surface waters. This situation is changing slowly. Legal processes have considered the following categories.

Subflow of Surface Streams

Subflow is "the saturated zone directly beneath and supporting a river or lake in direct contact with surface water. Where subflow can be identified, it is considered as part of the water course itself" (Goldfarb, 1988, p. 19). From a hydrologic standpoint, subflow, as defined here, is highly dependent on the hydrologic head of surface and groundwater and the considerable potential variation in groundwater discharge and recharge relationships to a stream, even over short distances (e.g., less than 0.8 km). Even the contiguous saturated substratum immediately maintaining a river or a lake may now be much larger than originally understood.

Underground Streams

An underground stream follows a definite channel below the ground surface. Typically, an underground stream is considered surface water unless evidence can be shown that the water flows in a "known" channel and does not "percolate" (Hutchins et al., 1971; Goldfarb, 1988). From a hydrologic perspective, "known" channels of underground streams would exist in carbonate formations (limestone or dolomite) because of solution channeling of water through what were first small fractures. As a result, underground streams do not exist in all subsurface environments, only in carbonates. In some parts of the United States (e.g., Florida, Central Texas, and Northeast Iowa), these areas are extensive.

Percolating Waters

Percolating waters are waters that have infiltrated the soil and move through the ground, but not by a defined channel (Goldfarb, 1988). These waters represent what is considered the principal body of groundwater. Most "percolating waters" begin as precipitation, infiltrate the ground surface becoming soil water for a time, and then, if not evapotranspired, travel (migrate) to the water table by way of the microscopic pore spaces between the soil particles, along fine soil and rock fractures, and down macropores—worm, insect, and animal holes in the soil and unsaturated zone.

Wastewaters

Certain waters may escape constructed works by seepage, loss, waste, drainage, or percolation. A legal and economic question is to whom the wastewater belongs when it is released (Goldfarb, 1988). Where water is scarce, it is possible that escaping wastewater may be an important water source. In some locations, escaping wastewater may be contaminating other potable waters.

While these definitions continue in legal use, many courts now attempt to incorporate modern understanding of hydrology. Because in many instances no clear distinction can be made between ground and surface waters, it is important to recognize the function of the hydrologic cycle in water quantity and quality issues.

WATER QUANTITY

Historically, groundwater law or doctrines developed separately from those for surface water because of a lack of understanding of the relationship between ground and surface water. English court case law related to groundwater was based on the principle that groundwater movement was unknowable (NRC, 1997). Currently, a disjointed, multifaceted system of groundwater law exists. Goldfarb (1988) and the National Research Council (1997) identify similar major categories of U.S. state groundwater doctrine that are important:

1. The rule of absolute ownership
2. The reasonable use rule
3. Correlative rights rule in the eastern United States, based on the Restatement of Torts rule
4. Correlative rights rule in the western states
5. State permits
6. Prior appropriation
7. Critical management areas

These are summarized in Exhibit 5.1.

EXHIBIT 5.1 STATE GROUNDWATER PRODUCTION LAW IN THE UNITED STATES

Legal Approach	Groundwater Owner	Pumping/Use	Water Shortage Conditions
1. Common law			
a. Absolute ownership (English rule)	Land owner	Unrestricted	
b. Reasonable use (American rule)	Land owner, but no legal interest until groundwater is produced	Use on own property without waste	
2. Correlative rights			
a. Western (overdraft situations)	All well owners have equal right to groundwater	If wasteful practice, court can order reduced use	Court can order comparable proportionate decrease among users
b. Eastern (from second restatement of Torts	Land owner using groundwater	If conflicts arise, court can assign groundwater use based on “most beneficial use”	Court can reduce use
3. Statutory approach			
a. Permits	Land owner must follow requirements of state permit	Well construction and use permits required (production may be specified)	User may be required to ration use; public water supply may have priority
b. Appropriation	State permit holder (not necessarily land owner)	Senior permit holder has rights over junior permit holders	Senior permit holder has rights over junior permit holders
4. Management area	Land owner	Use conditions specified by the state or management district; required metering and pumping reductions	

EXHIBIT 5.1 (continued) STATE GROUNDWATER PRODUCTION LAW IN THE UNITED STATES

Pumping Zone Encroachment	Groundwater Mining	Surface Water Influence	Example States
Land owner held harmless for encroaching an adjacent user's capture zone	Not addressed	Courts apply "underground stream" doctrine	Texas, Indiana
If use is flagrant waste, or user is not overlying, judicial remedy can be sought	If use is wasteful or adjacent, may be controlled by courts	Courts apply "underground stream" doctrine	Nebraska, Arizona, California, plus 11 eastern states
Users have proportional pumping interest in water shortage	Judicial action may provide proportional use or restrict production to safe yield	Courts apply "underground stream" doctrine	California, Nebraska
Users have proportional pumping interest in water shortage	Judicial action may provide proportional use or restrict production to safe yield	"Reasonable/beneficial use" doctrine applied	Eastern United States (MI, OH, FL, WI, NJ, MO, NE)
Addressed in permit by well placement and production limits; Public water and domestic use have priority in water shortages	Usually seasonal issue and not long-term problem	May be addressed in permit	Florida, Iowa, Wisconsin, Minnesota
Senior user may have to install new well to greater depth	Setup "management areas", such as bans on large volume production wells or pumping restrictions	Where problems from groundwater production reduce streamflow, priority of appropriation rights determines use	Most western states (except Texas, Nebraska, Arizona, and California)

Source: Modified from Goldfarb, W., *Water Law*, Lewis Publishers, Chelsea, MI, 1988.

Absolute Ownership

Under this doctrine, the landowner can pump as much groundwater from beneath his property as he desires, without the responsibility for the effects on neighbors. Indiana and Texas are the only remaining states with this system (Goldfarb, 1988). Economic implications are that the use can result in significant losses on adjacent property.

Reasonable Use

Under the reasonable use doctrine, a groundwater user may produce as much water as can be pumped under the conditions of water being used on overlying land without waste (Goldfarb, 1989, p. 44). The water can be transported only if it can be done so without any harm to the groundwater use of the adjacent overlying landowners (Goldfarb, 1988 p. 44). Eleven eastern states and Arizona apply the reasonable use rule. Economic implications are that this doctrine protects adjacent landowners from harm and wasteful practices of neighboring groundwater users.

Correlative Rights—Eastern United States (From the Restatement of Torts Rule)

Restatement of Torts (Second Edition), legal scholars' idealization of what law should be, defines a groundwater use rule for well owners. A well owner may produce groundwater for his and for nonoverlying land uses but cannot interfere unreasonably with other users. Any one of three factors determines "unreasonable interferences with a neighbor's use of groundwater: (1) causing unreasonable harm by lowering the water table or reducing artesian pressure, (2) exceeding the owner's reasonable share of the total annual supply, or (3) having a direct and substantial effect on surface supplies and causing unreasonable harm to surface users" (Goldfarb, 1988 p. 44).

The economic effects of the Restatement Rule are that it "promotes conjunctive management," "protects aquifers from mining," and "protects minimum flows in watercourses" (Goldfarb, 1989 p. 44). This rule is used in Michigan, Ohio, and Wisconsin with laws similar to it in Arkansas, Florida, Nebraska, New Jersey, and Missouri.

Correlative Rights—Western United States

In California, the State Supreme Court determines correlative rights to groundwater during water-short periods on the basis of the following (Goldfarb, 1988):

1. "Overlying owners are entitled to no more than their 'fair and just proportion' for onsite uses;
2. As between transportation out of the basin first in time is first in right;
3. Overlying users have priority over transporters" (Goldfarb, 1989 p. 45). A "fair and just proportion" is equated to the fraction of an owner's property to the total area overlying the aquifer.

Prior Appropriation

Appropriation of water rights has four main principles: (1) acquisition of a right of beneficial use, regardless of land ownership, (2) acquisition of a specific amount of water, (3) the transfer of the right separately from the land, and (4) the right is indefinite as to duration of time as long as the beneficial use continues in line with the law.

Many western states have nominally adopted this legal approach, individually modifying it to fit conditions. A major economic implication of this doctrine is that the priority of use is not based on the economic value of that use necessarily.

Management Area

The most complex legal systems for groundwater management have evolved in U.S. states and for areas with recurring water shortages, primarily in the west and also in Florida and New Jersey (Goldfarb, 1988). Typically, those systems involve the conjunctive use of surface water and groundwater. In these systems, groundwater use is controlled to protect certain uses or users. In these systems, water use, integration of ground and surface water rights, measures to affect use (such as taxes or fees), education and technical assistance, and control of mining are forms of management that may be exercised by the state (in Arizona, Colorado, and New Mexico), by local management districts (Kansas, Nebraska, and Texas), or by the courts in conjunction with water districts (California). Economic implications of the management area approach are protection of existing uses into the future and possible reduction of impacts to adjacent landowners.

State Groundwater Drainage Law

State drainage law deals with the rights of landowners to "repel" or "expel" water at their properties' boundaries (Goldfarb, 1989). The application of drainage law to groundwater covers two principal circumstances: (1) preventing groundwater from flowing into one's property and (2) lowering the water table which results in dewatering or subsidence of an adjacent landowner's property.

Preventing groundwater drainage into one's property is generally covered by the same rule as surface water drainage in those states (Goldfarb, 1988):

> Common enemy rule: A property owner can control drainage waters regardless of effects to adjacent property owners. Seven states follow this rule, some with modifications to lessen damages to neighbors.
>
> Natural flow rule: A property owner cannot obstruct the natural flow of water in situations where adjacent property owners would be affected. Agricultural drainage is an exception in some states applying this rule.
>
> Reasonable use: A property owner is able to make "reasonable use" of land and subsurface space below it even if the use causes injury to an adjacent owner. If a neighbor's damage becomes unreasonable, then the owner affecting the injurious use is liable. A majority of states follow this rule.

The cases of dewatering or subsidence typically relate to mining, and less typically to sewer construction. In "absolute ownership" states, damages from dewatering or subsidence are not recoverable. Property owners in reasonable use states are usually similarly affected, as long as use is not wasteful or waters are transported off-site. In "correlative rights" states, since neighboring land owners have common and equal rights to percolating waters, the damaged land owner generally wins. In western states with water rights appropriation, a property owner cannot interfere with the flow of a groundwater supply of prior appropriation. One prior appropriation state, New Mexico, allows mining operations to compensate adjacent owners or provide an alternate water supply.

Where subsidence may be a factor, adjacent property owners are under mutual obligations of support for the surface and subsurface. One owner's activities must not affect the subsidence of a neighboring owner's land, which breaks the obligation. If this results, the damaged owner, should he seek legal remedy, will likely win. Because courts have given mixed decisions on activities involving mining and removal of solids by water withdrawal and other means that have caused subsidence, the case law is not consistent (Goldfarb, 1988 p. 63–64).

State Laws for Well Installation

States have typically adopted laws and related regulations controlling the location and installation of water supply and monitoring wells to protect public health. A study done of 12 states in the north-central United States (Job and Gabanski, 1988) indicated a wide variety of state legal approaches to allowing access to groundwater by well installation. The analysis addressed both water supply and monitoring wells. The study found that

- Some states apply water supply well installation requirements to monitoring wells, even though disinfection and yield tests are contrary to most uses of monitoring wells.
- Most states have a requirement for one or some combination of licensing water well contractors, registering water well engineers, or a well permit. Typically, such requirements are intended to ensure that wells are properly installed to reduce contamination problems.
- Permanent abandonment requirements for unused wells are specified in most states to reduce the potential that a well will not be used for waste disposal or contribute to groundwater contamination as it is not being maintained.

A second study of all 50 U.S. states showed other important considerations in well installation. (USEPA, 1996b) This study found that 48 states have well construction standards, many following standards developed by the American Water Works Association. Forty-seven states have minimum setback distances from microbial contaminant sources (such as septic systems or sewer lines), with minimum setback distances ranging from 3 to 91 m. Thirty-six percent of the states had minimum microbial setbacks of 15.2 m, with an additional 30% having minimum setbacks from 22.9 to 30.5 m. Three states had no required microbial setback.

Additionally, 29 states use hydrogeologic criteria to guide well construction. Twenty-five states base minimum casing depth on hydrogeologic factors, such as an unconfined or confined aquifer. Other hydrogeologic factors included in state law or regulation for the consideration in well installation are review for setback, grouting depth and type, karst conduit flow, groundwater flow, and flooding setback. An emerging issue from a hydrogeologic standpoint is the use of groundwater as a medium for heat exchange through groundwater heat pumps. States are recognizing that groundwater may need protection from fluids in these heat pumps and are addressing these matters in state regulation, such as in Illinois, which requires a setback from 22.9 to 60.2 m depending on the type of heat pump.

Economic implications of well installation requirements include

- Standards for well installation raise the costs of wells and of access to groundwater.
- Contamination can travel along the casing of a poorly installed well and potentially affect other groundwater users with both acute and chronic illness depending on the contaminant source; health impacts and damage to the adjacent users are minimized by the application of the standards.

Federal Groundwater Quantity—Related Laws

A range of national/federal laws affect groundwater quantity. The Surface Mining Control and Reclamation Act (SMCRA) provides for the assessment of probable cumulative hydrologic impacts before the Department of the Interior approves a mining permit. Performance standards and a reclamation plan must protect groundwater. Water supplies, if affected, must be replaced. Economic consequences of loss of water supply represent infrastructure decline for a community with potential loss of jobs and income.

The Geothermal Steam Act provides for the use of superheated subsurface water and steam for many energy applications including heating and electrical output. These applications provide economic value for groundwater which might not be captured in typical water use.

The U.S. Internal Revenue Code was modified based on a decision in 1965 by the United States Court of Appeals, Fifth Circuit, in the case of the *United States v. Marvin Shurbet* et ux, 347 Fed. (2d) 103, in Internal Revenue Service (IRS) Revenue Ruling 65–296 (November 19, 1965) to allow landowners engaged in irrigated agriculture in the High Plains to deduct from income the depreciated value of the groundwater stock that they drew on for their livelihood. This depletion allowance reduces the federally taxable income of these farmers and subsidizes groundwater depletion over a vast area of eight mid-western states: Texas, New Mexico, Oklahoma, Kansas, Colorado, Nebraska, Wyoming, and South Dakota, with portions of all these states supplied by the Ogallala Aquifer (Jenkins, 1980; Smith and Wyatt, 1980). The depletion allowance taken was calculated by

1. Deriving the total value of groundwater based on the sales value of the property with and without groundwater and dividing by the number of acres of the property;
2. Dividing the water table decline for the year by the saturated thickness of the aquifer at the time of acquisition;
3. Multiplying the results of 1 and 2 to establish the per acre depletion allowance. (Smith and Wyatt, 1980, p. 49)

The High Plains States Groundwater Demonstration Program Act relates to the Ogallala Aquifer depletion. The law provided for demonstrating a range of artificial recharge approaches and their quantity and quality effects on the aquifer.

WATER QUALITY

Concerning groundwater quality protection, most U.S. states have adopted federal approaches, such as in the Resource Conservation and Recovery Act (RCRA), Underground Injection Control, Wellhead Protection and Superfund Programs, described briefly in the subsequent text. Many states have their own standards for certain uses of groundwater, some of which relate to both quantity and quality considerations, and may be enforceable standards. These are described to some degree in the Exhibit 5.2, State Groundwater Classification. Most frequently, states use groundwater classification systems as a basis of permitting discharges to groundwater. This use of a classification system is closely related to regulated activities affecting or potentially affecting groundwater quality and for establishing remedial objectives. States' approaches for the use of groundwater classification systems are basically (1) "a formal system with classes defined by state statute or regulation, and (2) a method which distinguishes groundwater by use, quality, or hydrogeologic characteristics without formal class designations" (Environmental Law Institute, 1990). Twenty-eight states have groundwater classification systems and the other twenty-two do not have them. However, 14 of these states protect all groundwater in the state for drinking water use. Several others have nondegradation standards to protect groundwater quality. Other states have been developing such classification systems (ICF, Inc., 1990). Examples of groundwater classification systems from three states are given in Exhibit 5.2.

EXHIBIT 5.2 EXAMPLES OF GROUNDWATER CLASSIFICATION IN THREE U.S. STATES

Colorado

Authority: Basic standards for groundwater, 3.11.0 (5 Colorado Code of Regulations 1002-8)

I. Domestic use and quality (less than 10,000 mg/L TDS)
II. Agricultural use and quality (less than 10,000 mg/L TDS)
III. Surface water protection (interacts with surface water)
IV. Potentially useable (less than 10,000 mg/L TDS)
V. Limited use and quality (10,000 or more mg/L TDS)

New Jersey

Authority: New Jersey Administrative Code, Title 7, Chapter 9, Subchapter 6

I. Aquifers that support special ecological systems
    A. Natural areas, high-quality surface waters, and exceptional ecosystems that depend on groundwater

PL. Aquifers in the New Jersey Pine Lands

II. Aquifers that provide potable groundwater
    A. With conventional treatment
    B. Subsequent to enhancement or restoration or water quality after extended period of time
III. Aquifers that provide groundwater that is not considered suitable for human consumption owing to natural hydrogeologic characteristics or natural water quality
    A. Aquitards
    B. Groundwater with natural or regional concentrations of chloride exceeding 3000 mg/L or more than 5000 mg/L. Total dissolved solids or contaminants not subject to conventional treatment that exceed-state standards

West Virginia

Authority: West Virginia Code, Chapter 20, Article 5 M
All groundwater is protected as if it was a source of drinking water.

State Law Affecting Land Management Practices with Groundwater Quality Implications

During the period from the late 1980s to the early 1990s, states were active in enacting legislation affecting land management practices for the purposes of groundwater protection. Major legislative initiatives passed into law were summarized by the National Conference of State Legislatures (NCSL) (NCSL, 1994). Exhibit 5.3 provides a brief description of these laws. During this time, most states, following U.S. federal laws, focused on protecting groundwater quality from underground storage tank leakage, pesticide use control, more comprehensive approaches to groundwater protection, and protecting groundwater sources of public water systems. An underlying theme in these laws is improved information to better manage the protection of groundwater resources. From an economic standpoint, more and better information on groundwater quality may affect an individual's tastes and preferences for land and its water supply.

State Groundwater Quality Protection

Perhaps the best current example of a comprehensive approach to groundwater protection in the United States is the local implementation of state wellhead protection programs. States are required under U.S. Safe Drinking Water Act (SDWA), Section 1428, to develop wellhead protection programs for approval by the U.S. Environmental Protection Agency based on addressing the following elements, with the expectation of local implementation required in some states:

- Specify roles and duties of state agencies, local government entities, and public water suppliers;
- Delineate the wellhead protection area (WHPA) for each wellhead;
- Identify potential sources of contaminants within each WHPA;
- Develop management approaches to protect the water supply within WHPAs;
- Develop contingency plans for each public water supply system to respond to well or well-field contamination;
- Site new wells properly to maximize yield and minimize potential contamination;
- Ensure public participation.

As of February 1997, 43 states and 2 territories have approved WHP programs. A review of this program (Job, 2007) reveals that

1. Most states apply a mix of approaches to delineate wellhead protection areas: fixed radius (0.1–0.4 km), modeling (5 year time of travel), or hydrogeologic mapping, and recognize both microbial and chemical protection zones.
2. States identified a wide range of resources to be used to develop potential contaminant source inventories locally, including historical documents, databases, previous contaminant source inventories, land use maps, zoning records, field inspection, and past aerial reconnaissance.
3. Sharing the implementation of WHP among state government, water suppliers, and other local agencies is the predominant approach for implementation. However, five states implement the program primarily by applying state law or revised regulations and four states leave implementation solely to local government.
4. The most prevalent management approaches include education, zoning, monitoring ambient groundwater quality, design/operating/performance standards, prohibition of uses/activities/facilities, technical assistance, permits, land acquisition, agricultural controls, and best management practices. Typically, states and local agencies rely on existing authorities related to groundwater protection to manage contaminant sources in WHPAs.

Public input to the development and implementation of this program is required. While historically little funding was provided to implement this program, a private nonprofit approach emerged.

EXHIBIT 5.3 SUMMARY OF STATE LAW AFFECTING LAND MANAGEMENT PRACTICES FOR GROUNDWATER PROTECTION, 1988–1992

Category	Brief Description	Example States
Comprehensive groundwater protection	May obligate state agencies to write a comprehensive plan addressing groundwater quality protection from contaminating sources, including classifying aquifers, setting ambient groundwater quality standards, groundwater discharge permits, nonpoint source best management practices, and critical groundwater area specification	Arizona, Arkansas, Connecticut, Idaho, Indiana, Massachusetts, Minnesota, New Hampshire, North Dakota, Oregon, South Dakota, Washington, West Virginia
Groundwater monitoring	Sets up a state monitoring program to test ambient groundwater quality and potential contaminant sources and define vulnerable zones	Idaho, Missouri, Montana, Nebraska, Washington
Wellhead protection	Allows state agency to define roles of local and state governments in conducting a wellhead protection program, including delineating a protection area around public wells, locating potential contaminant sources, giving technical support to communities and formulate regulations to prevent contamination of groundwater	Alabama, California, Connecticut, Delaware, Florida, Illinois, Minnesota, New Hampshire, New Jersey, North Dakota, Ohio, Rhode Island, South Dakota
Land use management	Allows local government to implement zoning laws and other control measures to manage land use that may affect groundwater quality	Florida, New Jersey, New York
Nonpoint source pollution	May specify that a state agency is to establish a priority list of state waters, including groundwaters, for future protection, and issue technical advice for the best management practices that will minimize contamination	Iowa, Maine, New York, Vermont
Pesticides	Controls the use, selling, labeling, and discarding of agricultural chemicals and nutrients; may also address use fees, education, and monitoring	Alabama, California, Colorado, Connecticut, Florida, Idaho, Illinois, Iowa, Kansas, Louisiana, Maryland, Michigan, Minnesota, Montana, New York, North Dakota, Oregon, South Carolina, South Dakota, Vermont, West Virginia, Washington, Wisconsin
Underground storage tanks	Specifies conditions for registering, building, improving, emplacing, abandoning, and monitoring underground storage tanks; may also set up funds for cleanup of UST leaks and contamination of adjacent properties and provide financing for tank improvements	Nearly all states

Source: National Conference of State Legislatures (NCSL). Groundwater Protection Legislation, Survey of State Action, 1988–1992, June 1994.

The Groundwater Foundation, started in 1988 in Lincoln, Nebraska, has used the recognition of communities' groundwater protection efforts to encourage groundwater protection. This program basically encourages communities to value a protected groundwater supply, albeit valuing may not be in monetary terms. This approach has principally relied on providing information to the public to change local tastes and preferences for groundwater quality protection.

Economic implications of wellhead protection include

- Several thousand communities around the United States have fully implemented wellhead protection programs, recognizing that it is less expensive to implement protective land management practices in the area supplying the public wells than to remediate contamination (USEPA, 1996a; Job, 2007; AwwaRF, 2004).
- Furthermore, businesses see that protecting the local water supply brings more value to the infrastructure of a community which can be attractive to other businesses and promote more environmentally sound economic development (Job, 1996; AwwaRF, 2004).

States continue to enact law and develop regulation in response to economic circumstances and environmental conditions affecting groundwater.

U.S. Federal Groundwater Quality Protection—Related Laws

Since the mid-1970s, the U.S. Congress has passed a number of laws with significance to groundwater quality and management. Many of the laws have similar counterparts at the state level. While quantity is largely dealt with at the local level, quality has principally been dealt with at the federal level in surface water, which has been carried over to groundwater only to a limited extent. This circumstance is attributable to the fact that most groundwater is perceived as traveling slowly, is a local issue therefore, and does not affect interstate waters. The latter point is often not the case. Groundwater maintains the baseflow of many streams and rivers in the United States and around the world, thus providing drinking water supply, habitat for aquatic fauna and flora, and a natural diversity for the food web and for hunters and nature enthusiasts, as well as navigation and recreation on those streams. Maintaining the quality and quantity of streamflow actively affects commerce among states, which is recognized in the Constitution and therefore should be a federal interest.

Most federal groundwater quality protection law focuses on eliminating, reducing, or managing the sources of actual or potential contamination. It promotes to a limited extent an individual or business incorporating the cost of protecting and maintaining groundwater quality as a cost of doing business—the concept that a "polluter pays" for the full cost of doing business, including waste disposal. The Clean Water Act (CWA), with many references to groundwater, does not provide a coherent framework for groundwater protection, as it exists. Under the CWA, groundwater could be considered in regional wastewater planning, but few of the regional wastewater management (Section 208) plans did this. After amendments, regulations provided for monitoring funds to be used to measure groundwater quality, and in 1987 the nonpoint source pollution control provisions were strengthened and allowed to apply to funding for projects protecting groundwater. A continuing shortcoming that has been the focus of several court suits is the lack of recognition in the act that groundwater and surface water interact extensively, with the quality of one affecting the other. This situation, in turn, may affect the amount of pollution permitted to be discharged but is usually not accounted for because of the need for more data on the variation in this interaction over time and from place to place. Related to groundwater–surface water interaction is the matter of public water systems drawing water from either source paying for the cost to treat water to be sufficiently clean and safe to meet federal standards—a cost transfer without compensation by the polluter(s).

The SDWA as amended in 1986 and 1996 principally to set standards for the safety of consumers' drinking water quality has focused more on promoting the prevention of contamination through the management and modification of potentially contaminating sources of wellhead protection areas around public water supply wells and wellfields. It also set up a control program to regulate the disposal of the largest volume of hazardous waste through underground injection into the deep subsurface zones below aquifers used for drinking water supply. SDWA also contains several consumer right-to-know provisions at the local, state, and national levels so that consumers could be informed about contaminants in their drinking water. Additionally, the Food and Drug Administration (FDA) is to consider whether to establish standards for bottled water quality. These sections of the law have implications for informing the larger populace about product quality, and therefore influence the public's tastes and preferences for different qualities of water.

Many other U.S. federal laws and their implementing regulations affect groundwater quality:

- The Resource Conservation and Recovery Act (RCRA) program controls the generation, storage, transportation, and disposal of chemicals and their wastes. These controls affect the amount of waste and chemicals potentially released to the subsurface environment. Under this act, underground storage tanks are also regulated to minimize the release of chemicals to the subsurface environment and groundwater.
- The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) controls the production and use of pesticides in the commerce of the United States through a registration process. Pesticide registrants must conduct research on the degradation and health effects of their products to demonstrate that damage will not be incurred or will be minimal and be balanced by the economic benefits of the pesticide.
- The Pollution Prevention Act promotes waste source elimination and reduction, and recycling and best management where necessary. Potentially, this reduces the waste requiring disposal in landfills or injected underground.
- The Toxic Substances Control Act provides for a Toxic Release Inventory, which, in combination with Wellhead Protection and Comprehensive State Groundwater Protection Programs, promotes the use of information in making sound decisions to protect groundwater and prevent its contamination. A major economic effect is to reduce the "spillover" effect of potential contaminant release to adjacent landowners.
- The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) provides for the cleanup of abandoned chemical waste sites. This activity has increased the information the public can use in influencing local decisions affecting groundwater.
- The Superfund Amendments and Reauthorization Act (SARA) provides for important information to be made available by commercial and government organizations to the public concerning hazardous and toxic substances used in and around communities.

GROUNDWATER QUALITY STANDARDS

While no U.S. federal groundwater standards exist, the Superfund program began applying federal drinking water standards to its contaminated sites as remedial goals. Because of the tremendous cost of remediating groundwater to safer low contaminant concentrations in many sites where groundwater was not used extensively and could be cleaned at less cost at the tap, alternative remedial concentrations were established. However, one major factor in U.S. federal environmental policy relative to the control of future releases of contaminants or remediation (or nonremediation) of existing contaminants has been the recognition of case law: a federal regulation applied to one property should not cause harm to adjacent properties. Furthermore, if natural degradation was the selected remedy, the federal government would need to maintain institutional control of the area under which the contaminant plume may move and ultimately degrade to levels at or below drinking water standards. As long as adjacent users can produce water that is drinkable by federal standards, no harm was done to that user and he/she would not have to incur the cost of additional treatment to safely consume the water. The federal drinking water standards, referred to as "maximum contaminant levels" (MCL), are presented in Chapter 6. Exhibit 5.4 presents a summary list and description of U.S. groundwater-related law.

EXHIBIT 5.4 A BRIEF LISTING OF UNITED STATES FEDERAL GROUNDWATER-RELATED LAW AND POLICY

Law or Policy	**Year**	**Brief Description/Significant Provisions**
Related to groundwater quality		
Clean Water Act (CWA)	1972	Groundwater to be considered in regional wastewater planning
Safe Drinking Water Act (SDWA)	1974	Established standards for contaminants in drinking water; setup regulatory program to control underground injection of wastes; established prevention program to protect groundwater as a water supply source and the Sole Source Aquifer Program
Resource Conservation and Recovery Act (RCRA)	1976	Set up program to control hazardous waste generation, storage, transportation, and disposal in response to discoveries of groundwater contamination from hazardous waste disposal around the country
Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)	1980	Established a federal program to remediate abandoned hazardous waste disposal sites and groundwater contamination, past landowners and operators joint and severally liable for costs of remediation [Note: drinking water standards were often applied as remedial standards in this program, making it expensive to implement]
Groundwater Protection Strategy	1984	Promoted development of state capacity to protect groundwater from contamination and proposed an aquifer classification method
RCRA, Amended	1984	Set up program to regulate underground storage tanks to protect groundwater
SDWA, Amended	1986	Established the wellhead protection program to prevent contamination of groundwater sources of public water supplies and authorized a critical aquifer management program under the Sole Source Aquifer Protection Program
Superfund Amendments and Reauthorization Act (SARA) and Emergency Planning and Community Right-To-Know Act (EPCRA)	1986	Provided communities with the “right-to-know” about contaminant releases to air, land, and water; created the Toxic Release Inventory under Section 313 of EPCRA
CWA, Amended	1987	Provided grants to states for groundwater protection programs and groundwater monitoring; strengthened the nonpoint source program, which included funding for groundwater-related nonpoint source control projects
Federal Insecticide, Fungicide, and Rodenticide Act, Amended	1988	Streamlined the pesticide re-registration process, which included consideration of leaching of pesticides to groundwater
Pollution Prevention Act	1989	Setup program to eliminate, reduce, recycle, and improve “housekeeping” of commercial and industrial wastes
Food, Agriculture, Conservation and Trade Act	1990 and later years	Provided that areas in a wellhead protection program designated under the SDWA may be eligible to allow farmers owning them to receive payments for not cultivating them and leaving them as “conservation reserves” for up to 10–15 years
Groundwater Protection Strategy for the 1990’s	1991	Promoted Comprehensive State Groundwater Protection Programs, including action through use of inter-program capabilities; consideration of use, value, and vulnerability of groundwater; and actions affecting water quality through ground and surface water interaction

EXHIBIT 5.4 (continued) A BRIEF LISTING OF UNITED STATES FEDERAL GROUNDWATER-RELATED LAW AND POLICY

Law or Policy	Year	Brief Description/Significant Provisions
SDWA, Amended	1996	Provided for source water (ground and surface water) assessments as a basis for local and state protection activities and for possible reduction in chemical monitoring of public water systems; set up local water system reporting to consumers on drinking water quality and other consumer right-to-know provisions including a national drinking water contaminant occurrence database; established regulatory requirements for drinking water contaminants found in groundwater: arsenic, radon, and sulfate and for a process to determine the conditions under which groundwater supplies should be disinfected; changed the technology cost-effectiveness test to benefit-cost test through the comparison of risk-reduction benefits with technology cost
Related principally to groundwater habitat		
Clean Water Act, Section 404	1972	To fill or dredge a wetland, must apply for a permit from the Corps of Engineers
Federal Agriculture Improvement and Reform Act	1996	Under Wetlands Reserve Program, allows wetlands to be restored through permanent easements, long-term easements (30 years or the maximum allowed by state law), and restoration of cost-share agreements without easements; requires one-third of area to be allocated to permanent easements, long-term easements, and restoration agreements; provides payments to be commensurate with those provided to landowners who enroll filter strips in conservation reserves.
Related principally to groundwater quantity		
Internal Revenue Service Ruling 65–296	1965	Allows farmers of irrigated areas in the High Plains to take a depletion allowance for depleting the regional aquifer
Surface Mining Control and Reclamation Act	1977	Requires assessment of probable cumulative hydrologic impacts before mining permit approval; performance standards to minimize effects on quantity of groundwater (and surface water) during and after mining operation; operators must replace water supplies affected; reclamation plan must act to protect ground and surface water
Geothermal Steam Act and Amendments	1970/1988	Federal government claims geothermal resource wherever it holds mineral rights; Department of the Interior authorizes leases on federal lands; prospective users must get exploratory, drilling, and production permits; air impacts controlled under Clean Air Act; water discharges controlled under CWA; owners can use percentage depletion allowance
High Plains States groundwater Demonstration Program Act	1983	Provides for the evaluation of the potential for artificially recharging the Ogallala (High Plains) Aquifer because of extensive overdrafting of the groundwater resource throughout the aquifer
Related to financing groundwater supply		
SDWA, amended	1996	Established grants to states to capitalize state revolving funds to finance public water systems which need to return to or maintain compliance with drinking water quality standards, with a focus on small systems

(*continued*)

EXHIBIT 5.4 (continued) A BRIEF LISTING OF UNITED STATES FEDERAL GROUNDWATER-RELATED LAW AND POLICY

Law or Policy	Year	Brief Description/Significant Provisions
Farm Security and Rural Investment Act	2002	Provides loans, grants, and loan guarantees for drinking water, sanitary sewer, solid waste, and storm drainage facilities in rural areas and cities and towns of 10,000 or less; authorizes a grant to a nonprofit organization to assist individuals in receiving water well financing through loans of up to $8000 each at a rate of 1% for up to 20 years.

Sources:

1. U.S. Environmental Protection Agency, Office of Water, Progress in Groundwater Protection and Restoration, February 1990 (EPA 440/6-90-001).
2. Campbell-Mohn, C. et al., *Sustainable Environmental Law: Integrating Natural Resource and Pollution Abatement Law from Resources to Recovery*, Environmental Law Institute, West Publishing Company, St. Paul, MN, 1993.
3. Smith, D.D. and Wyatt, A.W., *Proceedings of the 7th Annual Conference of Groundwater Management Districts Association*, North Platte, NE, December 8–9, 1980, 43–49.
4. United States Department of Agriculture (USDA), Rural Utilities Service, Water and Environment Program, 2005, URL: http://www.usda.gov/rus/water/index.htm (accessed January 29, 2005a).
5. United States Department of Agriculture (USDA), Economic Research Service, Farm Policy, 2005, URL: http://www.ers.usda.gov/Features/farmbill/ (accessed January 29, 2005b).

U.S. Federal Wetlands Laws

Wetland-related laws, while not specifically recognizing that most wetlands are locations of groundwater discharge during most of the year, protect these areas from contamination and destruction. Wetlands, as the term implies, are water-saturated soils and subsurface zones, in which the watertable is manifest near or slightly above the ground surface with vegetation growing from it that has adapted to these conditions which may, in certain times and locations, be anaerobic. During times of high precipitation, wetlands can allow excess waters to be held in wetland soils and low-lying areas and thereby not contribute to rapid overland flow. Wetlands can provide important wildlife habitat for fish, migratory animals, and birds, helping to maintain natural values and biodiversity beyond the location of the wetland. Economic consequences of wetlands loss include increased flooding and reduced fishing and hunting potential, as well as wildlife enjoyment opportunities.

U.S. FEDERAL ENVIRONMENTAL VALUATION OF GROUNDWATER-RELATED ACTIONS

U.S. Federal law and executive orders provide the bases for environmental valuation of groundwater-related actions. The U.S. Federal Office of Management and Budget (OMB) is charged by Presidential Executive Order (E.O.) 12291 and 12866 to administer an evaluation process through the other Federal Departments and Agencies that causes federal programs' costs to be compared with benefits prior to decisions for program implementation. Allowances can be made for unquantifiable and unmonetizable benefits being applied to environmental and other regulatory and federal decisions affecting groundwater as well as other resources.

In U.S. Environmental Protection Agency programs, these analyses are included in Regulatory Impact Analyses. Congress, on the other hand, has prescribed how environmental programs should take into account benefits and costs. Several major federal environmental programs take different approaches in their analyses under their respective laws.

Drinking Water Standards:

> The 1996 Amendments to the SDWA changed this law's requirements from cost-effectiveness of available technology to a comparison of risk-reduction benefits with implementation costs.

Underground Injection Control:

> The only economic test in underground injection control is whether the injection occurs in a zone below an aquifer used for public water supply and separated from it by a lower impermeable geologic zone to avoid drinking water contamination and associated costs; otherwise, it is basically a cost-effectiveness evaluation that is required.

Wellhead Protection:

> This voluntary approach uses cost-effectiveness and avoided costs of remediation as its principal economic rationale.

Resource Conservation and Recovery Act:

> This law addresses permits for treatment, storage, and disposal of solid and hazardous wastes. The law states that its "objectives are to promote the protection of health and the environment" and does not address economic considerations.

Comprehensive Environmental Response, Compensation, and Liability Act:

> CERCLA or Superfund provides for the use of Trust Fund monies through "fund balancing" which considers the use of funds to be "balanced" among cleanup projects. Remedial design compares cost among alternatives for each cleanup.

Federal Insecticide, Fungicide, and Rodenticide Act:

> FIFRA requires a risk-benefit analysis for special reviews of pesticides and an analysis of likely economic consequences of canceling a pesticide.

Small Business Regulatory Enforcement Fairness Act:

> This act requires evaluation of effects on small business and communities.

Unfunded Mandates Act:

> This law requires the effects of regulations on states and local governments to be evaluated to determine which costs will not be covered by the federal government.

Surface Mining Control and Reclamation Act:

> A cost-effectiveness assessment of performance standards to minimize effects on quantity of groundwater (and surface water) during and after mining operation; replacement of the affected water supplies; and reclamation plan to protect ground and surface water.

U.S. GROUNDWATER FINANCING LAWS

The United States has limited federal financing of water supply. Most water supply systems in the United States are small groundwater systems. Financing of water supply mainly occurs through the private sector or the states financing programs. Since the 1960s, U.S. agricultural legislation has been providing grants, loans, and loan guarantees for rural development. Additionally, the SDWA amendments in 1996 focused on small water systems needs and established grants to states to provide financing to systems that were not in or needed upgrading to maintain compliance with drinking water quality standards for public health protection. A significant economic aspect of both of these programs is a federal subsidy to targeted water systems through principal forgiveness for economically disadvantaged communities and below-market rate loans.

OTHER ECONOMIC IMPLICATIONS OF U.S. GROUNDWATER RIGHTS AND LAWS

Each groundwater legal doctrine in the United States establishes a set of relationships that forms the basis for economic transactions, hospitable or adversarial. These relationships include individual (or corporation) with individual, individual with community or state (or vice versa), and community with state (or vice versa). The doctrines describe "who can do what." In the western U.S. states, rights to use water may be purchased within the framework of the appropriate doctrine in a hospitable environment. If actions or results take place outside the doctrine, such as overpumping and wasteful mining or groundwater contamination, adversarial transactions may result in economic exchanges, such as court suits that may ultimately result in the payment of damages or penalties by one party to another.

The federal legal framework principally identifies the limits for the potentially groundwater withdrawing or contaminating activities to operate within to minimize any effects on the groundwater resource. The costs of operating within these limits must be borne by the economic activities or receive penalties that are identified in the law.

ENVIRONMENTAL SITE ASSESSMENTS

In the United States

One of the most effective activities at the local level in the United States that has influenced the inclusion of groundwater quality in economic and financial decision making has been the environmental site assessment for property transactions through the legal process known as "due diligence" These assessments are used to determine whether adverse environmental conditions caused by previous activities on a property could have negative economic consequences, including potential health and environmental impacts, for future buyers, financiers, or users of a property. (Flaherty and Laemmerman, 1992)

Beginning in the United States with CERCLA or Superfund, which considered all previous owners of a contaminated site jointly and severally liable for contamination, commercial property owners and financiers began evaluating the environmental conditions of their properties for future use, purchase, or sale. Serious attention began when the state of New Jersey enacted its Environmental Cleanup Responsibility Act (ECRA) of 1983, under which all commercial and industrial property transactions were required to have an environmental site assessment undertaken by the company financing the transaction, including the testing of wells. This action informed the buyer about the condition of the property relative to contamination. While other states debated whether to pass similar legislation, this one action had such a strong positive response among the financial community in protecting their investment and managing their potential future liability that lenders around the country required sellers to conduct such an assessment for commercial and industrial property transfers, regardless of which state the property existed in. Other states have enacted similar laws. Subsequently, the SARA expanded information that commercial and public operations with hazardous and toxic chemicals in their processes must provide to the communities in which they exist. Thus, in response to these laws, the financial community changed its "tastes and preferences" toward financing environmentally clean properties.

Environmental site assessments are often driven by concerns about groundwater contamination and protection (Willard and Carroll, 1992) and typically have two major components (Martella, 1992). The first element—also referred to as "Phase I"—is a site inspection and documentation review for the property, including identification of the use of materials and substances at the site. The second element, Phase II, is the physical evaluation of environmental conditions at the site if the Phase I assessment determines that contaminant or other environmental problems exist. Phase II may involve soil borings and monitoring well installation to determine if soil and groundwater contamination have occurred.

INTERNATIONALLY

Governments and businesses in the United States are drawing on environmental due diligence developed at the international level. Most recently, the application of consensus-derived, internationally accepted standards are used in business and government to guide transactions. The International Organization for Standards (ISO) has existed since 1947 to develop standards covering a range of commercial and industrial activities and recently has developed standards applicable to transactions between businesses and governments relating to environmental site assessments and associated planning activities to minimize their impacts on the environment and human health. Two standards are described briefly in Exhibit 5.5.

GROUNDWATER LAWS OF OTHER COUNTRIES

Other countries have taken approaches to their legal frameworks that are different from the United States, even when they have a common legal history or similar hydrogeology. An understanding of these differences assists in evaluating the economic consequences that may also be different then, because these laws may define "who pays and how much" in distinctly varied ways. Evaluations in international groundwater economics will draw on these differences as cases arise.

First, national groundwater-related laws of the two countries of North America neighboring the United States—Canada and Mexico—will be reviewed, followed by an overview of laws of the European Union (EU) and of selected Muslim countries. A review of national groundwater laws and policies of all countries is, unfortunately, beyond the scope of this text. Those countries reviewed provide a range of national legal perspectives.

CANADA

Canada has followed both the same as well as different approaches as the United States in its national legal framework for groundwater. The Canada Water Act addresses water quality issues for both ground and surface waters. The Canadian Environmental Protection Act directs government controls on the release of substances into the environment and the protection of human health. Canadian law also indicates that the nation is committed to carrying out the "precautionary principle," which states "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." Though this is not a stated principle in the laws of the U.S., the United States has followed a similar approach in some laws. Likewise, Canada explicitly cites in its laws the "polluter pays" principle: those who cause pollution pay to remediate it or compensate those affected by it. Again, while not explicit, the U.S. has incorporated this concept into its environmental laws affecting groundwater and other resources and circumstances.

In 2003, Canadian federal and provincial governments and other stakeholder groups cooperatively developed a "Canadian Framework for Collaboration on Groundwater," which serves as a guide for future groundwater use, conservation, and protection policy (Government of Canada, 2003). The framework focuses on four areas: (1) coordination and collaboration mechanisms among governments and stakeholders; (2) national cooperative programs for research, inventory, assessment, and monitoring of groundwater; (3) communication to raise the awareness of the public to its role

EXHIBIT 5.5 INTERNATIONAL QUALITY AND ENVIRONMENTAL MANAGEMENT STANDARDS ESTABLISHED BY THE INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO), GENEVA, SWITZERLAND

The ISO has developed generic management system standards for

- Any product or service of any organization, and
- Any commercial, industrial, or governmental activity

ISO 9000 and ISO 14000 are quality and environmental management standards that are widely used around the world. ISO 9000 is an accepted global reference applied to business among corporations for quality management. Organizations use ISO 14000 to respond to their environmental requirements. ISO 9000 and ISO 14000 standards are implemented by over 634,000 organizations in 152 countries.

The ISO 9000 standards are primarily concerned with quality management to address

- The customer's expectations for quality results, and
- Required regulatory outcomes

while in the process of

- Increasing customer fulfillment, and
- Obtaining regular progress in its conduct of achieving these objectives

The ISO 14000 standards focus on environmental management (aspects of this standard were updated by ISO 19000 standards) addressing

- Reduction and abatement of damages to the environment from an organization's activities, and
- Regular betterment of its environmental results

Regardless of an organization's mission and objectives, the ISO quality management system and environmental management system (EMS) under ISO 9000 and ISO 14000, respectively, have critical characteristics to address improving their performance.

ISO 9000 standards cover documentation, audits, review, professional competence and training, customer communication and feedback, product monitoring, analysis, product improvement/corrective action/problem prevention.

ISO 14000/19000 standards address development and implementation of EMSs, principles of environmental auditing, audit of an EMS, qualification criteria for environmental auditors and lead auditors, audit program review and assessment material, labeling issues, performance targets and monitoring within an EMS, and life cycle issues.

Both of these sets of standards will apply to environmental site assessments in terms of their conduct and completeness.

Source: ISO Web site, URL: http://www.iso.ch/iso/en/iso9000-14000/index.html, http://www.isoeasy.org/, and http://www.iso14000-iso14001-environmental-management.com/ (accessed January 28, 2004).

in groundwater protection, to exchange data, and to hold forum on groundwater issues; (4) performance standards and uniformity across Canada with respect to training and accreditation of groundwater professionals (including scientists, engineers, and well installers), best management practices, and technology transfer. Future implementation of such a framework through policy, law, and regulation has the effect of improving information for the public's decisions about groundwater-related use and investment. Exhibit 5.6 gives an overview of the legal and policy framework at the Canadian federal level related to groundwater use and protection.

Other aspects of groundwater stewardship are managed and protected through the federal framework of laws or through provinces or other levels of government. For example, wetlands policy is based on the legal framework of the Canada Water Act, which provides for comprehensive water management plans developed through federal, provincial, and other stakeholders, as well as for

EXHIBIT 5.6 OVERVIEW OF CANADA'S MAJOR FEDERAL LAWS AND POLICY RELATED TO GROUNDWATER

Law/Policy	**Date**	**Brief Description**
Canada Water Act	1970	Establishes intergovernmental arrangements for policy development for water quality (both ground and surface water); provides for an inventory of all waters and for comprehensive water management plans; provides for grants and loans to agencies to address pollution control; establishes water quality standards for the controlled deposition of wastes into Canadian waters and effluent discharge fees for this deposition; water quality management agencies are to develop water quality plans with public input; provides for regulation of monitoring, treatment and compliance with standards for wastes and discharges of wastes to waters; establishes an inspection program
Canada Oil and Gas Operations Act	1985	Provides for regulations to prescribe measures necessary for the disposal or gathering and injection into an underground formation of water, gas, oil, or other substances produced from a pool or oil deposit
Canadian Environmental Protection Act	1999	Establishes legal standing of persons to sue for damages caused by substances introduced into the environment and for compensation; provides for the gathering of information on and monitoring of substances in the environment; requires the formulation of plans for pollution prevention and the control and abatement of pollution as well as the restoration of the environment as necessary; requires the issuance of objectives, guidelines, limits, and codes of practice relating to the release of substances into the environment to ensure sustainable development; mandates the issuance of objectives, guidelines, and codes of practice with respect to the elements of the environment that may affect the life and health of people
Pest Control Products Act	2002	In registering pest control products, set maximum residue limits to protect health by considering exposure through dietary sources including drinking water
National Water Supply Expansion Program		Provides federal financial assistance along with provincial assistance to rural agricultural infrastructure including wells and pipelines as well as groundwater assessments and plans for safe reliable water supply

controlling wastewater discharges to waters, including wetlands. Nutrients and other substances that would cause their degradation are controlled under the Canadian Environmental Protection Act. Provincial governments have parallel laws controlling wastewater releases and waste disposal, and specifically address wetlands protection, such as Alberta provincial law, Environmental Protection and Enhancement Act, and Water Act. Alberta's Water Act also regulates potable water supply and its allocation and well installation, maintenance, and remediation as well as the qualification of well drillers. Wellhead protection is implemented in provinces largely as a voluntary matter at the local level. This voluntary approach may be changing, as suggested by the events and actions in Ontario.

The Province of Ontario conducted a comprehensive review of laws and activities affecting a "watershed-based approach" to protect water sources in light of groundwater contamination that resulted in deaths and illness from drinking water in one of its communities (O'Connor, 2002). This review recognized the "shared responsibility of all governments and stakeholders to contribute to our collective goal of ensuring a sustainable supply of safe clean drinking water" (Ontario, 2003). The Ontario Advisory Committee conducting the review recommended the watershed protection approach to be focused on managing and reducing water quality and quantity threats in vulnerable areas and for sensitive waters, including groundwater. It also called for a watershed-based source protection law and amending numerous other acts to provide consistency in water source protection, including its Conservation Authorities Act (dealing with local controls of land use), Environmental Protection Act, Municipal Act, Planning Act, Nutrient Management Act, Drainage Act, Brownfields Statute Law Amendment Act, and the Mining Act, as well as other related laws. The Advisory Committee identified the following measures that were not addressed in law at that time and that should be incorporated in new laws and regulations:

- "Require routine disclosure of chemicals used or stored on-site, with appropriate confidentiality requirements.
- Require measures for the containment of chemicals, including plans for addressing leaks and spills.
- Require monitoring, including the installation of monitoring wells in specific high-risk circumstances.
- Enter into agreements with property owners and to attach relevant water protection conditions (e.g., secondary containment for chemical storage and monitoring requirements) on development applications.
- Control the drilling of new private wells and require proper plugging and sealing of unused wells in vulnerable areas where municipal drinking water supplies are potentially affected.
- Require regular maintenance and repairs and enable periodic inspection of septic systems.
- Require the effective decommissioning of septic systems prior to redevelopment.
- Require appropriate notification of contaminants associated with historic activities, as they are discovered through redevelopment.
- Require or promote conservation initiatives.
- Deal effectively with noncompliance (e.g., adding a charge to the associated property tax bill for the work done by the municipality as a way to deal with noncompliance)" (Ontario, 2003).

Throughout this review, the Advisory Committee emphasized a watershed-based source protection program as a "cost-effective" and "efficient" approach to minimize contamination of water sources (Ontario, 2003); however, the review did not include an evaluation of cost-effectiveness or efficiency. Changes in the laws to protect ground and surface water will affect the economic relationships currently influencing pollutant release and water use by individuals, businesses, and governments.

MEXICO

In the past, rights to water were owned by the national government exclusively based on revisions to the Mexico Constitution in 1917 as a result of land reforms at that time (NRC, 1995, p. 71), but that is changing to provide for water markets through private transferable water use concessions (Hearne and Trava, 1997, p. 12). Most of the federal law having to do with groundwater use, quantity, and quality are covered in the National Water Law and the General Law of Ecological Equilibrium and Environmental Protection. Major provisions of these laws are described in Exhibit 5.7. Notably, Mexican law provides for managing both ground and surface water in a watershed context and establishes a National Water Commission, regional authorities, and water associations to set requirements and oversee water use and quality.

EXHIBIT 5.7 OVERVIEW OF MEXICO'S MAJOR FEDERAL LAWS AND POLICY RELATED TO GROUNDWATER

Law/Policy	Date	Brief Description
Federal Law for the Prevention and Control of Environmental Pollution	1971	(Ley Federal para Prevenir y Controlar la Contaminación Ambiental). Regulates releases of pollutants to air, water, and the sea
Federal Law for the Protection of the Environment	1982	(Ley Federal de Protección del Ambiente). Provides for the protection and preservation of ecosystems through a revised approach to protect plants, animals, soil, and water; establishes guidance for inclusion of ecosystem factors in economic development
National Water Law	1992; amended in 2004	(Ley de Aguas Nacionales) Creates a National Water Commission to set requirements and oversee water use and quality in watersheds; establishes irrigation districts/water user associations to oversee and allocate ground and surface waters; establishes domestic water use as the priority water use; sets up a national hydrologic program to inventory and classify water bodies; provides for a water rights registry of users and for concessions for water use; allows the federal government to delineate protection zones to conserve water, preserve sources of water and the ecosystem, protect against contamination, and control water quality; directs the federal government to set measures to control substances in wastewaters; sets fines for water polluters; requires environmental impact assessments for new permits; prescribes prevention of contamination of national waters and their return to an adequate condition for reuse; provides for water quality standards based on water body classification and assimilation capacities of the subsurface; sets discharge permit requirements, monitoring, maintenance of records, and allowance of facility inspections; requires cleanup of accidental releases to waters and cost recovery by the government; allows suspension of discharges when no permit, monitoring results not available, and water use fees not paid; requires violators of the law to be responsible for remediation and environmental damage and to return water to previous quality.

(*continued*)

EXHIBIT 5.7 (continued) OVERVIEW OF MEXICO'S MAJOR FEDERAL LAWS AND POLICY RELATED TO GROUNDWATER

Law/Policy	Date	Brief Description
General Law of Ecological Equilibrium and Environmental Protection	1988; amended in 1996	(Ley General del Equilibrium Ecológico y la Protección al Ambiente). Warrants an individual's rights to a safe, healthful environment and public involvement in environmental protection; sets objective of biodiversity preservation and protection of natural areas; provides for sustainable use of water and other natural resources; controls hazardous wastes and radiological pollutant sources; provides for evaluating risks of actions affecting the environment; allows establishment of management areas to protect ecosystem function; defines enforcement of law and penalties for noncompliance
Law for Establishing Norms and Standards	1992	Establishes a "Federal Prosecutor for the Environment" to prosecute violators of environmental standards; requires use of benefit–cost analysis in future regulations and consideration of market-based approaches rather than regulatory means
General Health Law	1984; amended in 1988	Establishes standards for contaminants in drinking water; forbids releases of polluted water to sources of drinking water

Sources:

1. El Congreso de Los Estados Unidos de Mexico, Ley de Aguas Nacionales, 1992.
2. Gonzalez, G.R. and Gastelum, M.E., *Overview of the Environmental Laws of Mexico*, National Law Center for Inter-American Free Trade, 1999, URL: http://www.natlaw.com/pubs/spmxen13.htm (accessed February 11, 2005).
3. National Research Council (NRC), *Mexico City's Water Supply*, National Academy Press, Washington, DC, 1995, 71–77.
4. Nido, L.M., and Hutt, J.B., Significant changes to Mexico's water laws, 2004.

Mexican federal law affects groundwater and water resources generally in a number of ways. Significantly, changes in the Mexican federal laws allowing individuals to appropriate water use rights for the purpose of irrigation provides for the market exchange of ground and surface waters and their pricing in water transactions. Additionally, Mexican federal law allows protection zones to be established for the purposes of preserving ecosystem factors, preventing contamination and groundwater mining, thereby recognizing these values nationally. Requirements for application of benefit–cost analysis in regulatory development promote cost-effectiveness and economic efficiency to be considered. Market-based approaches as an alternative to regulatory mandates support more economically efficient outcomes where market failure is an issue in dealing with groundwater use, allocation, and quality.

EUROPEAN UNION

The EU consists of 25 member states (countries),* which "have set up common institutions to which they delegate some of their sovereignty so that decisions on specific matters of joint interest can

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* Austria, Belgium, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Spain, Slovakia, Slovenia, Sweden, and the United Kingdom comprise the European Union as of 2008.

be made democratically at the European level" (EU, 2005). It is a legal union largely to address common interests that have an economic basis. Those common interests include groundwater use and protection. A review of the groundwater-related laws of the EU and its member states on a comparable level with that given previously for the United States would be even more complex than the review for the U.S., if it started at the substate level (states of the member countries) and then covered each member's national laws and then the EU "Directives" as its mutual laws are known. The review here will focus on the EU level, which provides an interesting amalgam of the perspectives of the member states reflecting common concerns related to groundwater and water resources in general.

Notably, the EU perspective embraces the "polluter pays" and "precautionary" principles explicitly and most recently consolidated several water-related directives into one "Water Framework" Directive and specifically a "Groundwater Directive" targeted at controlling pollution of groundwater. The approach of the first directive is to treat ground and surface water as one resource, except where unique features (e.g., underground injection of liquid substances) suggest otherwise and its sustainability. The second directive recognizes unique features of groundwater needing regulation. These and the other groundwater-related directives are summarized in Exhibit 5.8.

Of particular significance to groundwater, these directives do not treat groundwater as a separate resource except where this is important. Both ground and surface water quality must be regularly monitored and limits on their abstraction (withdrawal) set. Specific law focuses on injection of

EXHIBIT 5.8 EUROPEAN UNION GROUNDWATER RELATED DIRECTIVES

Directive	Date	Brief Description/Significant Provisions
Directive 2006/118/EC concerning groundwater	2006	Developed in response to Article 17 of the Water Framework Directive; defines groundwater areas in river basins (watersheds); requires classification of groundwater areas relative to meeting Water Framework objectives; establishes a register for groundwater areas based on uses, including protection of habitats and species; establishes groundwater monitoring based on classification; requires river basin plan to include the summary of pressures and impacts, economic analyses of water uses, and the summary of programs for protection, pollution control, and remedial measures; provides for cost recovery of measures based on "polluter pays" principle; establishes a program to meet Water Framework measures for groundwater extraction and pollution prevention and control, including artificial recharge to be updated every six years.
Directive COM 2003 550 concerning groundwater protection against pollution	2003	Sets a policy framework for protecting groundwater from pollution; establishes criteria for assessing groundwater chemical status and a compliance regime for quality standards; provides a process for setting pollutant threshold values (or concentration limits) in groundwater; specifies criteria for identifying significant increasing pollutant concentration trends and for determining initiation of actions to reverse trends, considering risks to aquatic and terrestrial ecosystems and human health; provides continuity with Directive 2000/60/EC by linking to its list of pollutants to be controlled; prevents or limits indirect pollutant discharge to groundwater that would affect achieving good chemical status in waters of river basins; provides for review and updating of river basin plans.

(*continued*)

EXHIBIT 5.8 (continued) EUROPEAN UNION GROUNDWATER RELATED DIRECTIVES

Directive	Date	Brief Description/Significant Provisions
Directive 2000/60/EC establishing a framework for water policy	2000	Focuses on sustainability of water resources; recognizes interaction of ground and surface water; protects water for drinking water supply and ecological functions; specifies objectives to reverse contamination of groundwaters and coordinate measures for surface and ground quality through a river basin management approach through river basin plans; states goal for the elimination of pollution of water from man-made substances; specifies that common minimum environmental standards and emission limits must be adopted by member states; less stringent environmental objectives can only be implemented for specific water bodies for which technically infeasible and economically expensive actions can be demonstrated as needed; requires monitoring for surface and groundwater quality; directs member states to recover full costs of water service; establishes point and diffuse (nonpoint) pollution controls and measures (standards), including prohibition of injection of contaminants into groundwater; sets controls for abstraction (withdrawal) of surface and groundwaters; provides for the development of the prevention and control of pollution to surface and groundwaters; provides for ecological monitoring and economic assessments of required actions.
Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources	1991	Requires designation of vulnerable zones, which have surface and groundwaters that could be affected by nitrate from agricultural sources; provides for establishing codes of good agricultural practices, voluntary action, training, and information for farmers to protect these waters in vulnerable zones from nitrate; allows action to protect water in vulnerable zones to vary based on environmental conditions and activities; provides for taking additional protective actions; requires monitoring for nitrate to be repeated over time; report every four years on the implementation of the program; requires member states to bring laws, regulations, and other administrative provisions into alignment with the Directive.
Council Directive 96/61/EC concerning integrated pollution prevention and control	1996	Sets out requirements to achieve integrated prevention and control of emissions to air, water, and land; requires permits for pollution emission in existing and new facilities and provides for the Council to set emission limit values; mandates integrated approach to issuing permits, including evaluation of the potential for shifting pollution from one media to another, protection of soil and groundwater, and monitoring of releases; requires that best available techniques be used for prevention and control of pollutants; sets conditions for facility operator to report results of emission monitoring; provides access to information and to allow exchange of information among member states; requires consideration of transboundary effects of pollution among member states.
Council Directive of April 26, 1999 on the landfill of waste	1999	Requires member states to establish a national strategy for the reduction of biodegradable wastes going to landfills; specifies that landfills will not accept liquid wastes and wastes that are explosive, corrosive, oxidizing, or flammable, medical and veterinary wastes, tires and certain other

EXHIBIT 5.8 (continued) EUROPEAN UNION GROUNDWATER RELATED DIRECTIVES

Directive	Date	Brief Description/Significant Provisions
		wastes, and mixtures of diluted wastes; identifies permit conditions for landfills, including consideration of hydrogeologic characteristics and financial security; ensures that landfill disposal prices reflect the full cost of disposal, including long-term maintenance of the landfill; provides for conditions to accept waste including appropriate documentation and for inspections; requires monitoring of landfills; establishes landfill closure and postclosure care requirements; requires member states to report on implementation of the Directive and to bring their laws, regulations, and administrative procedures into alignment with the Directive.
Council Directive 80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances	1979	Establishes policy to prevent the pollution of groundwater by substances belonging to the families and groups of substances that have harmful effects in groundwater; prevents substances of a toxic, persistent, and bioaccumlative nature and limits heavy metals and other pollutants from entering groundwater; authorizes reinjection into the same aquifer of geothermal, mining, and construction waters; limits indirect discharge of substances on or in the ground that might cause groundwater pollution; authorizes artificial recharge if no adverse effect to groundwater; requires hydrogeologic investigations before allowing indirect discharges of substances; requires groundwater quality monitoring before indirect discharges and artificial recharge may occur; specifies authorizations of indirect discharge must include essential precautions related to the characteristics of the substances, for monitoring the substances and groundwater quality, and for proximity to other water uses such as drinking water; mandates that authorizations be reviewed every four years; requires checking compliance with the Directive; stipulates that consultation shall occur among member states for discharges that affect transboundary groundwaters; requires member states to bring their laws, regulations, and administrative procedures into alignment with the Directive.
Council Directive 98/83/EC on the quality of water intended for human consumption	1998	Establishes policy to protect human health from the adverse effects of any contamination of water intended for human consumption by ensuring that it is wholesome and clean regardless of its origin and whether it is supplied from a distribution network, from a tanker, or in bottles or containers; requires water to be free from any microorganisms and parasites and from any substances which, in numbers or concentrations, constitute a potential danger to human health and to meet minimum requirements; requires member states to take steps to prevent contamination of drinking water sources; sets parametric values as maximum occurrences of contaminants allowed in drinking water at points of compliance; requires regular monitoring at compliance points; specifies remedial action when parametric values are exceeded and health is endangered; provides for short derogations from the parametric values to allow time to address quality problems; mandates that member states report on drinking water quality every three years; requires member states to bring their laws, regulations, and administrative procedures into alignment with the Directive.

liquids into the subsurface, which is prohibited unless a permit is obtained. Groundwater monitoring must occur before any injection or indirect discharge to the subsurface. A comprehensive groundwater monitoring program is mandated. Integrated pollution prevention requires evaluation of shifting waste releases from one media to another, including soil and groundwater. Likewise, an evaluation of transboundary effects across national borders of contaminant releases must be conducted. Wellhead protection is required around wellfields that are sources of water supply, using nitrate as an indicator that must be monitored around those wellfields. Wetlands are covered by the comprehensive Water Framework Directive. Member states must bring their national laws into alignment with the EU directives within a timeframe specified in the directive, if they are not already.

MUSLIM COUNTRIES

Groundwater law in Muslim countries derives its basis from the Quran and Laws of Mohammad. These laws were defined as applying to all waters in most cases and applied to local circumstances typically. Aspects of them have found application on a national basis. Additionally, some national water laws in Muslim countries were derivatives of the British and French influences in these regions. Caponera (1973a,b) and Schiffler (1998) have reviewed water law in Muslim countries from which this summary is taken. Water law of Muslim countries provides an interesting and different perspective on water rights that define not only interpersonal but also economic relations on a different basis. Within the Muslim world, distinctions exist between the different religious groups concerning the use of water, such as for the priority of use.

Schiffler describes Islamic law for water in these countries in the following ways (1998, p. 122):

> "Islamic law (Shari'a) is a comprehensive legal system covering all aspects of life. Its most important sources are the Quran and the sayings of the Prophet Muhammad (the Sunna). From these two sources Muslim scholars have over the centuries elaborated Islamic law through interpretation (idjtihad), analogies (qiyas) and consensus (Ijm'a)… the Quran does not lay down any clear and specific rules on [water] use, and few such rules can be found in the Sunna. Water law in Muslim countries is heterogenous. It incorporates elements of pre-Muslim traditions in informal water law and of western tradition in formal law. Rules concerning water use also differ between the two main branches of Islam (Sunni and Shi'i) and among the four main Sunni schools of law… All these differences make it difficult to speak of Islamic water law as such. The common basic trait of water law in Muslim countries seems to be the principle of the "community of interest", as derived from the saying of the Prophet…"

Caponera (1973a,b) has prepared a summary and blend of water law in Muslim countries, which is abstracted here in Exhibit 5.9 as it applies to groundwater. The codification of water law in the area of Muslim countries first took place during the time of the Ottoman Empire (1300–1922 A.D.) (Caponera, 1973a, p. 36). Exhibit 5.9 describes some common elements of that code and the subsequent Turkish Republic civil code, which replaced it and still guides legal actions relative to groundwater in Muslim countries, as well as gives highlights of groundwater-related laws in selected Muslim countries, including one beyond the historical Ottoman Empire, Indonesia. Indonesian water law evolved from a succession of influences: (1) traders first from India who brought Hindu and from Indochina who instilled Buddhism through the fourteenth century, (2) later Muslim traders, (3) from the seventeenth through the early twentieth centuries, European interests, (4) and then after World War II, the independent Indonesia land and water law based on the traditional *adat* law derived largely from earlier Hindu propensities (Caponera, 1973b, pp. 54–55).

COMPARISON OF APPROACHES

At the center of any comparison of approaches at national levels is the recognition of who controls the groundwater resource. In the United States and Canada, the federal government controls waters

EXHIBIT 5.9 WATER LAW IN MUSLIM COUNTRIES AS RELATED TO GROUNDWATER

Traditional Concepts—based on the *Shari'a* and interpretations of it.

Water definition—water is a nonsaleable good to which all have a right (right of thirst); groundwater belongs to the community.

Water ownership—water is the property of the state (country); traditionally, a person can own the right to water use through receipt as a gift or inheritance, or by occupying land to maintain it; a person may possess water if it is in a receptacle.

Water use—an owner may control access to persons who desire drinking water; if no public water source is available, the owner must provide drinking water on the condition that the person does not damage the well.

Water rights transfer through sale—water rights are rights of use; an owner may sell water rights with the land or not do so.

Protected area around a well and spring—traditionally, well owners may control areas around their wells from trespass or the installation of wells within a small area that could influence flow to their well.

Law/Policy	Date	Brief Description
Saudi Arabia		
Shari'a and local customary law	Historic	Water is God's property and available to all; ownership only occurs when water is contained in a receptacle (jar, cistern, pool, etc.); all lands adjacent to a well or spring have right to a portion of the available water; community allocates rights to water use; surplus waters should be available for use as long as not detrimental to rights of owner or user; wells and springs must not be used in a way that causes harm to adjacent land and water users; animals are to be provided from the same sources or from surplus waters, like people; communities are responsible for well operation and maintenance; a right to use water is recorded locally and controlled by the community through a water use supervisor.
Ministerial resolution No. 328—Digging of wells for drinking water and the extension of drinking water networks	1968	Approval of applications for drinking water wells will consider site suitability, distance from settlement, water availability, and source; 37.8–56.8 L/day is the minimum that must be available to each person.
(Draft) Water code		Ground and surface waters are the property of the state; existing land and water rights are protected as long as they are in accordance with the principles of Islamic law; domestic use and household use have priority.
Royal decree on operational procedure of the distribution of public land ordinance		Permits are required for drilling wells; drillers must demonstrate qualifications; minimum distance between wells is 500 m.
Royal orders 17697, 8949, 2092, 7553		Well drilling is prohibited in protected zones.
Jordan		
Undergroundwaters Control Regulation	1966	Gives to the state full powers to control use and disposal of groundwater; groundwater use permit holders must take all necessary actions to preclude infiltration of saline water into usable aquifers;
Law on Settlement of Land and Water Rights	1952	Relative to groundwater, only water brought to the surface is owned by the land owner; water rights are for the registered use of water, which may be sold or leased with the approval of the Natural Resources Authority;

(*continued*)

EXHIBIT 5.9 (continued) WATER LAW IN MUSLIM COUNTRIES AS RELATED TO GROUNDWATER

Law/Policy	Date	Brief Description
Water Control Law	1953	A permit for other than irrigation purposes is a personal right and may be sold separately from the land; the “right of thirst” is recognized as not needing a permit.
Law on establishment of the Natural Resources Authority	1968	Water permits are required for groundwater use, for its use in excess of 5 m^3/day; for water used for industrial and mining purposes, for new wells, for modified wells, for installation of pumping devices; for pollutant discharges; for drilling wells; water users must not wastewater under the threat of limiting the amount of use by the state; well drillers must obtain a license; groundwater extraction permits may be refused in case of unreasonable use or depletion minimum distances between wells may be established.
Indonesia		
Local customary water law	Historic	Members of a community give mutual help (derived from the Hindu cosmology), a concept similar to Muslim customary water law; a water master controls water allocation.
General Water Regulation	1936	Provides for economic water use criteria and for free use of groundwater from dug wells of 15 m in depth; wells deeper than 15 m and wells of less than 15 m deep for agricultural and industrial purposes are subject to a concession from the government; requires that responsible authority allocate water for other uses, such as irrigation or emergencies; allows landowner free use of springs while requiring maintenance of their head, conservation of their flow, and protection of a 20 m zone around the spring head; requires a concession for modifying, sealing, deepening, and cleaning of wells; provides for agricultural uses to have priority over domestic and sewerage uses with cultivation plans being subject to approval of provincial administration; in times of water shortage, specifies that drinking water supply has priority and then sewerage; regulates the discharge of liquid and solid wastes for which a government concession is required;
Constitution of Indonesia	1945	Land and water are controlled by the state for the benefit of the people
Law No. 11 for Public Service Undertakings	1962	Establishes the Department of Health to protect water quality for all aspects of consumption; controls water use for mineral bottling and food processing through concessions provided by the Public Health Administration
Presidential Instruction on Government organization and coordination in the implementation of the five-year plan	1969	Identifies the Department of Finance as establishing and supervising water charges
Circular of the Minister of Mines	1971	Specifies groundwater use conditions such as depth and amount subject to the decision of the Department of Mines; provides for licensing of all well drillers and companies and requires them to report activity and data

EXHIBIT 5.9 (continued) WATER LAW IN MUSLIM COUNTRIES AS RELATED TO GROUNDWATER

Law/Policy	Date	Brief Description
Water Resources Law	1974	Places the responsibility for beneficial use of water in Central and provincial governments; establishes an inventory of water resources; requires the Central government to formulate plans, development, use, rights, and control of water treatment and pollution as well as management of harmful effects of water use and discharge; establishes the National Development Planning Board to coordinate water resource planning with other development, including river basin development; controls use of groundwater, geothermal waters, and hotsprings by the Department of Mines, including drilling and development; provides for penalties for violations of concessions and regulations; delegates certain authorities to Provinces

Sources:

1. Caponera, D.A., *Water Laws in Moslem Countries. Irrigation and Drainage Paper 20/1*, Food and Agriculture Organization, United Nations, Rome, Italy, 1973a.
2. Caponera, D.A., *Water Laws in Moslem Countries. Irrigation and Drainage Paper 20/2*, Food and Agriculture Organization, United Nations, Rome, Italy, 1973b.

that are defined to be interstate or interprovincial, and even then in limited ways. In more arid countries, such as Jordan and Saudi Arabia, all waters are under the authority of the national government. This relation alone affects who can pursue water rights damages and in what ways resolution may be accomplished. In other words, the perspectives defined in the laws affect the transaction costs of dealing with any problems arising out of water use and whether a person or company has the standing to sue in court.

At the local level, in the United States, states principally have administrative authority over groundwater. This allows states to specify whether the rights to a certain volume can be owned by individuals, particularly in arid states, or whether those rights to volumes are managed by states in some way. Again, who has the rights determines how problems in groundwater use are addressed and the extent of the transaction costs from place to place. These circumstances are also reflective of the climate and hydrology of an area: if arid, individual groundwater volume rights may be protected by law, whereas in a more humid state, individual rights may not be protected in the same way and in fact may be controlled by the state through local governments.

The legal approaches to water rights are the product of the regional climate and hydrology as well as the historical cultural and economic development. The more heavily industrialized economies have required extensive laws and regulations on pollution control and on water uses that affect human health and the environment. These concerns have evolved to a high level in the EU, which now has laws focusing on watersheds at the level to more fully integrate water resource management across its varying hydrologic zones and economic interests. Such an approach recognizes that groundwater migrates under political boundaries and has transitory physical boundaries depending on local geological conditions, precipitation, and pumping (abstraction).

While no one perfect approach may exist, several legal themes central to groundwater use and management are emerging and have relevance around the world. First, groundwater is a limited resource. Second, groundwater should not be considered separately from surface water, but rather as one resource existing in different physical conditions. Third, what affects groundwater in one place cannot be isolated physically and so should not be isolated legally, since it is one resource with surface water. Fourth, as population and water use expand, legal institutions should be updated to recognize the current science of hydrology and specifically hydrogeology to more fully address transboundary issues, whether property boundaries at the local level or state boundaries at the international level. Fifth, water laws reflect values of and for ground and surface water in the local and national economies recognizing that they are together a fundamental resource for which controls on access to water for a range of uses should not abrogate affordable access to a sufficient and safe volume of water to sustain life for all. Sixth, as population grows, the sustainability of the resource becomes more paramount and is now being recognized in law at national and international levels such as in Canada, Mexico, and the EU (and further addressed in a later chapter).

CONCLUSION

The water laws of many other countries can and should be examined and understood to allow a better understanding of groundwater management and value among different nations. The summaries above are just a sampling. The significance of reviewing these different approaches is to underscore how groundwater is valued in various legal doctrines. The range of legal ways to address groundwater defines rights to control and to use the resource, rights to discharge pollutants into it, and rights to respond to damages to the resource, all of which affect the economic and financial conditions of individuals, companies, and governments in different ways depending on the organization of the law. More integrated water policies recognizing the significance of the hydrologic cycle for both water quantity and quality may facilitate having ecologically and economically sustainable water supplies for the range of their uses.

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6 Groundwater Consumption for Health and Food

We can consume groundwater in at least two significant ways—directly through drinking it and indirectly through food produced by using it as an input. Drinking groundwater is obvious if you have a well on your property or used by your community as a water supply. Less obvious to most people, except the farmers, is the consumption of groundwater through food. Irrigated agriculture is the largest use of groundwater in many countries. Groundwater may also be the primary water supply for animals consumed by humans. Since food grown in one location using groundwater usually leaves that place to be consumed in another location, interest has grown in "virtual water" use or supply. That is, the consumption of food, or any product, by one group that is not the producer of the commodity but requires water in its production. The first way of groundwater consumption we explore is drinking it and then consider irrigated agriculture for food supplies that require it.

PART 1: GROUNDWATER AND HEALTH

If we consume groundwater, we must be concerned about its consequences for our health and that of other living organisms, as well as in commercial use. Water makes up 60% of the human body's composition and affects bodily hydration, conversion of food to energy, nutrient transfer, and waste elimination (Schrecengost, 1998). In many locations, groundwater may be the only source of water supply and, therefore, critical to be maintained (McCabe et al., 1997). As noted previously, all commercial (agricultural, industrial, and mining) applications account for about 76% of all fresh groundwater uses in the United States (USGS, 1998) and range from approximately 10% to 80% of groundwater uses in the European Union (EU) (EEA, 1999). The remainder is for drinking water.

While essential to the health of all living organisms, groundwater naturally contains minerals and microorganisms. Groundwater may also have chemical, biological, and radiological constituents that were derived from human activities. In low concentrations, all of these substances may be harmless and, in some cases, even healthful. In other circumstances, at high concentrations, these constituents may present health threats. In 1980, an estimated 25,000 people around the world died everyday from drinking contaminated water (Danielopol et al., 2003, p. 114). An estimated 0.75–5.9 million illnesses result each year from consuming contaminated groundwater in the United States with 1400–9400 deaths as a consequence (Danielopol et al., 2003, p. 114). In both cases of naturally occurring and human-caused contaminants, governments establish health-based standards to protect people from illness and mortality. Typically, the establishment of these standards attempts to balance the cost of removing the contaminants with the health risk-reduction benefits of mandating the standard. Human health effects may be evaluated in economic terms, covered in Chapter 13. Economists usually assess policies having health effects through cost–benefit analysis and evaluate specific health interventions by applying cost-effectiveness analysis (Dickie, 2002). The economic effects of contaminants are generally covered in subsequent chapters. This chapter briefly highlights the health effects associated with consuming groundwater that may have a range of chemical, radiological, and microbiological constituents for further economic examination.

POSITIVE HEALTH EFFECTS

While myths exist about the curative abilities of springs, one prominent nineteenth-century European doctor classified the continent's mineral springs by chemical content and ailment treatment (Figures 6.1 and 6.2) (Chapelle, 2000). In the twentieth and twenty-first centuries, interest has focused on the negative health effects of contaminants—both natural and human caused—in groundwater. As indicated in Chapter 2, many of these naturally occurring constituents are metals. Groundwater may also contain naturally occurring organic chemicals and microorganisms (Gibert et al., 1994).

FIGURE 6.1 Healing Spring, Hot Springs, Virginia.

FIGURE 6.2 Spring house along the Tanana River, Alaska.

EXHIBIT 6A.1 SIMPLE GROUNDWATER CLASSIFICATION BASED ON TOTAL DISSOLVED SOLIDS

Category	Total Dissolved Solids (mg/L)	Potential Uses
Freshwater	0–1,000	Drinking water, irrigation, industrial processes, cattle watering
Brackish water	1,000–10,000	Cattle watering (at low range of TDS)
Saline water	10,000–100,000	Raw material source of some chemicals
Brine water	Greater than 100,000	Raw material source of some chemicals

Source: Adapted from Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1986, 1089. With permission.

The concentrations of many of the natural chemical constituents found in groundwater are low and present minimal constraints on the use of groundwater (Driscoll, 1986, p. 98; note limitations below). Exhibit 6A.1 shows the ranges of dissolved solids (or minerals) in groundwater, as measured as total dissolved solids (TDS) in parts per million (ppm) and also referred to as “salinity.”

Groundwater may contain trace amounts of chemicals that are important for human physiology. Because groundwater can dissolve chemicals in soil and rock, in part due to the length of time it is in contact with those materials, it can have a range of chemicals in solution. The longer the groundwater is in the subsurface, the more mineralized it could become (Alley, 1993, p. 131). Chapelle (2000, citing Linn, 1893) notes the historical healthful aspects of the following chemicals known to be present in springs:

- Sulfur (dissolved hydrogen sulfide)—treatment of chronic rheumatism, gout, tuberculosis, paralysis, and chronic bronchitis
- High-iron—treatment of anemia
- Iodine—treatment of goiter (thyroid gland enlargement)

Additionally, some groundwaters may have natural fluoride that helps prevent cavities in teeth. Groundwaters that are highly mineralized from calcium and magnesium are often referred to as “hard water,” leaving pipes and taps encrusted with a hard residue. Calcium is an essential mineral for bones and muscle function. Exhibit 6A.2 lists the dissolved inorganic constituents that may be found in groundwater and indicates those which are considered essential minerals in human beings. In an economics context, the value of these dissolved minerals found in groundwater and the groundwater in which they occur could be evaluated in a number of ways, including least-cost alternative means to deliver these minerals to people needing them, such as vitamin supplements, and to provide water from nearby sources if groundwater were considered no longer locally available.

NEGATIVE HEALTH EFFECTS

Chemicals in groundwater may also have negative health effects. These chemicals can be natural occurring, meaning that they have been dissolved from soil and rock by groundwater and are carried by it and occur at high concentrations. They may also be human caused or anthropogenic. Negative health effects (illness and death) can occur sooner in the case of contaminants with acute human responses, such as certain microorganisms, or later for those with a latency period before manifesting responses (Cropper and Sussman, 1990), as low long-term doses of inorganic or organic chemicals.

EXHIBIT 6A.2 DISSOLVED INORGANIC CONSTITUENTS IN GROUNDWATER AND ESSENTIAL MINERALS

Dissolved Inorganic Constituent in Groundwater	Essential Mineral for Biological Processes	Principal Health Significance
Major Constituents (greater than 5 mg/L)		
Bicarbonate		
Calcium	Yes	Maintains bone health, blood pressure, reduce colon cancer, and manage weight
Chloride	Yes	Maintains electrolyte balance with sodium or potassium
Magnesium	Yes	May have role in reducing chronic disease and hypertension
Silicon		Present in skin, fingernails, bones, connective tissues
Sodium	Yes	Helps regulate water balance and the distribution of fluids
Sulfate		
Minor Constituents (0.01–10.0 mg/L)		
Boron	Yes	Important for growth and health; reduces calcium loss from bones
Carbonate		
Fluoride		Tooth decay reduction
Iron	Yes	Main carrier of oxygen to all cells
Nitrate		
Potassium	Yes	Regulates water balance within the body
Strontium		Can replace calcium
Trace Constituents (less than 0.1 mg/L)		
Aluminum		
Antimony		
Arsenic		
Barium		
Beryllium		
Bismuth		
Bromide		
Cadmium		
Cerium		
Cesium		
Chromium	Yes	With insulin, removes glucose from blood; involved in fat metabolism
Cobalt	Yes	Part of Vitamin B12; red blood and other cell function
Copper	Yes	Important for growth, connective tissues, and iron use
Gallium		
Germanium		Antioxidant and oxygen regulator
Gold		
Indium		

EXHIBIT 6A.2 (continued) DISSOLVED INORGANIC CONSTITUENTS IN GROUNDWATER AND ESSENTIAL MINERALS

Dissolved Inorganic Constituent in Groundwater	Essential Mineral for Biological Processes	Principal Health Significance
Trace Constituents (less than 0.1 mg/L) (*continued*)		
Iodide	Yes	Thyroid gland development and function controlling metabolism
Lanthanum		
Lead		
Lithium		Plays a key role in treating clinical depression
Manganese	Yes	Important for bone structure and metabolism
Molybdenum	Yes	Aids in final stages of making urine
Nickel	Yes	Factor in hormone, lipid, and membrane metabolism
Niobium		
Phosphate		
Platinum		
Radium		
Rubidium		
Ruthenium		
Scandium		
Selenium	Yes	Maximizes antioxidant enzyme
Silver		May be used as an external bactericide and disinfectant
Thallium		
Thorium		
Tin		Deficiency may be associated with hair loss, anorexia, and acne
Titanium		
Tungsten		
Uranium		
Vanadium		
Ytterbium		
Yttrium		
Zinc	Yes	Important for growth and development and may improve immune system function in elderly
Zirconium		

Sources:

1. Adapted from Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1986, 1089. With permission.
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4. RuralTech Services, Organic Facts, 2006, URL: http://www.organicfacts.net/health-benefits/minerals/ (accessed November 30, 2008). With permission.
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Naturally Occurring Contaminants

The soil and rock that water in the subsurface flows through consist of natural-occurring chemicals and compounds. Water dissolves these natural constituents and carries them as it flows in the ground and through aquifers. Chemicals occurring naturally in groundwater at high concentrations can be considered contaminants that may limit the use of groundwater. Some naturally occurring contaminants may also have human-caused sources, addressed here. The United States Environmental Protection Agency (USEPA), the EU, and the World Health Organization (WHO) have set health-based maximum concentration levels for contaminants in drinking water, which are often applied to groundwater when it is a source of drinking water. High concentrations of these naturally occurring contaminants may have adverse health effects. Exhibit 6A.3 provides the drinking water standards for these contaminants in the United States and potential health effects. Typically, the USEPA uses a risk range of 10^{-4} to 10^{-6} to establish these standards, as well as considers the capability and cost of technology to remove the contaminants. Exhibit 6A.4 summarizes the results of the process in the United States for setting a standard for arsenic.

EXHIBIT 6A.3 DRINKING WATER STANDARDS FOR CONTAMINANTS THAT MAY BE NATURALLY OCCURRING IN GROUNDWATER

Under the Safe Drinking Water Act (SDWA), the U.S. Environmental Protection sets health-based "maximum contaminant levels" (MCLs) and "treatment technique" standards for contaminants in water used for drinking supplied by public water systems. The standards below are current as of 2008 for inorganic and radionuclide constituents that may be in groundwater. Note that not all of them will be in all groundwaters. The implementing regulations require that the water be treated or otherwise meet the standards before being delivered to consumers. In setting the standards, the law (SDWA) requires the agency to balance the costs of implementing the standards with the health risk-reduction benefits, which may be denominated in dollars or illness and death averted. The EU and the WHO set similar standards, which may be different for some contaminants.

Inorganic Chemicals That Are Non-Radiologic

Inorganic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Antimony	0.006	0.006	Increase in blood cholesterol; decrease in blood sugar	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder
Arsenic	0[c]	0.010 as of 01/23/06	Skin damage or problems with circulatory systems, and may increase the risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass and electronics production wastes

EXHIBIT 6A.3 (continued) DRINKING WATER STANDARDS FOR CONTAMINANTS THAT MAY BE NATURALLY OCCURRING IN GROUNDWATER

Inorganic Chemicals That Are Non-Radiologic

Inorganic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Asbestos (fiber >10 µm)	7 million fibers per liter	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Barium	2	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits
Beryllium	0.004	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries
Cadmium	0.005	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints
Chromium (total)	0.1	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits
Copper	1.3	TT[d] action level = 1.3	Short-term exposure: gastrointestinal distress Long-term exposure: liver or kidney damage People with Wilson's disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits

(*continued*)

EXHIBIT 6A.3 (continued) DRINKING WATER STANDARDS FOR CONTAMINANTS THAT MAY BE NATURALLY OCCURRING IN GROUNDWATER

Inorganic Chemicals That Are Non-Radiologic

Inorganic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Cyanide (as free cyanide)	0.2	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories
Fluoride	4.0	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	0	TT[d] action level = 0.015	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits
Mercury (inorganic)	0.002	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands
Nitrate (measured as nitrogen)	10	10	Infants below the age of 6 months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits

EXHIBIT 6A.3 (continued) DRINKING WATER STANDARDS FOR CONTAMINANTS THAT MAY BE NATURALLY OCCURRING IN GROUNDWATER

Inorganic Chemicals That Are Non-Radiologic

Inorganic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Nitrite (measured as nitrogen)	1	1	Infants below the age of 6 months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome	Runoff from fertilizer use; leaching from septic tanks, sewage; erosion of natural deposits
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines
Thallium	0.0005	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories

Radiological Constituents

Radionuclides	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Alpha particles	None[c] Zero	15 picocuries per liter (pCi/L)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit a form of radiation known as alpha radiation
Beta particles and photon emitters	None[c] Zero	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation

(*continued*)

EXHIBIT 6A.3 (continued) DRINKING WATER STANDARDS FOR CONTAMINANTS THAT MAY BE NATURALLY OCCURRING IN GROUNDWATER

Radionuclides	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Radium 226 and radium 228 (combined)	None[c] Zero	5 pCi/L	Increased risk of cancer	Erosion of natural deposits
Uranium	Zero	30 mg/L as of 12/08/03	Increased risk of cancer, kidney toxicity	Erosion of natural deposits

Additionally, the USEPA has established standards for drinking water that address aesthetic qualities (taste, odor, or appearance) for constituents that may naturally occur in drinking water but are not considered threats to human health.

Drinking Water Contaminant Secondary Standards

Aluminum: 0.05–0.2 mg/L
Color: 15 (color units)
Copper: 1.0 mg/L
Corrosivity: Noncorrosive
Fluoride: 2.0 mg/L
Iron: 0.3 mg/L
Manganese: 0.05 mg/L
Odor: 3 threshold odor number
pH: 6.5–8.5
Sulfate: 250 mg/L
Total dissolved solids: 500 mg/L
Zinc: 5 mg/L

Source: U.S. Environmental Protection Agency, Drinking Water Standards Website, 2003b.

[a] Maximum contaminant level (MCL): The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. Maximum contaminant level goal (MCLG): The level of a contaminant in drinking water, below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are nonenforceable public health goals.

Treatment technique: A required process intended to reduce the level of a contaminant in drinking water.

[b] Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to ppm.

[c] MCLGs were not established before the 1986 Amendments to the SDWA. Therefore, there is no MCLG for this contaminant.

[d] Lead and copper are regulated by a treatment technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps. For copper, the action level is 1.3 mg/L, and for lead is 0.015 mg/L.

EXHIBIT 6A.4 SETTING A HEALTH-BASED STANDARD FOR ARSENIC

Under Section 109 of the SDWA as amended in 1996, the United States Congress required the U.S. Environmental Protection Agency (EPA) to set a new standard for arsenic in drinking water by 2001. A 1999 report by the National Academy of Sciences concluded that the then existing standard of 50 parts per billion (ppb) did not achieve EPA's goal of protecting public health and should be lowered as soon as possible. While the standard EPA issued on January 22, 2001, applies to most public water systems (except those for transient use), those

EXHIBIT 6A.4 (continued) SETTING A HEALTH-BASED STANDARD FOR ARSENIC

systems most affected are small groundwater-supplied systems. Arsenic is a human health concern, because it can contribute to bladder, skin, and other cancers, as well as heart disease and diabetes. Arsenic is a naturally occurring element in rocks and soils and the water in contact with them releases arsenic to water supplies. When people either drink this water or eat animals that drink it or plants that take it up, they are exposed to arsenic. For most people in the United States, eating and drinking are the most common ways that people are exposed to arsenic, although it can also come from industrial sources. To protect human health, in January 2001, EPA revised the standard for arsenic in drinking water from 50 ppb to 10 ppb to be implemented by 2006, unless water systems obtain additional time to comply through an exemption.

Sources of Arsenic Contamination in Water

- Naturally occurs in rocks and soil, water, air, and plants and animals.
- Released also by volcanic action, erosion of rocks, forest fires, or through human actions.
- About 90% of industrial arsenic in the United States is currently used as a wood preservative.
- Also used in paints, dyes, metals, drugs, soaps, and semiconductors.
- Also released by agricultural applications, mining, and smelting.

Analysis of Arsenic Occurrence in Drinking Waters

- In the late 1990s, the U.S. Geological Survey sampled 18,864 locations with wells, of which 2,262 were public water supply sources. For example, see Figure 6.3.
- 1,528 counties with sufficient data included 76% of all large public water supply systems (serving more than 10,000 people) and 61% of all small public water supply systems (serving more than 1,000 and less than 10,000 people) in the United States.
- Summarized data associated arsenic concentrations in the groundwater resource with public water supply systems using groundwater.
- Targeted arsenic concentrations of 1, 2, 5, 10, 20, and 50 μg/L were exceeded in the groundwater resource associated with 36%, 25%, 14%, 8%, 3%, and 1%, respectively, of all public water supply systems accounted for in the analysis.
- Higher levels of arsenic are found more in groundwater sources than in surface water sources (i.e., lakes and rivers) of drinking water.
- Compared with the rest of the United States, western states have more systems with arsenic levels greater than 10 ppb.
- Parts of the Midwestern United States and New England have some systems whose current arsenic levels are greater than 10 ppb, but more systems with arsenic levels that range from 2 to 10 ppb.
- While many systems may not have detected arsenic in their drinking water above 10 ppb, there may be geographic "hot spots" with systems that may have higher levels of arsenic than the predicted occurrence for that area.

Health Effects of Arsenic in Drinking Water

In most drinking water sources, the inorganic form of arsenic tends to be more predominant and can exert toxic effects after acute (short-term) or chronic (long-term) exposure. Although

(*continued*)

EXHIBIT 6A.4 (continued) SETTING A HEALTH-BASED STANDARD FOR ARSENIC

acute exposures to high doses of inorganic arsenic can cause adverse effects, such exposures do not occur from public water systems in compliance with the previous MCL of 50 μg/L. The rule addresses the long-term, chronic effects of exposure to low concentrations of inorganic arsenic in drinking water, which studies indicate including the following:

Cancerous effects: skin, bladder, lung, kidney, nasal passages, liver, and prostate cancer; and *Non-cancerous effects:* cardiovascular, pulmonary, immunological, neurological, and endocrine (*e.g.*, diabetes) effects.

Regulatory Significance
EPA set the new arsenic standard for drinking water at 10 ppb to protect consumers against the effects of long-term, chronic exposure to arsenic in drinking water. After careful consideration of the benefits and costs, EPA used its discretionary authority under 1412(b)(6) of SWDA decided to set the drinking water standard for arsenic higher than the technically feasible level of 3 μg/L, because EPA believed that the costs would not justify the benefits at this level. EPA believes that the final MCL of 10 μg/L maximizes health risk reduction at a cost justified by the benefits.

Requirements of the Rule
All community water systems (CWS) (regularly serving 25 or more persons or 15 or more connections) and all nontransient noncommunity water systems (NTNCWS) (such as schools, restaurants, hospitals, or factories that have their own water supply) that exceed the MCL of 10 μg/L will be required to come into compliance 5 years after the publication of the final rule. Beginning with reports that are due by July 1, 2002, all CWSs will begin providing health information and arsenic concentrations in their annual consumer confidence report (CCR) for water that exceeds ½ the new MCL.

Of the 74,000 systems regulated by this MCL, approximately 3,000 systems will have to install treatment or take other steps to comply with this MCL. Water systems must meet this standard by January 2006.

People and Systems Affected by the Rule
About 3,000 (or 5.5%) of the nation's 54,000 CWSs and 1,100 (or 5.5%) of the 20,000 NTNCWSs will need to take measures to lower arsenic in their drinking water. Of the affected systems, 97% serve less than 10,000 people.

Benefits of Setting the Standard at 10 ppb
Reducing arsenic from 50 to 10 ppb will prevent

- 19–31 cases of bladder cancer per year; preventing 5–8 deaths from this cancer
- 19–25 cases of lung cancer, preventing 16–22 deaths from this cancer
- Numerous cases of other non-cancerous diseases such as diabetes and heart disease

Cost of the Regulation
USEPA estimates the total national annualized costs of treatment, monitoring, reporting, recordkeeping, and administration for this rule to be approximately $181 million (using 1999 dollars at a three percent discount rate—Table 6.1). Most of the cost is due to the cost of installing and operating the treatment technologies needed to reduce arsenic in public water systems (both CWSs and NTNCWS). USEPA estimates the total treatment cost to be approximately $177 million per year. Annual monitoring and administrative costs will be about $2.7 million and States' costs will be approximately $1 million.

EXHIBIT 6A.4 (continued) SETTING A HEALTH-BASED STANDARD FOR ARSENIC

TABLE 6.1
Annual National System and State Compliance Costs (3% Discount Rate, 1999 $ in millions)

System Costs	CWS	NTNCWS	Total
Treatment	$170	$7.0	$177
Monitoring/administrative	$1.8	$0.9	$2.7
State costs	$0.9	$0.1	$1.0
Total cost	$173	$8	$181

The average annual household costs for the homes served by the approximately 2,387 CWSs that require treatment are expected to be approximately $32 per year (Table 6.2). The average annual household costs are shown categorized by system size in Table 6.3. The disparity in household costs between systems sizes is due to economies of scale. Larger systems are able to spread the costs they incur over a larger customer base.

TABLE 6.2
Total Annual Costs ($, 1999) per Household for CWSs

	System Size			
	25–500	501–3300	3.3k–10k	10k and above
Annual Household Costs	$327–$162	$71–$58	$38	$32–$0.86

The estimated average annual costs for CWSs, which exceed the final MCL of 10 µg/L and are required to treat, are shown in Table 6.3 categorized by system size.

TABLE 6.3
Average Annual Costs per CWS ($, 1999)

CWS System Size	Costs ($)
25–500	$6,494–$12,358
501–3,300	$22,100–$53,086
3,300–10,000	$111,646
10,000 and above	$531,584–$1,340,716

Sources:
1. U.S. Environmental Protection Agency (USEPA), Arsenic Web site, 2001, URL: http://www.epa.gov/safewater/arsenic.html (accessed December 2001).
2. Job, C., *Ground Water Monitoring and Remediation*, Winter, 40–43, 2002.

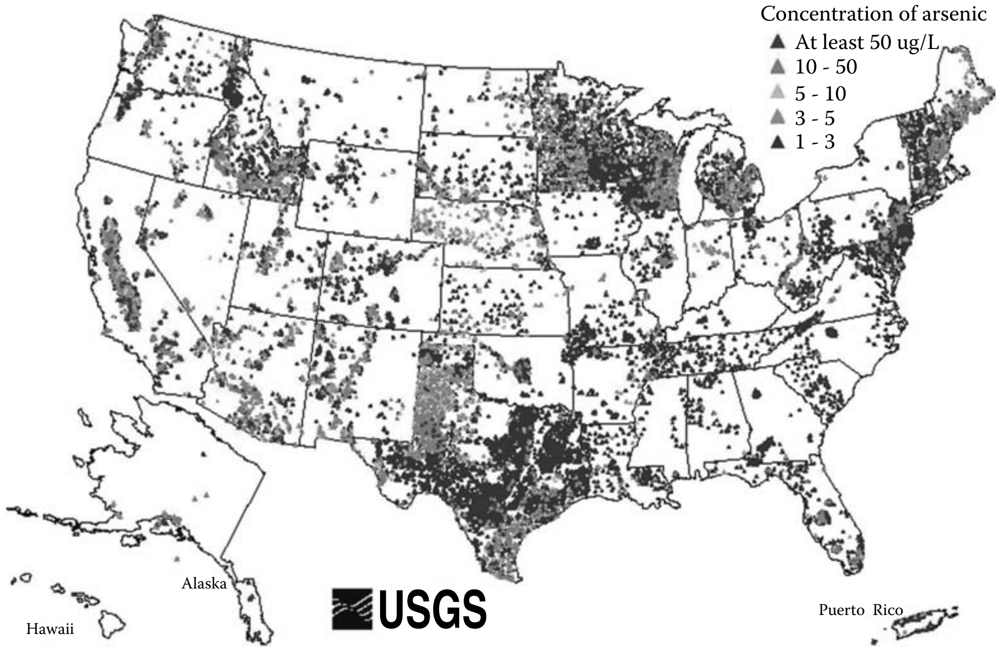

FIGURE 6.3 Map of concentrations of arsenic in the United States. (Source: U.S. Geological Survey)

Microorganisms also live in groundwater and in sufficiently high concentrations can cause illness and even death. Some organisms may occur naturally in groundwater (Exhibit 6A.5). Wildlife excrement can be one source for such organisms. Environmental and health organizations have set levels of the organisms that can be typically tolerated in drinking water without serious health consequences. Exhibit 6A.5 provides one set of standards for these microorganisms and the associated potential health effects.

EXHIBIT 6A.5 DRINKING WATER STANDARDS FOR MICROBIOLOGICAL CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Microorganisms	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Cryptosporidium	Zero	TT[c]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and fecal animal waste
Giardia lamblia	Zero	TT[c]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste
Heterotrophic plate count	n/a	TT[c]	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is	HPC measures a range of bacteria that are naturally present in the environment

EXHIBIT 6A.5 (continued) DRINKING WATER STANDARDS FOR MICROBIOLOGICAL CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Microorganisms	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Legionella	Zero	TT[c]	Legionnaire's disease, a type of pneumonia	Found naturally in water; multiplies in heating systems
Total coliforms (including fecal coliform and *Escherichia coli*)	Zero	5.0%[d]	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present[e]	Coliforms are naturally present in the environment; as well as feces; fecal coliforms and *E. coli* only come from human and animal fecal waste
Turbidity	n/a	TT[c]	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites, and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches	Soil runoff
Viruses (enteric)	Zero	TT[c]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste

Source: U.S. Environmental Protection Agency (USEPA), Drinking Water Standards Web site, 2003b, URL: http://www.epa.gov/ogwdw/creg.html (accessed March 1, 2003).

[a] *Maximum contaminant level (MCL)*: The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. *Maximum contaminant level goal (MCLG)*: The level of a contaminant in drinking water, below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are nonenforceable public health goals.

Treatment technique: A required process intended to reduce the level of a contaminant in drinking water.

[b] Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to ppm.

[c] EPA's surface water treatment rules require systems using surface water or groundwater under the direct influence *of* surface water to (1) disinfect their water and (2) filter their water or meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

Cryptosporidium (as of 1/1/02 for systems serving >10,000 and 1/14/05 for systems serving <10,000) 99% removal.

Giardia lamblia: 99.9% removal/inactivation.

Viruses: 99.99% removal/inactivation.

Legionella: No limit, but EPA believes that if *Giardia* and viruses are removed/inactivated, *Legionella* will also be controlled.

(*continued*)

EXHIBIT 6A.5 (continued) DRINKING WATER STANDARDS FOR MICROBIOLOGICAL CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Turbidity: At no time can turbidity (cloudiness of water) go above 5 nephelolometric turbidity units (NTU); systems that filter must ensure that the turbidity go no higher than 1 NTU (0.5 NTU for conventional or direct filtration) in at least 95% of the daily samples in any month. As of January 1, 2002, turbidity may never exceed 1 NTU, and must not exceed 0.3 NTU in 95% of daily samples in any month.

HPC: No more than 500 bacterial colonies per milliliter.

Long-Term 1 Enhanced Surface Water Treatment (Effective Date: January 14, 2005); Surface water systems or (GWUDI) systems serving fewer than 10,000 people must comply with the applicable Long-Term 1 Enhanced Surface Water Treatment Rule provisions (e.g., turbidity standards, individual filter monitoring, *Cryptosporidium* removal requirements, updated watershed control requirements for unfiltered systems).

Filter Backwash Recycling: The Filter Backwash Recycling Rule requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state.

[d] More than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-positive samples, and one is also positive for *E. coli* fecal coliforms, system has an acute MCL violation.

[e] Fecal coliform and *E. coli* are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.

Human-Caused or Anthropogenic Source Contaminants

Many contaminants of concern in groundwater are human caused or anthropogenic due to chemical, radiological, or biological production and use. These contaminants exist because we have manufactured and used chemicals in human activities from household maintenance and production processes to agricultural pesticide control and fertilization. Some chemicals have degraded into other chemicals. We have concentrated natural-occurring elements (such as uranium and its degradation products) through our uses or treatment of water. We have disposed of chemical, radiological, and biological wastes. As many as 70,000–100,000 chemicals may be in commerce in all their various types of applications (Saxena, 1996). All of these activities may result in these constituents entering the subsurface by direct placement (e.g., landfilling, well injection, or storm drain) or by being carried through the soil and rock to the groundwater table by percolation and infiltration of water that does not runoff the ground surface. Some of these human-caused contaminants may be harmful to the health of people and animals. Clearly, pesticides are specifically produced to kill agricultural, house, and garden pests but are designed to be used in small quantities that will not be injurious to human beings if indirectly consumed in low concentrations. Environmental protection agencies have set standards for such contaminants in drinking water and these have been applied to remediation of groundwater where it is used for water supply, such as at abandoned hazardous waste and chemical spill sites. Exhibit 6A.6 provides the drinking water standards used in the United States for these anthropogenic contaminants.

Groundwater containing contaminants from whatever source can influence the quality and use of it for a range of health-related purposes. In the United States, SDWA requires that the USEPA consider the needs of sensitive subpopulations in setting any standards for drinking water contaminants (U.S. Congress, 1996). These sensitive groups may include children, pregnant women, the elderly, and immunocompromised individuals. In many situations, groundwater is consumed

EXHIBIT 6A.6 DRINKING WATER STANDARDS FOR ANTHROPOGENIC CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Organic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Acrylamide	Zero	TT[c]	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment
Alachlor	Zero	0.002	Eye, liver, kidney, or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops
Benzene	Zero	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills
Benzo(a)pyrene (PAHs)	Zero	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines
Carbofuran	0.04	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa
Carbon tetrachloride	Zero	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities
Chlordane	Zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
Chlorobenzene	0.1	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dalapon	0.2	0.2	Minor kidney changes	Runoff from herbicide used on rights of way
1,2-Dibromo-3-chloropropane (DBCP)	Zero	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards
o-Dichlorobenzene	0.6	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories
p-Dichlorobenzene	0.075	0.075	Anemia; liver, kidney, or spleen damage; changes in blood	Discharge from industrial chemical factories

(*continued*)

EXHIBIT 6A.6 (continued) DRINKING WATER STANDARDS FOR ANTHROPOGENIC CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Organic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
1,2-Dichloroethane	Zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
1,1-Dichloroethylene	0.007	0.007	Liver problems	Discharge from industrial chemical factories
cis-1,2-Dichloroethylene	0.07	0.07	Liver problems	Discharge from industrial chemical factories
trans-1,2-Dichloroethylene	0.1	0.1	Liver problems	Discharge from industrial chemical factories
Dichloromethane	Zero	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories
1,2-Dichloropropane	Zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
Di(2-ethylhexyl) adipate	0.4	0.4	Weight loss, liver problems, or possible reproductive difficulties	Discharge from chemical factories
Di(2-ethylhexyl) phthalate	Zero	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables
Dioxin (2,3,7,8-TCDD)	Zero	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Endrin	0.002	0.002	Liver problems	Residue of banned insecticide
Epichlorohydrin	Zero	TT[c]	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals
Ethylbenzene	0.7	0.7	Liver or kidneys problems	Discharge from petroleum refineries

EXHIBIT 6A.6 (continued) DRINKING WATER STANDARDS FOR ANTHROPOGENIC CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Organic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Ethylene dibromide	Zero	0.00005	Problems with liver, stomach, reproductive system, or kidneys; increased risk of cancer	Discharge from petroleum refineries
Glyphosate	0.7	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use
Heptachlor	Zero	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide	Zero	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor
Hexachlorobenzene	Zero	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories
Hexachlorocyclopentadiene	0.05	0.05	Kidney or stomach problems	Discharge from chemical factories
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens
Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock
Oxamyl (Vydate)	0.2	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes
Polychlorinated biphenyls (PCBs)	Zero	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals
Pentachlorophenol	Zero	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories
Picloram	0.5	0.5	Liver problems	Herbicide runoff
Simazine	0.004	0.004	Problems with blood	Herbicide runoff
Styrene	0.1	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills
Tetrachloroethylene	Zero	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners

(*continued*)

EXHIBIT 6A.6 (continued) DRINKING WATER STANDARDS FOR ANTHROPOGENIC CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Organic Chemicals	**MCLG[a] (mg/L)[b]**	**MCL or TT[a] (mg/L)[b]**	**Potential Health Effects from Ingestion of Water**	**Sources of Contaminant in Drinking Water**
Toluene	1	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories
Toxaphene	Zero	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle
2,4,5-TP (Silvex)	0.05	0.05	Liver problems	Residue of banned herbicide
1,2,4-Trichlorobenzene	0.07	0.07	Changes in adrenal glands	Discharge from textile finishing factories
1,1,1-Trichloroethane	0.20	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories
1,1,2-Trichloroethane	0.003	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories
Trichloroethylene	Zero	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories
Vinyl chloride	Zero	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories

Disinfection Byproducts	**MCLG[a] (mg/L)[b]**	**MCL or TT1 (mg/L)[b]**	**Potential Health Effects from Ingestion of Water**	**Sources of Contaminant in Drinking Water**
Bromate	Zero	0.010	Increased risk of cancer	Byproduct of drinking water disinfection
Chlorite	0.8	1.0	Anemia; infants and young children: nervous system effects	Byproduct of drinking water disinfection
Haloacetic acids (HAA5)	n/a[d]	0.060	Increased risk of cancer	Byproduct of drinking water disinfection
Total trihalomethanes (TTHMs)	None[e]	0.10	Liver, kidney, or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection
	n/a[d]	0.080		

Disinfectants	**MRDL[a] (mg/L)[b]**	**MRDL[a] (mg/L)[b]**	**Potential Health Effects from Ingestion of Water**	**Sources of Contaminant in Drinking Water**
Chloramines (as Cl_2)	MRDLG = 4[a]	MRDL = 4.0[a]	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes

EXHIBIT 6A.6 (continued) DRINKING WATER STANDARDS FOR ANTHROPOGENIC CONTAMINANTS THAT MAY OCCUR IN GROUNDWATER

Organic Chemicals	MCLG[a] (mg/L)[b]	MCL or TT[a] (mg/L)[b]	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Chlorine (as Cl_2)	MRDLG = 4[a]	MRDL = 4.0[a]	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chlorine dioxide (as ClO_2)	MRDLG = 0.8[a]	MRDL = 0.8[a]	Anemia; infants and young children: nervous system effects	Water additive used to control microbes

Source: U.S. Environmental Protection Agency (USEPA), Drinking Water Standards Web site, 2003b, URL: http://www.epa.gov/ogwdw/creg.html (accessed March 1, 2003).

[a] *Maximum contaminant level (MCL):* The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. *Maximum contaminant level goal (MCLG)*: The level of a contaminant in drinking water, below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are nonenforceable public health goals. *Maximum residual disinfectant level (MRDL)*: The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants. *Maximum residual disinfectant level goal (MRDLG)*: The level of a drinking water disinfectant, below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants. *Treatment technique*: A required process intended to reduce the level of a contaminant in drinking water.

[b] Units are in milligrams per liter (mg/L) unless otherwise noted. Milligrams per liter are equivalent to ppm.

[c] Each water system must certify, in writing, to the state (using third-party or manufacturer's certification) that when acrylamide and epichlorohydrin are used in drinking water systems, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:

- Acrylamide = 0.05% dosed at 1 mg/L (or equivalent)
- Epichlorohydrin = 0.01% dosed at 20 mg/L (or equivalent)

[d] Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 mg/L). Chloroform is regulated with this group but has no MCLG.

Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.3 mg/L). Monochloroacetic acid, bromoacetic acid, and dibromoacetic acid are regulated with this group but have no MCLGs.

[e] MCLGs were not established before the 1986 Amendments to the SDWA. Therefore, there is no MCLG for this contaminant.

directly or after treatment for drinking, or it may reach surface waters, then affecting their quality and use. Contaminated groundwater may impact the health of humans and animals when they drink or bathe in it. Furthermore, contaminated groundwater can affect food products, such as meat or vegetables, if it has been consumed or used in the growth or preparation of them (USEPA, 2003b). Since the 1980s, the U.S. Environmental Protection Agency received reports on more than 37,000 abandoned hazardous waste sites in the United States, and 80% of the most seriously contaminated sites involve groundwater contamination (USEPA, 1996). Exhibit 6A.7 highlights the result of uncontrolled chemical use and disposal that resulted in contaminating a groundwater resource that in turn was used for drinking water supply and led to serious illness and death in one community.

EXHIBIT 6A.7 INDUSTRIAL CONTAMINATION OF A GROUNDWATER RESOURCE THREATENING A COMMUNITY'S WATER SUPPLY

In the early 1970s, townspeople in eastern Woburn (1990, pop. 35,943), Massachusetts, north of Boston, realized that they were experiencing significant levels of acute lymphocytic leukemia, especially among their children, and other diseases. In 1979, Woburn police investigated 184 barrels of industrial waste left on vacant land just west of the city's two wells in northeast Woburn. The barrels were removed before the contents were tested. However, the state environmental agency required the groundwater from the wells to be tested and reported high levels of trichloroethylene (TCE), 267 ppb in one well and 183 ppb in the other, as well as four other contaminants, including tetrachloroethylene (commonly referred to as "perc"). The USEPA had listed both of these contaminants as "probable" carcinogens at that time. Trichloroethylene is a solvent used for metal degreasing. Tetrachloroethylene is also a solvent used in industrial processes and drycleaning. [*Note:* At that time, the USEPA had not yet issued a drinking water standard for either of these contaminants. The current MCLs for both of them have been set at 5 ppb.] The wells were ordered closed. The wells had been installed to avert water shortages in the city and supply additional water, but most of the water served neighborhoods in southeastern Woburn. They were turned on and off numerous times after that discovery. Near the wells were the locations of past and active industrial operations. The Centers for Disease Control were eventually called in to evaluate the situation and found 12 families in east Woburn with members suffering from leukemia (some of whom had died), an incidence that was seven times the national occurrence. The trial that ensued documented uncontrolled chemical waste disposal by the industrial operations that contaminated the groundwater supplying the city's wells. The families eventually received an $8 million settlement, with $4.8 million going to trial costs and legal fees. The USEPA conducted a detailed investigation and determined in the early 1990s that its plan for remediating the soil and groundwater would require 50 years at an estimated cost of $69.4 million, making it the most expensive remediation in New England at that time.

Source: Harr, J., *A Civil Action*, Vintage Books, Random House, New York, 1996, 502.

Note: This reference documents the true story of a community, Woburn, Massachusetts, that dealt with the health issues from contaminated groundwater used for public water supply. The summary above was abstracted from that account reported by Jonathan Harr in his book A Civil Action.

VALUING HEALTH RISKS

As we will see in later discussions, a key part of economic analysis related to groundwater policies is the valuing in cost terms of human health risk. These costs are usually referred in such analyses as "damages." They are sometimes evaluated relative to the amount a person may be willing to pay to avoid the risk, usually for illness or death. As noted previously in this chapter, some negative health effects can occur very immediately, while others may take decades to manifest themselves (referred to as a latency period). One analysis indicated that, considering data on lifetime earnings potential and mortality rates, the amount "an individual is willing to pay today to reduce future risk equals the amount the same individual would be willing to pay in the future for a reduction in current risk, discounted back to the present" (Cropper and Sussman, 1990, p. 173). Comparing an individual of age 18 to one of age 60 in that context showed that the younger person who experienced a risk with a latency period had a discount factor that was one-twentieth that of the older person about to experience the effect of an immediate risk. In monetary terms, this implied a willingness by the younger person to pay $93,600 compared with $1.6 million by the elder person (both in 1985 US$). Willingness to pay and discounting will be addressed further in Part III. If the risk associated with not exceeding a drinking water standard is reduced from six people to two people in one million, then four statistical lives are saved and a distribution of the population by age is used to calculate the value of risk reduction, as one approach in valuing health. Cropper's examination (1990) suggested that the monetary value associated with willingness to pay to reduce the risk of immediate death may be the highest around an age of 40 years. A 1986 review of the "value-of-life" studies suggested a range of $2–$10 million for the value of a statistical life (Fisher et al., 1989). Other methods to estimate the value of health-related considerations include evaluating the cost of illness and avoiding contaminated water (Levin and Harrington, 1995).

BARRIERS PROTECTING HEALTH

A series of natural and constructed barriers can provide significant health protection from consuming contaminated groundwater, but they are not absolute. Barriers are points that may be used to control the risk to health by minimizing the delivery of contaminants in water to the final user (Fewtrell and Bartram, 2001). The subsurface itself may provide a barrier for some contaminants. Recognizing the characteristics of the contaminant to move through the subsurface or be impeded by the subterranean environment first may contribute significantly to health protection by minimizing risk of contamination to the groundwater resource. The value of the subsurface as a barrier may be evaluated as the least-cost alternative that would provide the same protection result or risk reduction. The value may also be determined by health costs avoided through preventing contamination, assuming that the barriers are fully effective, which may not be the case.

Source Water Protection and Contaminant Characteristics

Protecting the public health by reducing or eliminating the risk of contaminating the groundwater resource first through prevention is an essential barrier. The countries of the EU since the 1970s and the United States since 1986 have initiated programs referred to as wellhead protection to prevent contamination of groundwater used as a source of drinking water. Wellhead protection entails identifying potential sources of contamination around wells or their zones of recharge and managing them in ways that mitigate the risk of groundwater contamination.

The nature of the contaminants produced, used or disposed of, and in the case of microorganisms, living in, wellhead protection areas can affect groundwater quality and its potential to influence health. For example, contaminants characterized as dense nonaqueous phase liquids (DNAPLs) can sink deep into an aquifer, confounding their removal but leaving shallow wells less affected if the source of the contaminant is removed. Other contaminating substances, some with limited solubility in water, may float on top of the water table. An example is gasoline, which could be released from a leaking underground storage tank or from a spill. Such substances, if not removed from the subsurface, may imperil shallow wells used for water supply. Similarly, some microorganisms are longer-lived and can survive in the subsurface for extended time durations. Many microorganisms live in groundwater environments and some actually help degrade chemical contaminants (Gibert et al., 1994), but such activity may take years or decades.

Protective Aspects of the Subsurface

The prevalence of groundwater (nearly everywhere under the ground surface) and existence of natural processes that may possibly serve as a barrier to some contaminants are factors in groundwater's wide use for water supply (USGS, 2002). Groundwater by its location in the subsurface may have features that allow chemicals to degrade or microorganisms to die off before they could harm one's use of the water. These features include (but may not be limited to)

- Depth—A groundwater table at significant depth may have an unsaturated zone above it that attenuates the flow of contaminants, providing sufficient time for degradation or die-off of some contaminants. Additionally, installing a well that has considerable depth past the groundwater table could provide a similar protection.
- Slow Movement—Some groundwater environments constrain water movement to be very slow so that if sufficient time passes between contaminant entry into the subsurface and the point of use, again degradation or die-off may occur. Not all groundwater environments or points of use provide this factor (see Chapter 2).
- Adsorption—Some soil and subsurface matrices that contain silts and clays provide electrical attraction of certain contaminant ions allowing them to be bound by the soil particles.
- Confinement—A confining strata situated above the aquifer may act as an impervious zone (but not perfectly impervious) to retain contaminants and keep them from moving into the aquifer (Jorgenson et al., 1998; USGS, 2002).

The regulated deep underground injection of liquid wastes relies on confinement and confining strata below aquifers used for water supply to keep contaminants from migrating upward into groundwater in use for drinking water.

All these factors would not necessarily be present at every location of groundwater, nor be needed in each case to provide some qualities of a barrier. These factors may add value to groundwater and its use.

Unprotective Aspects of the Subsurface

Some groundwater environments may not provide much health protection from contaminants. Factors that contribute to the lack of a subsurface barrier include (but are not limited to)

- Shallow groundwater table—If the depth to groundwater is not great, then contaminants may reach the water table before degradation or die-off.
- Rapid movement—Highly porous gravel and sand or fractured bedrock may provide for rapid movement of groundwater with contaminants through the subsurface to the point of use, allowing little possibility of degradation or die-off.
- No adsorption—Porous gravel and sand or fractured bedrock may not provide for the possibility of soil particles to adsorb contaminants that might be electrically attracted to such particles.
- No confinement—If no confining zone exists to constrain contaminant movement, contaminants may be pulled in toward producing wells.

Treatment of Groundwater

A final barrier to protect the health of people and animals from contaminants in groundwater is physical, chemical, and biological treatment. Groundwater typically requires less treatment because of the natural features of the subsurface that may provide for its quality improvement. In many situations, treatment is a last but necessary resort to ensure that the quality of groundwater is healthful. Water treatment is one of the subjects of the next chapter.

GROUNDWATER SOURCE QUALITY FOR OTHER LIVING ORGANISMS

Other living organisms, animals and plants, depend on water and, in many cases, groundwater for their survival. Groundwater is used for watering livestock and is used in the irrigation of plants for human consumption. The quality of that groundwater may determine the health and longevity of those organisms. Groundwater with high TDS (also referred to as “salinity” or “electrical conductance”) when used for livestock watering can result in low performance, illness, and even death (University of Nebraska-Lincoln, 2003) (see Exhibit 6A.8). Similarly, plants exposed on a continuing basis to higher

EXHIBIT 6A.8 WATER QUALITY FOR ANIMALS

TABLE 6.4
A Guide to the Use of Saline Water for Livestock and Poultry

Total Dissolved Solids (Parts per Million)[a]	Comments
Less than 1,000	Water for all classes of livestock.
1,000–2,999	Satisfactory for all classes of livestock. Waters near upper limit may result in watery droppings in poultry, not adverse to bird health or production.
3,000–4,999	Satisfactory for livestock but may take time to adapt. High-sulfate salts may result in temporary diarrhea, but no harm. Poor to unsatisfactory water for poultry resulting in watery feces, and possible increased mortality and decreased growth, especially in turkey poults.
5,000–6,999	Use for livestock except pregnant or lactating cows. Some laxative effects. Unsatisfactory for poultry.
7,000–10,000	Poor for livestock and do not use for poultry or swine; use for older, low-producing grazers not pregnant or lactating with reasonable safety.
Over 10,000	Unsatisfactory for all livestock.

[a] Electrical conductivity expressed in micromhos per centimeter at 25°C can be substituted for total dissolved solids without introducing a great error in interpretation.

TABLE 6.5
A Guide to the Use of Waters Containing Nitrate for Livestock and Poultry

Nitrate Content[a] (ppm Nitrate Nitrogen)	Comments
Less than 100[b]	Should not harm livestock or poultry.
100–300	Not harmful to livestock or poultry. Combined with nitrate-containing feed, it will be dangerous. Particularly problematic for cattle and sheep in drought years with waters having elevated nitrate.
Over 300[c]	May cause typical nitrate poisoning in cattle and sheep and is not recommended. Use for swine, horses, or poultry is to be avoided.

Source: University of Nebraska-Lincoln, Cooperative Extension, Institute of Agriculture and Natural Resources, *Livestock Water Quality*, 2003, Web site URL: http://www.ianr.unl.edu/pubs/beef/g467.htm (accessed March 16, 2003).

[a] Includes nitrite nitrogen.

[b] Less than 443 ppm of nitrate or less than 607 ppm of sodium nitrate.

[c] Over 1329 ppm of nitrate or over 1821 ppm of sodium nitrate.

EXHIBIT 6A.9 WATER QUALITY FOR PLANTS

Recommended Limits for Constituents in Reclaimed Water for Irrigation

Constituent Name	Long-Term Use (mg/L)	Short-Term Use (mg/L)
Aluminum (Al)	5.0	20
Arsenic (As)	0.10	2.0
Beryllium (Be)	0.10	0.5
Boron (B)	0.75	2.0
Cadmium (Cd)	0.01	0.05
Chromium (Cr)	0.1	1.0
Cobalt (Co)	0.05	5.0
Copper (Cu)	0.2	5.0
Fluoride (F^-)	1.0	15.0
Iron (Fe)	5.0	20.0
Lead (Pb)	5.0	10.0
Lithium (Li)	2.5	2.5
Manganese (Mg)	0.2	1.0
Molybdenum (Mo)	0.01	0.05
Nickel (Ni)	0.2	2.0
Selenium (Se)	0.02	0.02
Vanadium (V)	0.1	1.0
Zinc (Zn)	2.0	10.0

Source: Texas Agricultural and Mining University, Agricultural Extension Service, *Ions, Trace Elements and Other Problems*, 1998, Web site URL: http://agnews.tamu.edu/drought.drghtpak98/drght59.html (accessed March 16, 2003).

TDS can have low yields and even die (see Exhibit 6A.9). Other trace elements may also cause added problems. From least sensitive to most sensitive to salinity, plants resistance to TDS in order are forage crops, field crops, vegetables, and fruit crops (Texas Agriculture and Mining University, 1998).

Costs of losses from reduced production of animals and plants in agriculture due to deteriorated or inadequate water quality can be evaluated and compared with costs of treating the water to a quality level that provides a sufficient economic return.

GROUNDWATER SOURCE QUALITY FOR COMMERCIAL APPLICATIONS

Water quality requirements for commercial applications vary widely based on the use (Driscoll, 1986, p. 110). Brackish waters can be used for cooling, but disposal may be a problem if concern exists about the environmental effects from concentrating constituents. Some commercial processes have water quality requirements that exceed drinking water standards because of sanitary protection considerations, such as processing for milk, canned goods, meat, and beverages (Driscoll, 1986, p. 110). Because of its low constant temperature, groundwater is useful in some processes such as heat exchange (Driscoll, 1986, p. 784). Natural groundwater hardness may be desirable in some industries, such as distilling, baking, and brewing, but not in others, as paper manufacture. Exhibit 6A.10 indicates water quality tolerances for some commercial processes. Costs to treat groundwater to bring its quality into a tolerable range will depend on the natural quality and the desired use in commerce. For many uses, groundwater that meets potable water standards will be sufficient.

EXHIBIT 6A.10 WATER QUALITY TOLERANCES FOR SELECTED COMMERCIAL PROCESSES

Industry	Turbidity	Color	Hardness as mg/L of $CaCO_3$	Alkalinity as mg/L of $CaCO_3$	Fe + Mn, mg/L	Total Solids, mg/L	Other
Food Products							
Baked goods	10	10	*	—	0.2	—	a
Beer	10	—	—	75–150	0.1	500–1000	a, b
Canned goods	10	—	25–75	—	0.2	—	a
Confectionery	—	—	—	—	0.2	100	a
Ice	5	5	—	30–50	0.2	300	a, c
Laundering	—	—	50	—	0.2	—	—
Manufactured Products							
Leather	20	10–100	50–135	135	0.4	—	—
Paper	5	5	50	—	0.1	200	d
Paper pulp	15–50	10–20	100–180	—	0.1–1.0	200–300	e
Plastics, clear	2	2	—	—	0.2	200	—
Textiles, dyeing	5	5–20	20	—	0.25	—	f
Textiles, general	2	20	20	—	0.5	—	—

Source: Adapted from Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1986, 1089. With permission.

Note: Indicated values are general averages only; local variance may be considerable.

* Some hardness is desirable. (a) Must conform to standards for potable water; (b) NaCl no more than 275 mg/L; (c) SiO_2 no more than 10 mg/L, Ca and Mg bicarbonates are troublesome; sulfates and chlorides of Na, Ca, and Mg each ≤300 mg/L; (d) no slime formation; (e) noncorrosive; and (f) constant composition; residual alumina ≤0.5 mg/L.

SUMMARY

Water is essential to the health of human and other living beings, as well as to commercial processes. Groundwater exists under most land surfaces and is widely used for water supply for people and animals, thereby potentially affecting their health. The resource contains naturally occurring minerals, which in low concentrations are healthful, but high doses may be harmful. Groundwater quality may also be affected by anthropogenic contaminants. For both naturally occurring and anthropogenic contaminants, governments have set health-based standards that define MCLs still considered safe for healthful use. Health-related costs from contaminants in groundwater form the basis of evaluating economic damages to communities and of developing health protection measures. The quality of groundwater may be protected by series of barriers, including wellhead protection to manage risks of contamination, natural features of the subsurface that may facilitate degradation or attenuation of chemicals and die-off of microorganisms, and treatment as a final step. Wellhead protection and these natural subsurface features may add value to the groundwater in use, the value of which can be evaluated in terms of the next least-cost health risk-reduction barrier or treatment, or the value of health effects avoided, assuming a fully successful barrier.

Animal and plant health must also be considered in using groundwater in agricultural applications. High salinity levels reduce performance and can cause illness and even death. Costs of losses from inadequate water quality can be determined through comparisons to expected production and with costs of water treatment. Costs to commercial applications to treat groundwater to meet their purposes will vary based on natural quality and use.

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PART 2: GROUNDWATER AND FOOD PRODUCTION

LARGEST USE OF GROUNDWATER

By far the largest use of groundwater is for irrigation to raise food for an expanding global population. World population is expected to grow at a rate of 1.1% annually from 2002 to 2030, while food production is forecast to increase at a rate of 1.5% per year during the same period (UNFAO, 2002). Even so, in 1998, the world had an estimated 815 million undernourished people, 99% of whom were in developing or transitional countries (UNESCO, 2003a, p. 210). During the time period 2002–2030, irrigated land is projected to increase by 20% (40 million hectares) (UNESCO, 2003a, p. 204). In the United States alone, groundwater is the water source for about two-thirds of the irrigated agricultural area (Arabiyat, 1999). Because water is a basic input for food production, the demand for water is a derived demand. As such it responds to the fundamental laws of economics (Tsur et al., 2004, p. 64).

Irrigating crops allows farmers to manage risk to their incomes. Irrigation reduces the probability of low production because soil moisture is below the necessary level to sustain the crop. Irrigating crops involves significant capital investment. The financial return on such an investment must be beneficial to enable farmers to enter into this form of agriculture (Buchanan and Cross, 2006).

EXTENT OF IRRIGATION WATER DEMAND

As population expands, food demand increases and, therefore, water demand for irrigation to meet this food demand increases. Irrigation is necessary because rain-fed lands do not appear to be capable of providing sufficient food, especially in countries with high population growth rates and some with low rainfall rates (UNESCO, 2003a, pp. 204–205). Worldwide, irrigated farmland covers approximately 2.5 million km^2, about 16% of the world's cropland (Sundquist, 2006). Exhibit 6B.1 highlights the cultivated land area currently having irrigation infrastructure around the world. The greatest irrigation potential exists in the Near East and India, relative to the lands already being irrigated. The United Nations projects that the portion of food grown using irrigation will increase, with developing countries expanding irrigated lands by 20% by 2030, which will also translate into 60% of lands having "irrigation potential" being brought into cultivation during that time (UNESCO, 2003a, p. 204). Note that rain-fed agriculture accounts for 60% of food production in developing countries (UNESCO, 2003a, p. 203).

EXHIBIT 6B.1 PERCENTAGE OF CULTIVATED AREAS WITH IRRIGATION INFRASTRUCTURE IN PLACE (BY COUNTRY, 1998)

Greater than 40%

Albania
Armenia
Azerbaijan
Bangladesh
Chile
Djibouti
Egypt
Georgia
Iraq
Israel
Japan
Korea (North and South)
Kyrgyzstan
Netherlands
Pakistan
Saudi Arabia
Surinam
Tajikistan
Taiwan
Turkmenistan
Uzbekistan
Vietnam

20%–40%

Afghanistan
Bhutan
China
Columbia
Costa Rica
Ecuador
Greece
Guyana
India
Iran
Italy
Libya
Madagascar
Mexico
Nepal
Peru
Portugal
Romania
Swaziland
Syria
Thailand
Yemen

10%–20%

Bulgaria
Denmark
French Guiana
Indonesia
Jordan
Laos
Moldova
Morocco
Myanmar
Norway
Philippines
Somalia
Spain
Sudan
Turkey
United States
Uruguay
Venezuela

5%–10%

Algeria
Argentina
Bolivia
Cambodia
France
Guatemala
Guinea
Kazakhstan
Macedonia
Mauritania
Mongolia
South Africa
Switzerland
Tunisia
Ukraine

Less than 5%

Russia and countries not previously listed

Source: United Nations Educational, Scientific and Cultural Organization (UNESCO), Water for People, Water for Life, The United Nations Water Development Report prepared by the UN World Water Assessment Programme, 2003a, 207.

Irrigated food production requires extensive amounts of water. The amount of water a person consumes in 1 day, ideally, is four liters (about four quarts), directly or indirectly through other beverages and food with high water content. Water use by plants that provide food require 2000 L of water to produce one person's food for 1 day (Brown, 2004, p. 99), because of plant transpiration leading up to a ripe crop for human consumption. Worldwide, groundwater and surface water used for irrigation equals 3500 km^3 of water (approximately equal to covering the combined area of Brazil, Uruguay, and Argentina with 0.3 m of water) each year (Sundquist, 2006).

Irrigated agriculture may have one of several bases for being used (Southgate, 2000):

- A shift from lower- to higher-value crops.
- Intensification of production to obtain the results of higher yields or to allow production of successive crops over a longer growing season not limited by rainfall.
- Extensification through bringing new land into production.

Intensification and extensification of irrigation has been a significant factor in land and water use. Globally, from 1950 to the late 1970s, land irrigated for agriculture increased almost 3% per year.

From 1970 to 1982, this irrigated land expanded by 2% per year. Over the time from 1982 to 1994, this slowed to 1.3% per year. Overall, however, from 1978 to the present, irrigated land on a per person basis declined 5% (Sundquist, 2006). Factors contributing to this per capita reduction of irrigated farmland include aquifer depletion (Brown, 2004) and waterlogging and salination of agricultural land (UNFAO, 2003a), discussed further later. Adding to pressure to irrigate to increase production, lower soil quality has resulted in declines in productivity on greater than 80% of cultivable land globally (WI, 2005). Furthermore, world grain production area per capita is declining, while per capita fertilizer use is growing to address expanding population needs for food with finite land area (Muir, 2005). From an ecological standpoint, the limiting factors of nutrients and water are being applied with a food production focus.

Notably, as world demand for food grows, the source of water supply to meet the need is changing. Over the period from about 1950 to 1975, an estimated 1000 large dams were completed each year. During the first part of 1990s decade, each year saw approximately 260 large dams coming on line. Additionally, these dams on average fill in with sediment at the rate of about 1% annually. This decline in dam construction represents a major factor in the worldwide increase in reliance on groundwater as a source for irrigating farmland (Sundquist, 2006). Because water from rivers in the world's major agricultural zones has become nearly completely utilized, further expansion of irrigation has drawn on groundwater (Brown, 2004, p. 100).

Exhibit 3.1 indicated that in the drier climatic areas of the western United States, groundwater was the source for 28% of irrigation water. In the more humid eastern United States, groundwater accounts for 72% of irrigation water (USGS, 2004). The amount and distribution of irrigated farmland in the United States is described in Exhibit 6B.2, totaling approximately 22.3 million hectares.

EXHIBIT 6B.2 IRRIGATED FARM LAND IN THE UNITED STATES, 1997

"Irrigated land [area] reached new heights in 1997, with over 22.3 million irrigated hectares of crop and pasture land. The most reliable estimate of area actually irrigated is developed every 5 years from census of agriculture data, last collected in 1997. There are other estimates of areas irrigated and areas with irrigation capability (infrastructure in place but no water applied), but these estimates lack statistical reliability. These sources report current estimates from 23.5 to 25.1 million hectares.

Cropland is irrigated in all 50 States. In 1997, irrigated land ranged from about 1012 ha in Vermont, New Hampshire, and Alaska to about 3.5 million hectares in California. Irrigated areas have historically been concentrated in the West (89% of area in 1969). The West still retains the bulk of the irrigated land (78% in 1997), but the trend is for faster growth in the East. Since 1969, irrigated land in the East has increased by almost the same number of hectares as in the West, with a much faster rate of growth (187%–23%). More recently (1987–1997), irrigated land in the West increased by about 2.2 million hectares (14%) and 1.3 million hectares (38%) in the East."

Sources:

1. U.S. Department of Agriculture, Economic Research Service (USDA), *1997 Census of Agriculture,* USDA, Washington, DC, 2002a, URL: http://www.nass.usda.gov/census/index1997.htm (accessed September 20, 2008).
2. U.S. Department of Agriculture, Economic Research Service (USDA), *Irrigation and Water Use: Questions and Answers*, Economic Research Service, USDA, Washington, DC, 2002b, URL: http://www.ers.usda.gov/Briefing/WaterUse/Questions/qa1.htm (accessed April 21, 2006).

BIOFUELS DEMAND ON GROUNDWATER

Worldwide, production of biofuels grew by three times from 18 million kiloliters in 2000 to about 60 million kiloliters in 2007 providing less than 3% of the fuel for transportation globally. The United States, Brazil, and European Union account for 90% of this production at 43%, 32%, and 15%, respectively (USDA, 2007). In the United States in 2007, corn for ethanol production required nearly 6 million hectares and was projected to increase to over 8 million hectares in 2008 (Hart, 2007). Soybean production for biodiesel also is forecast to increase. Wheat and other grasses contribute to biofuel production.

The production of biofuels is forecast to be 89% of growth of water consumption in the U.S. energy sector. In the United States, most of the biofuels are projected to be grown in the West North Central region and increase by 72 million cubic meters per day, or by 2.5 times, between 2005 and 2030. Sixty percent of this increase is for corn-based ethanol production (ANL, 2008). Typical irrigation for corn production uses groundwater at a rate 25% greater than it is naturally recharged in the United States (Pimental, 2001). Water consumed for biodiesel production is projected to expand from about 6 million cubic meters per day in 2005 to about 28 million cubic meters per day in 2030 mainly in the South Central and Pacific regions (ANL, 2008). Thus, expanding corn, soybean, and wheat production through irrigation using groundwater and the associated agricultural chemicals applied to achieve high yields will place both quantity and quality demands on the resource.

BRIEF HISTORY OF GROUNDWATER IRRIGATION

Prior to the 1940s, well-drilling technology consisted largely of using augers to create a hole in the ground from which to extract groundwater, but this technique was primarily for shallow wells with walls that were not supported and were subject to collapse. A second method was to hammer a “drive point” into the ground until it reached the groundwater table. However, the diameter of the hole was typically small, limiting the amount of water that could be produced. In the 1940s, borrowing technology from oil well drillers, the irrigation industry began using drill bits with industrial diamonds in the drill bit which could produce a wider hole. This drilling method forced water down the hole either on the outside or through a pipe on the inside through the hollow drill stem to push the drill cuttings up to the surface. Dense clay was used to make a firm wall for the well. The drills were mounted on the back of trucks, rather than using a stationary derrick, and moved to different sites easily. A screened casing is placed in the bottom of the well to allow water to flow into the well but keep larger solid material out. A solid casing is placed above the screened section to pump the water to the ground surface. Gravel is used to fill in around the casing and stabilize it.

During the same time (1940s), irrigators began installing turbine pumps used in the oil industry to literally push the water up the well. Early shallow wells could be pumped by horsepower. Because water is heavy (1001.2 kg/m^3), powerful pumps are necessary to lift a column of water through deep wells, some of which may be hundreds of meters deep. The pumps were submerged in water at the bottom of the well. Engines at the top of the well that were used to power the pump first used steam and then were developed to use gas, oil, diesel, or electricity, depending on what was available (WLHF, 2006).

RECENT DEVELOPMENTS IN IRRIGATION WELLS

Electric pumps have been made smaller and hand pumps are still used with small diameter wells that can be installed by driving a well point into the ground. The small pumps have been effectively used in developing countries where at present millions of wells have been installed in countries such as China and India. Wells now use widely available polyvinyl chloride (PVC or plastic) pipe. Even bamboo has been adapted to well casing in shallow, low-volume wells. With so many wells in use withdrawing large volumes of groundwater, problems have emerged, such as lowering the groundwater table, producing even more brackish water from deeper subterranean zones, as well as causing land subsidence. Exhibit 6B.3 covers some of these developments around the world.

EXHIBIT 6B.3 IRRIGATION WELL DEVELOPMENT EXAMPLES AROUND THE WORLD

India (2002)

- One-half of the total irrigated area relies on groundwater wells
- 60% of irrigated food production from groundwater
- 10.5 million dug wells and 6.7 million shallow tubewells in 1994
- Shallow tubewells doubled every 3.7 years from 1951 to 1991
- Groundwater irrigation has double the yield of surface water irrigation
- Overexploitation in some states has been significant with water tables declining

Nigeria (2002)

- About 30,000 ha irrigated with tubewell–pump package
- 30,500 pumps distributed to farmers
- Farmer income rose with reduction in poverty
- Economic rate of return in Fadama project estimated at 40%
- Additional benefits identified:
  - Development of simplified well-drilling technology
  - Farmers trained to help other farmers construct wells
  - Infrastructure for transportation and storage of products
  - User association established
  - Development of groundwater monitoring and evaluation system

China (2002)

- Groundwater at present is the major source of irrigation in Ninjin County
- Rapid increase in irrigated areas resulted in overexploitation of groundwater with serious environmental consequences
- Density of tubewells greater than one per 5 ha with average depth to water level increasing from 3.7 to 7.5 m over 30 years
- One-tenth of the wells go dry in summer
- Farmers' use of plastic tube to convey water has reduced water loss, but basin irrigation still inefficient using twice the standard for North China
- Irrigation is 30% of total farm production costs
- Overexploitation of groundwater resulted in declining profitability because of greater water lift costs and poorer quality water
- Salt content of groundwater increasing soil salinity
- Area facing critical groundwater recharge problem and groundwater use is unsustainable

Source: World Bank, Investments in Shallow Tubewells for Small-Scale Irrigation, Agricultural Investment Sourcebook, 2004, URL: http://www-esd.worldbank.org/ais/index.cfm?Page=mdisp&m=8&p=04 (accessed March 3, 2006).

IRRIGATION WELLS IN USE

The number of irrigation wells in use is large. In the United States, 401,193 irrigation wells were capable of use in 2003 (USDA, 2003), which is 40% more wells than are used for all public water systems supplied by groundwater. Only 16% of the wells in use had meters to check the amount of groundwater used, while 57% had backflow prevention devices to preclude contamination of the wells and their adjacent groundwater. Exhibit 6B.4 has more detailed information on irrigation wells in the United States by Water Resource Area (large river basins).

EXHIBIT 6B.4 IRRIGATION WELLS ON FARMS IN THE UNITED STATES, 2003

United States Water Resource Area	Farms	Wells Capable of Use	Wells Used	Wells with Meters	Wells with Backflow Prevention
WRA 01 New England	830	1,236	1,100	56	424
WRA 02 Mid-Atlantic	2,537	5,137	4,242	354	2,321
WRA 03 South Atlantic-Gulf	10,970	25,652	24,193	4,165	15,533
WRA 04 Great Lakes	2,221	5,673	5,338	381	3,559
WRA 05 Ohio	1,007	2,294	2,155	54	1,338
WRA 06 Tennessee	215	286	257	(D)	81
WRA 07 Upper Mississippi	3,476	10,278	10,023	1,584	7,463
WRA 08 Lower Mississippi	6,879	56,976	53,235	1,011	15,970
WRA 09 Souris-Red-Rainy	358	1,692	1,618	590	1,308
WRA 10 Missouri	20,893	89,393	86,654	18,399	47,281
WRA 11 Arkansas-White-Red	7,504	45,416	42,663	11,764	27,448
WRA 12 Texas-Gulf	6,977	49,010	46,483	3,854	35,138
WRA 13 Rio Grande	2,287	8,591	7,553	2,245	3,442
WRA 14 Upper Colorado	471	533	532	(D)	12
WRA 15 Lower Colorado	1,331	5,834	4,953	708	2,696
WRA 16 Great Basin	1,387	4,029	3,684	772	2,005
WRA 17 Pacific Northwest	9,424	21,137	20,192	3,697	11,766
WRA 18 California	25,871	67,835	64,615	11,560	38,104
WRA 19 Alaska	54	62	57	5	19
WRA 20 Hawaii	84	129	127	32	47
Total	104,778	401,193	379,674	61,259	215,955

Source: U.S. Department of Agriculture, Economic Research Service (USDA), Census of Agriculture; Table 10; Irrigation Wells on Farms: 2003 and 1998, Washington, DC, 2003, URL: http://151.121.3.33/Census_of_Agriculture/2002/FRIS/tables/fris03_14.pdf (accessed February 19, 2007).

LAND AREA IRRIGATED

Land area irrigated by groundwater is significant and increasing, as previously noted. Of agricultural lands irrigated, "India has over 50% of its area irrigated from groundwater, followed by the United States (43%), China (27%), and Pakistan (25%). That percentage can reach as much as 80% in developed countries with mild climate (Germany) and in arid countries (Saudi Arabia, Libya)" (UNFAO, 2003c).

IRRIGATION WELL COSTS

Irrigation well costs depend on a range of factors, including the principal factors of size and type of well, depth, and geology. A shallow PVC tube well of 45 m in South Asia may cost $240, exclusive of the pump, which adds $580 to the total well cost (2004 US$). By comparison, a 15 m well in India of bamboo construction costs $67 and of cast iron construction costs $150 (2004 US$) (Meghalaya, 2004), while in the United States (Minnesota), a well of the same depth costs $1661 for PVC casing and screen and $3020 for steel materials (Job and Gabanski, 1988 (1987 US$ adjusted to 2004)) (see Chapter 4 for other well costs). Shallow wells installed in Africa with truck-mounted drill rigs cost approximately $2250 per well (2006 US$) (LWC, 2006). Figures for irrigation wells elsewhere in the world range from $2,260 to $56,500 per well (adjusted to 2005 US$, based on 1989 estimates from Foster, 1989, p. 59), depending on depth, construction, size, and application.

For shallow irrigation wells, the pump may be the largest cost. Navarro indicates that for a typical irrigation well and distribution system in Spain, the proportion of costs is (Navarro, 1989, p. 50):

Well bore and casing: 18%
Pump: 28%
Distribution system: 54%.

The pump costs for shallow irrigation wells may be the largest capital cost as suggested in Exhibit 6B.5, which describes the costs of irrigation tubewells in India as well as financing those costs for the well. Exhibit 6B.5 gives example costs for shallow bamboo wells, which are about one-third the cost of wells of iron construction. This exhibit also shows that farmer income from irrigation increases by over 450%, a real business and financial incentive to irrigate. Exhibit 6B.5 compares an example of bamboo and iron tubewell costs. In the case cited, an iron-cased well cost more than two times a bamboo well. Exhibit 6B.6 gives a component breakdown of a typical tubewell.

EXHIBIT 6B.5 EXAMPLE OF IRRIGATION TUBEWELL COSTS AND FINANCING

Unit costs for a shallow tubewell (STW) and pumpset in the state of Meghalaya, India, are estimated to be (2004 Indian) Rs. 36200.00 (2004 US$ 788). [June 30, 2004 currency conversion: 1 Indian Rupee = 0.02177 US$] The cost of a pumphouse is optional.

1. Unit Costs of Shallow Tubewells with Pumpset in Meghalaya State, India, 2004

a. Well

Diameter (mm): 100
Depth (m): 45
Type: PVC
Plain pipe: 33 m
Slotted pipe: 12 m
Spacing (if more than one well): 150 m

		Rate		Amount	
Item	**Quantity (m)**	**Rs.**	**US$**	**Rs.**	**US$**
Drilling charges[a]	50	100/m	2.18/m	5000.00	108.85
Plain pipe (100 mm)	33	100/m	2.18/m	3300.00	71.84
Slotted pipe (100 mm)	12	150/m	3.27/m	1800.00	39.19
Pipe accessories and bail plug				400.00	8.70

(*continued*)

EXHIBIT 6B.5 (continued) EXAMPLE OF IRRIGATION TUBEWELL COSTS AND FINANCING

Contingency at the rate of 5%	525.00	11.43
Subtotal – well	11,025.00	240.01
b. Pumpset[b]		
Pit for installation of centrifugal pump: 6.5 m depth		
(RCC rings 1.25 m dia. × 0.6 m height) at the rate of Rs. 800 per m depth	5,200.00	113.20
Diesel pumping system	18,000.00	391.86
Belt, shaft, and pulley arrangement	2,000.00	43.54
Subtotal – pumpset	25,200.00	584.60
Total – tubewell with pumpset	36,225.00	788.61
c. Optional Structure		
Pump house (2.5 m × 2.5 m × 2.1 m) @ Rs. 10,000 per unit	10,000.00	217.70

[a] Includes development and gravel packing charges.

[b] Details of pumpset are (1) centrifugal pump, discharge (Q) = 2.5 L/s, total head = 16.5 m, efficiency = 50%; (2) HP of diesel engine = 5; and (3) suction pipe = 100 mm, delivery pipe = 100 mm, reflex valve = 100 mm.

2. Project Financing of 300 Shallow Tubewells in Meghalaya, India

Financial Institution

Reserve Bank of India/National Bank for Agriculture and Rural Development (RBI/NABARD)

Interest Rate for Ultimate Borrowers

Banks are free to decide the rate of interest within the overall RBI/NABARD guidelines. Project assumption is an interest rate of 12% per annum.

Repayment Period

The repayment period of loan for pumpset may be 9 years, and for shallow tubewells, 11–13 years excluding 11 months grace period. For the purpose of the project, 12 years was used.

Security

Banks may follow the RBI guidelines.

Pre- and Postdevelopment Incomes

The annual incremental income for individual farmers having a 2 ha farm is estimated to be Rs. 12,480/year (2004 US$ 272).

Projected Cash Flows

The discounted cash flows result in the following values:

Discount rate: 1.98%
Internal rate of return: 33%
Benefit–cost ratio: 1.78

(*continued*)

Installment Payment

Using the standard amortization equation, we can calculate a farmer's installment payment for a shallow tubewell and pumpset. The amortization formula is $C = rB/[1 - (1 + r)^{-n}]$, where

C = annual installment (the amount to be calculated),
r = annual interest rate (12%),
B = initial loan balance (Rs. 36,225), and
n = number of years to repay the loan (12 years).

For the program, C, the annual installment, was calculated to be Rs. 5551 (2004 US$ 121). Please see Table 6.6.

Table 6.7a and b compares estimated farmer income before and after installing tubewells for irrigation during the growing seasons.

TABLE 6.6
Discounted Cash Flow Analysis of Tubewells in Meghalaya

		End of Year					
Specific Item	**Units**	**Year 0**	**Years 1–8 (Repeats Each Year)**	**Year 9**	**Years 10–12 (Repeats Each Year)**	**Years 13–14 (Repeats Each Year)**	**Year 15**
Investment cost	Rs.	36,200					
Other cost (replacement)	Rs.			20,000			
Total cost	Rs.	36,200	0	20,000	0	0	0
Incremental income	Rs.		12,480	12,480	12,480	12,480	12,480
Other income (salvage)	Rs.			2,000			9,215
Total benefit	Rs.	0	12,480	14,480	12,480	12,480	21,695
Net benefit	Rs.	−36,200	12,480	−5,520	12,480	12,480	21,695
NPV of total costs	Rs.	41,885.25					
NPV of total benefits	Rs.	74,676.18					
Benefit cost ratio		1.78					
NPV of net benefits	Rs.	32,790.93					
Internal rate return	%	33%					
Equal annual repayment	Rs.		5,551.81	5,551.81	5,551.81		
Discount rate			2.25	−0.99	2.25		
Average discount rate		1.98					

TABLE 6.7
Pre- and Postdevelopment Cropping Pattern and Income – Analysis for 1 ha Farm Plots

(a) Predevelopment

Season	Crops	Area (in ha)	Yield (Qtl per ha)	Total Yield (Qtl)	Price (in Rs per Qtl)	Gross Income (in Rs.)	Cost (per ha)	Cost Incurred	Net Income (in Rs.)
Kharif (April–June)	Paddy	0.50	14.00	7.00	550.00	3,850.00	6,340.00	3,170.00	680.00
	Maize	0.50	8.00	4.00	500.00	2,000.00	2,630.00	1,315.00	685.00
								Total	1,365.00
Rabi (October–February)	Gram	0.75	5.50	4.13	1,200.00	4,950.00	4,350.00	3,262.50	1,687.50
	Mustard	0.25	5.20	1.30	1,200.00	1,560.00	4,300.00	1,075.00	485.00
								Total	2,172.5
								Rounded	2,173
Total Predevelopment income									3,538.00

(b) Postdevelopment

Season	Crops	Area (in ha)	Yield (Qtl per ha)	Total Yield (Qtl)	Price (in Rs. per Qtl)	Gross Income (in Rs.)	Cost (per ha)	Cost Incurred	Net Income (in Rs.)
Kharif (April–June)	Paddy	0.75	20.00	15.00	550.00	8,250.00	6,340.00	4,755.00	3,495.00
	Maize	0.25	11.00	2.75	500.00	1,375.00	2,630.00	657.50	717.50
								Total	4,212.50
								Rounded	4,213
Rabi (October–February)	Wheat	0.50	21.00	10.50	700.00	7,350.00	8,720.00	4,360.00	2,990.00
	Gram	0.25	7.50	1.88	1,400.00	2,625.00	4,350.00	1,087.50	1,537.50
	Potato	0.25	260.00	65.00	150.00	9,750.00	9,890.00	2,472.50	7,277.50
								Total	11,805.00
Total Postdevelopment income									16,018.00

Postdevelopment income of Rs. 3,538 less predevelopment income of Rs. 16,018 equals incremental income of Rs. 12,480 (2004 US$ 272, rounded).

Source: Meghalaya, India (Government of), Shallow Tubewells with Pumpsets in Alluvial Areas, 2004, URL: http://www.megcooperation.gov.in/ (accessed March 4, 2006).

A range of tubewell costs extracted from the literature shows expenditures affected by technology and location:

- In India, a 12.2 m tubewell with 7.5 submersible pump and pump house cost 2000 Rs. 259,000 (2000 US$ 5,880) (Dhillon, 2000).
- A shallow tubewell in Bihar state, India, cost 2006 Rs. 28,864 (2006 US$ 653) (Bihar, 2006).
- Tubewell irrigation in South Asia cost 2000 US$ 800–1000/ha (IWMI, 2000).

EXHIBIT 6B.6 BAMBOO TUBEWELL COST EXAMPLE

Bamboo hollowed out is used as a wellbore in South Asia. This example gives the capital cost for a 15 m well, with a comparison to an iron-cased well.

Average Cost/Boring (in 2004 Rs.)

	Bamboo Casing	Iron Casing
Iron sheet	258	—
Bamboo	87	—
Coconut coir	308	—
Iron wire	18	—
Blank pipe/iron pipe	1,120	3,020
Bottle tee/socket	120	230
Check valve	115	195
Iron nails	5	5
Socket and nipple	89	—
Sand and gravel	15	—
Gunny bag	10	—
Socket	—	120
Strainer	—	2,000
Labor charge	525	385
Transport of material	55	130
Miscellaneous	50	65
Overhead/supervision	275	620
Total	3,041	6,770

Annual Cost of Bamboo Tubewell Investment and Operation (2004)

	Annual Cost	
Category	**Rs./Year**	**US$/Year**
Fixed cost		
Interest	188.35	4.16
Depreciation	1,071.42	23.66
Operating cost		
Fuel	20,108.50	444.00
Lubricant	402.17	8.88
Pump maintenance	74.66	1.65
Engine maintenance	75.00	1.66
Operator wage	589.00	13.01
Miscellaneous	186.20	4.11
Total	22,695.50	501.12

Assumes:
- Interest on fixed cost at 12%
- 8 hp diesel engine uses fuel at rate of 1.25 L/h
- Pump life of 15 years

Note: In 2004, 1 Indian rupee = 0.02208 US$.

(*continued*)

EXHIBIT 6B.6 (continued) BAMBOO TUBEWELL COST EXAMPLE

In 2004 in Bihar state, India, 7,946,435 ha were cropped with 61% of that land being irrigated, half with tubewells. The state estimated that 43% of the available groundwater was in use, with the remainder to be planned for further irrigation use. The India Planning Commission calculated a benefit–cost ratio for bamboo tubewells of 2.22, comparing the return from irrigation pumping to the cost of pumping. Farmer income rose 29% after using bamboo tubewells for irrigated agriculture. While bamboo tubewells appear to have cost advantages for poor farmers, some disadvantages include unreliability of electric power in some locations, high cost of metal components and motors, high cost of fuel, potential for vandalism, and rotting in 5 years (IPC, 2004).

In terms of land area supplied with irrigation water from shallow tubewells, a study in India found that a STW could irrigate an area of 4.0–6.0 ha, but on average served 2.3 ha. The principal factors for this small land size being serviced are that the individual farmers own small farms and the distribution systems are inefficient (Kansakar, 2001).

Source: India (Government of) Planning Commission (IPC), *Economics of Bamboo Boring: A Study of the North-East Region of Bihar*, IPC, New Delhi, India, 2004, 78.

Well operation requires substantial energy. In some states of India, the electricity used to produce groundwater equals half the power consumed in those states (Brown, 2004, p. 104). However, treadle pump technology (a simple foot pump) provides much lower pumping cost with a cost of 2000 US$ 100–120/ha in South Asia (IWMI, 2000).

IRRIGATION METHODS AND COSTS

Irrigating crops was practiced by the Mesopotamians and Egyptians (WHI, 2005) thousands of years ago using canals to carry water to fields to ensure adequate food supply. Irrigation method refers to the technique of delivering water to the fields being irrigated. The type of irrigation method has a significant effect on the volume of water used. Flood irrigation is still one of the most widely used methods of irrigating crops because it is simple and inexpensive (USGS, 2005). Other principal methods include spray, center pivot, and drip irrigation.

Factors in selecting an irrigation method include (UNFAO, 2006)

Natural conditions (soil type, slope, climate, water availability, water quality)
Type of crop
Type of technology
Previous experience with irrigation
Required labor inputs
Costs and benefits

Exhibit 6B.7 reviews the major irrigation methods in use. Some have variations that have evolved as a result of technological advances, scarcity of water, and type of crop.

EXHIBIT 6B.7 MAJOR IRRIGATION METHODS

Method	Description	Suitability
Flood	*Flood*: The application of irrigation water where the entire or nearly all the surface of the soil is covered by ponded water (USGS, 2005). Several types of flood irrigation methods are used:	
	Furrow: A type of flood irrigation in which partial surface flooding is used with clean-tilled crops where water is applied in furrows or rows made to carry water to irrigate the crop. The crop is usually grown on the ridges between the furrows (USGS, 2005).	*Furrow* irrigation may be applied to many crops, particularly crops planted in rows that would be damaged by water covering the plant's stem or crown. Application is best for uniform flat or gentle slopes and most soil types. Not recommended for coarse sands because of high evaporation rates (UNFAO, 2006).
	Basin: A type of flood irrigation in which water is diverted to basins created by embankments with the basins next to each other (UNFAO, 2006).	*Basin* irrigation may be applied to many field crops. Most suitable for crops which can tolerate roots being submerged in water, such as paddy rice. Flat land surface provides ease in constructing flood basins, which can also be constructed on steeper grades by building a series of terraces. Soil suitability for this method is dependent on the type of crop (UNFAO, 2006).
	Border: A type of flood irrigation with borders of long flat strips of land, separated by shallow embankments to guide the water flow through the field (UNFAO, 2006).	*Border* irrigation is most appropriate to larger farms with long field distances facilitating machine operations. Border distances may be up to 800 m or longer and 3–30 m wide. This method is not as applicable to smaller farms relying on hand labor or cultivation using animals. It is best for closely spaced crops such as pasture or alfalfa (UNFAO, 2006).
Note on a cost of flood irrigation: A significant quantity of water from flood irrigation methods may be lost due to runoff along the sides of the fields. This loss can be minimized by capturing the runoff in ponds and pumping it back up to the front of the field for reuse (USGS, 2005).		
Sprinkler/spray	*Sprinkler*: A planned irrigation system in which water is applied by means of perforated pipes or nozzles operated under pressure so as to form a spray pattern (USGS, 2005). A hand-moved portable sprinkler system is moved by uncoupling and picking up the pipes manually, requiring no special tools. A solid set sprinkler system covers the complete field with pipes and sprinklers in such a manner that all of the field can be irrigated without moving any of the system. A side-roll (linear) sprinkler has the supply pipe typically mounted on wheels with the pipe as the axle with the system being moved across the field by rotating the pipeline by engine power.	*Sprinkler* irrigation is applicable to most row, field, and tree crops with water sprayed over or under the crop canopy. This method should not be used with delicate crops (e.g., lettuce) since water drops can damage them. The method can be used on farmable slopes, is most appropriate for sandy soils having rapid infiltration, but can be adapted to a range of soil types (UNFAO, 2006).

(*continued*)

EXHIBIT 6B.7 (continued) MAJOR IRRIGATION METHODS

Method	Description	Suitability
	Traveling Gun: A variation of a sprinkler irrigation system consisting of a single large nozzle that rotates and is self-propelled. The name refers to the fact that the base is on wheels and can be moved by the irrigator or affixed to a guide wire (USGS, 2005).	
	Center Pivot: An automated rotating sprinkler pipe or boom supported by towers on wheels, supplies water to the sprinkler heads or nozzles, as a radius from the center of the field to be irrigated. Water is applied at a uniform rate by progressive increase of nozzle size from the pivot to the end of the line. The depth of water applied is determined by the rate of travel of the system. Single units are ordinarily about 381–396 m long and irrigate about a 52.6 ha circular area (USGS, 2005).	*Center pivot* irrigation has been proven to be very flexible and can accommodate a variety of crops, soils, and topography with minimal modification (USDA, 2001).
Drip	A *drip irrigation* system applies water directly to the root zone of plants by means of applicators (orifices, emitters, porous tubing, perforated pipe, etc.) operated under low pressure with the applicators being placed either on or below the surface of the ground (USGS, 2005).	*Drip irrigation* is best applied to row crops (vegetables, soft fruit), tree, and vine crops. Owing to high installation costs, this method is used for high-value crops. The method can be applied to any farmable slope following the land contour and to a range of soil types with application rates based on soil type. Drip irrigation is suitable for most soils with application rates varying on soil type: low rates on clay soils; high rates on sandy soils to provide sufficient lateral wetting (UNFAO, 2006).

Sources:

1. Abstracted from United Nations Food and Agricultural Organization (UNFAO), Irrigation Water Management: Irrigation Methods, 2006, URL: http://www.fao.org/docrep/S8684E/s8684e00.htm (accessed March 11, 2006).
2. U.S. Department of Agriculture, Economic Research Service (USDA), *Irrigation and Water Use: Glossary; Irrigation Systems and Land Treatment Practices; Onfarm Water Conveyance Systems*, USDA, Washington, DC, 2001, URL: http://www.ers.usda.gov/briefing/WaterUse/Questions/glossary.htm (accessed March 24, 2006).
3. United States Geological Survey (USGS), *Irrigation Techniques and Some Irrigation Methods, USGS, Reston, VA, 2005, URL:* http://ga.water.usgs.gov/edu/irmethods.html (accessed March 11, 2006).

The differences in capital costs of various irrigation methods reflect the relative reliance on technology to bring water to fields (Figure 6.4). Exhibit 6B.8 indicates that in the United States (Kansas), on a unit basis, flood irrigation has the lowest capital cost ($2898/ha) and drip irrigation, the highest ($4826/ha) (2004 US$) (Dumler and Rogers, 2004, p. 3). In this case, drip irrigation cost 66% more to install than a flood irrigation system. As will be seen here, however, drip irrigation

FIGURE 6.4 Center pivot irrigation in Delaware.

EXHIBIT 6B.8 CAPITAL COSTS OF IRRIGATION METHODS IN THE HIGH PLAINS OF THE UNITED STATES

Area in Hectares	**50.6**		**62.7**		**62.7**	
Irrigation Method	**Center Pivot**		**Flood**		**Drip System**	
	/ha	**/Area**	**/ha**	**/Area**	**/ha**	**/Area**
Expense Category (2004 US$)						
Land	$1,779	$90,000	$1,866	$117,025	$1,866	117,025
Well	521	26,400	420	26,400	420	26,400
Pump and gearhead	427	21,600	343	21,600	343	21,600
Power unit	198	10,000	161	10,000	161	10,000
Water meter	20	1,000	15	1,000	15	1,000
At well connectors	15	750	12	750	12	750
System (pipe and related items)	*1127*	57,053	*82*	5,125	*2009*	125,952
Total per irrigated hectare	$4,087		$2,899		$4,826	
Pivot corner adjustment[a]		$15,600				
Total per 62.7 ha		$222,403		$181,900		$302,727
Total per hectare		$3,546		$2,899		$4,826

Source: Dumler, T.J. and Rogers, D.H., *Irrigation Capital Requirements and Energy Costs*, Kansas State University Agricultural Experiment Station and Cooperative Extension Service, MF-836, 2004, 4.

[a] Adjustment is for value of nonirrigated corners associated with center pivot systems (12.14 ha × $1,285 per ha).

systems are considerably more efficient in terms of water use, which translates into lower operating costs for pumping water. In using overhead sprinkler irrigation, often employed with groundwater sources, irrigation efficiency may improve from 65% to 80% by converting from a high-energy to a low-energy system (Brown, 2001). Using a low-energy precision sprinkler system may increase the efficiency to 90% or more (Brown, 2001). Investigations of drip irrigation systems in a range of countries indicate potential water reductions of 30%–70% (Brown, 2001).

While drip irrigation systems are more expensive, because of the labor needed for them, they can be easily adapted and profitably applied to the small farm sizes of South and East Asia. Drip systems developed specifically for farms can have a payback period of 1 year (Brown, 2001).

IRRIGATION EFFICIENCY

The efficiency of irrigation systems is defined as the percent of water used beneficially for irrigation purposes. Clearly, as evapotranspiration is part of the hydrologic cycle, it is also an essential process for crop growth and must be factored into water demand for irrigation. Water may be lost through distribution lines, and this is a cost to the farmer since it represents water pumped that does not reach the field. Exhibit 6B.9 indicates the efficiency of a range of irrigation methods along with defining the key terms in describing irrigation water use efficiency. Critically, the efficiency of any irrigation method depends on how the delivery system is operated and maintained, and, therefore, each system has a range of efficiency, which may be quite wide. Flood irrigation methods typically use more water than spray or drip irrigation. Drip irrigation can reduce water use by farmers from 30% to 60% or more (UNFAO, 2003a,b), as suggested in the exhibit. Such reductions in actual water use translate into substantial operating cost savings to farmers. The land area being irrigated to which farmers have applied more efficient irrigation methods is under 1% in India and China to only as much as 4% in the United States (Brown, 2004, p. 113). Arabiyat et al. (1999) modeled low-energy precision irrigation (drip) systems combined with biotechnology and some crop conversion for the area of Texas (United States) supplied by the Ogallala (High Plains) Aquifer and found significant returns to agriculture and reductions in depletion of the aquifer through more efficient irrigation.

IRRIGATION USE OF GROUNDWATER

Irrigation use of groundwater increased significantly over the latter part of the twentieth century (Brown, 2004, p. 100). In the United States, irrigation use of groundwater has expanded, while that of surface water has declined, even though surface water use is larger. Exhibit 6B.10 provides an overview of groundwater use around the world for countries which had available data.

IRRIGATION PRODUCTIVITY

Irrigated agriculture can produce more crop than rain-fed farming. "While only 20% of the world's farmland is irrigated, it produces 40% of our food supply. The highest yields obtained from irrigation are more than double the highest yields from rain-fed agriculture – even low-input irrigation is more productive than high-input rain-fed farming" (UNFAO, 2003a). In the example from Meghalaya state, India, in Exhibit 6B.5, on a per land unit basis using groundwater tubewells, estimated farmer production increased 43% for paddy (rice) and 38% for maize.

A further consideration of the productivity of the range of irrigation techniques is useful. Flood irrigation loses considerable water to evaporation. Current studies have shown that flood irrigation, typically applied to rice production, in certain conditions allowing for lower quantity of application under periodic rather than continuous flooding, may provide the same level of production (Brown, 2001). Investigations of irrigated cotton production comparing flood and drip systems demonstrated water use reductions from 43% to 79%, while yields improved by 25%–40% (Polak and Sivanappan,

EXHIBIT 6B.9 IRRIGATION WATER USE EFFICIENCY

Water Conveyance Efficiency (Ec): The percentage of source water that reaches the field:

Ec = 100 (Wf/Ws)
Wf = water delivered to field
Ws = water diverted from source

Water Application Efficiency (Ea): The percentage of water delivered to the field is used by the crop:

Ea = 100 (Wc/Wf)
Wc = water available for use by the crop
Wf = water delivered to field

Irrigation Efficiency (Ei): The percentage of water delivered to the field that is used beneficially:

Ei = 100 (Wb/Wf)
Wb = water used beneficially
Wf = water delivered to field

Irrigation efficiency is more broadly defined than water application efficiency in that irrigation water may have more uses than simply satisfying crop water requirements. Other beneficial uses could include salt leaching, crop cooling, pesticide, or fertilizer applications, or frost protection. Most irrigation systems are single purpose, that is to supply water for crop use, which allows water application efficiency and irrigation efficiency to be used interchangeably.

TABLE 6.8
Range of Application Efficiencies for Various Irrigation Systems

System Type	Application Efficiency Range[a] (as a Percent, %)
Flood/surface irrigation	
Furrow	50–90
Basin	60–95
Border	60–90
Sprinkler irrigation	
Handmove	65–80
Traveling gun	60–70
Center pivot and linear	70–95
Solid set	70–85
Drip/microirrigation	
Point source emitter	75–95
Line source emitter	70–95

Source: Abstracted from Rogers, D.H. et al., *Efficiencies and Water Losses of Irrigation Systems*, Kansas State University, Research and Extension, 2006, URL: http://www.oznet.ksu.edu/library/ageng2/mf2243.pdf (accessed March 3, 2006).

[a] Efficiencies can be much lower due to poor design or management. These values are intended for general system type comparisons and should not be used for specific systems.

EXHIBIT 6B.10 GROUNDWATER USED FOR IRRIGATION IN SELECTED COUNTRIES

Country	Groundwater Used for Irrigation (million m³/year)	Country	Groundwater Used for Irrigation (million m³/year)
India	243,800	Morocco	3156
United States	79,183	Egypt	1816
China	73,404	Peru	1793
Pakistan	51,204	South Africa	1724
Iran	32,080	Tunisia	1665
Mexico	16,524	Malaysia	776
Saudi Arabia	14,698	Indonesia	692
Bangladesh	8,694	Jordan	407
Nepal	3,444	Mali	40

Source: United Nations Food and Agricultural Organization (UNFAO), *The Irrigation Challenge. Issues Paper 4*, Rome, Italy, September 2003c, URL: http://www.fao.org/documents/show_cdr.asp?url_file=/DOCREP/006/Y4854E/y4854e04.htm (accessed April 8, 2006).

2006). Precision delivery of water to plants through drip irrigation systems has raised yields from 20% to 90% in some applications (Brown, 2001).

Growing more water-efficient crops can also improve irrigation productivity. Wheat, in most situations, provides 50% more grain per unit of water than rice does. At least one country (Egypt) sets controls on rice cultivation because of this factor (Brown, 2001).

Relative to extensification of farmland, irrigation has contributed to expanding food production. From the mid-1960s to the mid-1980s, the expansion of land utilizing irrigation "contributed over 50% of the increase in global food production" (Sundquist, 2006).

Globally, "irrigated cropland is about 3.6 times more productive per unit-area than nonirrigated cropland. The dollar-value of production of a given area of irrigated cropland is about 6.6 times that of nonirrigated cropland and about 36 times that of rangelands. The ratio of the productivity of irrigated land to that of nonirrigated cropland is thus larger in dollar-terms (6.6) than in weight-terms (3.6), reflecting the fact that irrigated croplands must be used to grow higher-value crops to justify the high capital costs involved" (Sundquist, 2006).

Financing Irrigation Systems

Irrigation systems, including wells, intakes, pumps, and distribution works, are expensive infrastructure and may require financing, including for small systems. Worldwide, lending for irrigation systems declined from a high of nearly US$ 2.3 billion to about US$ 0.8 billion (assumed 2000 US$) (UNESCO, 2003a, p. 194). The United Nations cites a range of typical irrigation system costs from US$ 1,000 to 10,000/ha with extremes of as high as US$ 25,000/ha, depending on location and type of system (UNESCO, 2003a, p. 206).

Financing may take different forms, including loans to individuals or groups of individuals in water user associations or subsidies through lower rates or tax credits from governments. Most governments provide assistance to water use in agriculture, but the focus should be on the effectiveness of the investment (INPIM, 2004). Financial institutions may not understand approaches of lending to water user associations, complicating the development of local capacity of small farm irrigators for financially sustainable irrigation projects (INPIM, 2004). For example in a financing program in India, small farmers who could have benefitted from group projects were largely not served by a subsidized rate-financing program, even when subsidies were increased for water user associations (Kansakar, 2001). Often, reporting on investments for irrigation projects does not account for the contribution made directly by the farmer, such as land improvement (e.g., grading or terracing) or on-farm irrigation, which may be as much as 50% of the total investment (UNESCO, 2003a, p. 206).

A range of approaches to financing irrigation of agricultural lands exists. For example, in India, the government-sponsored Agriculture Development Bank (ADB) had provided subsidized rates for well drilling up to certain limits and incentive subsidy rates for water user associations. The ADB has also eliminated these subsidies. In Nepal, farmers installed private shallow tubewells without government assistance to irrigate 21% of groundwater-irrigated area of 11,400 ha in 1995, indicating that the private benefit offset the risk (Kansakar, 2001). In the United States, the federal government provides a depletion allowance, which farmers, who irrigate with groundwater, use to reduce their taxable income.

Approaches cited to improve financing to small farm irrigators who often are reliant on groundwater, especially those in water user associations (WUA), include (INPIM, 2004)

- Linking government subsidies to local resource mobilization, through eligibility criteria, matching formulas, and other mechanisms.
- Offering grants on a competitive basis, subject to eligibility criteria for local contributions and WUA performance in maintaining irrigation infrastructure.
- Creating an irrigation investment fund.
- Encouraging incremental irrigation system improvements rather than large investments.
- Establishing reserve funds to cover future costs of maintenance of the shared infrastructure.

ECOSYSTEM EFFECTS OF IRRIGATION

Irrigated agriculture, while improving crop yields and production, can have significant effects on the ecosystem and groundwater specifically, if not conducted in a manner compatible with the soils and climate of the area. Major impacts of large withdrawals of groundwater for irrigation include

- Waterlogging and salination of farm lands (UNFAO, 1992; UNFAO, 2003a)
- Depletion of aquifers (Brown, 2004, pp. 99–104)
- Land subsidence (Gelt, 1992)
- Accumulation of salts, fertilizer, and pesticide residuals in groundwater (UNFAO, 1992; WSLH, 2003; Barbash and Resek, 1996)

These effects may result in damage to the ecosystem, lost agricultural production, and costs and reduced income to affected property owners.

Waterlogging and Salination

Waterlogging results from overwatering land during irrigation and lack of adequate drainage (UNESCO, 2003a, p. 219). Salination is the accumulation of salts and minerals in agricultural land because of excess water applied during irrigation. As water on the fields evaporates, dissolved salts from the soil accumulate on the surface, creating a crust. High soil salinity reduces seed germination, and limits crop production (UNFAO, 1992) and land value, affecting 75 million hectares of agricultural land worldwide (WAF, 2006). Twenty (20) percent of irrigated lands are affected by salination (about 2% of rain-fed croplands are similarly affected) (WAF, 2006).

Depletion of Aquifers

Five to eight percent of the irrigated area worldwide relies to some extent on groundwater being overdrafted with this proportion increasing. In the United States, this fraction is 20%–25% (Sundquist, 2006). The effects of overdrafting “tend to be permanent and cumulative” (USDA, 1997a, p. 70).

In the area of Texas (United States) supplied by the Ogallala (High Plains) Aquifer, an estimated 30%–35% of the predevelopment groundwater resource has already been depleted (Arabiyat, 1999). Brown has a descriptive overview of groundwater depletion from irrigation, abstracted in Exhibit 6B.11. Brown notes that the declining groundwater tables are a relatively recent circumstance historically and that the difference between groundwater use and sustainable levels increases each year translating into ever-deeper water tables. This situation threatens not only water supply but also the world's ability to feed itself (UNESCO, 2003a, p. 13; Brown, 2004, p. 117).

Land Subsidence

Land subsidence from groundwater exploitation is a significant problem in many areas in which the water is used for irrigation (Figure 6.5). The problem is so extensive worldwide that the United Nations is establishing a database to track it (UNESCO, 2003b). Subsidence can be a substantial cost to farmers affected by it, resulting in (Gelt, 1992)

- Broken irrigation ditches and canals from fissures and crevices
- Alteration of the slope of previously level fields, disrupting the flow of irrigation water, and causing fields to be releveled
- Collapse of well casing necessitating expensive repairs and replacement of wells with large irrigation wells costing from \$100,000 to \$200,000
- Land taken out of production and abandoned because of developing fissures
- Crevices are hazards to people, livestock, and wildlife

Subsidence can affect extensive areas as evidenced in Arizona, United States. In the area around Stanfield, Arizona, 1101 km^2 of land have subsided by nearly 3.7 m (Gelt, 1992). This is an area nearly half the size of the Grand Duchy of Luxembourg or the U.S. state of Rhode Island.

EXHIBIT 6B.11 GROUNDWATER DEPLETION FROM IRRIGATION USE IN SELECTED COUNTRIES

Country	Description
Mexico	Aquifers are being depleted in northern and semiarid regions from irrigation.
United States	Overpumping the Ogallala aquifer in the High Plains has caused wells to go dry resulting in a decrease of irrigated area by 24%.
Saudi Arabia	Rapid depletion of large fossil aquifer for irrigation has caused wheat production to drop 61% from 1992 to 2004.
Yemen	With one of the world's fastest growing populations, its water table is falling 2 or more meters per year.
Israel	Coastal and mountain aquifers shared with the Palestinians are being depleted resulting in a ban on irrigated wheat and tightening of water supplies.
India	Most states have falling water tables and thousands of wells go dry each year from extensive irrigation.
China	Water tables are declining across northern China, with dry irrigation wells causing a significant decrease in wheat production.

Source: Brown, L.R., *Outgrowing the Earth: The Food Security Challenge in an Age of Falling Water Tables and Rising Temperatures*, Earth Policy Institute, W.W. Norton & Company, New York, 2004, 101–102.

FIGURE 6.5 Fissure has been attributed to land subsidence related to groundwater pumping in the Antelope Valley area, California. (Source: U.S. Geological Survey)

Accumulation of Salts, Nutrients, and Pesticides Residuals

Salts dissolved from the soil, as well as residual nutrients and pesticides may be carried by irrigation water percolating below the soil zone. Exhibit 6B.12 shows that world fertilizer use increased over 4.5 times from 29 million metric tons in 1961 to 129 million metric tons in 2002, principally representing nitrogen, phosphates, potash, and sulfur products applied in agriculture (WI, 2002; IFA,

EXHIBIT 6B.12 WORLD FERTILIZER USE

	Mil. Metric		Mil. Metric		Mil. Metric		Mil. Metric		Mil. Metric
Year	**Tons**	**Year**	**Tons**	**Year**	**Tons**	**Year**	**Tons**	**Year**	**Tons**
		1970	62.6	1980	106.1	1990	125.2	2000	122.5
1961	28.1	1971	66.2	1981	104.3	1991	122.5	2001	125.2
1962	30.8	1972	71.7	1982	104.3	1992	113.4	2002	128.8
1963	34.5	1973	77.1	1983	114.3	1993	108.9		
1964	38.1	1974	74.4	1984	118.8	1994	110.7		
1965	42.6	1975	82.6	1985	117.0	1995	117.9		
1966	47.2	1976	86.2	1986	120.7	1996	122.5		
1967	50.8	1977	91.6	1987	126.1	1997	124.3		
1968	54.4	1978	98.9	1988	131.5	1998	125.2		
1969	57.2	1979	101.6	1989	129.7	1999	127.0		

Source: Worldwatch Institute (WI), State of the World 2005, Trends and Facts, Cultivating Food Security, 2005, URL: www.worldwatch.org/features/security/tf/10 (accessed April 19, 2006). With permission.

EXHIBIT 6B.13 WORLD PESTICIDE USE, 2001

	World Market (Million kg of Active Ingredient)	U.S. Market (Million kg of Active Ingredient)
Herbicides	848	251
Insecticides	559	48
Fungicides	215	33
Other	666	214
Total	2288	546

Source: Fishel, F.M., *Pesticide Use Trends in the U.S.: Global Comparison. PI-143*, Pesticide Information Office, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL, 2007, URL: http://edis.ifas.ufl.edu/pdffiles/PI/PI18000.pdf (access March 19, 2009).

2006). Exhibit 6B.13 indicates that world pesticide use was 2,449,400 kilograms of active ingredient in 2000 (Fishel, 2007). These salts and residuals can pose health hazards to people as well as wildlife when consumed from the "return flow" groundwater from wells in shallow aquifers and from affected wetlands. This polluted groundwater also can pollute streams to which it discharges (UNFAO, 1992). "Pesticides not taken up by plants, adsorbed by soils or broken down by sunlight, soil organisms, or chemical reactions may ultimately reach groundwater sources of drinking water. This will depend upon the nature of the soil, depth to groundwater, chemical properties of the pesticide, and the amount and timing of precipitation or irrigation in an area. Usually the faster a pesticide moves through the ground, as with sandy soils and heavy rainfall or irrigation, the less filtration or breakdown" (WSLH, 2003). Soil permeability and organic-matter content are the primary factors affecting migration of pesticide residues through soil to groundwater (Barbash and Resek, 1996, p. 274).

Monitoring studies of nutrients and pesticides in groundwater show occurrence of these chemicals across regions. In a study of over 1400 wells of varying depths across the United States from 1993 to 1995, nearly 50% of the wells less than 30.48 m had nitrate concentrations exceeding the 10 mg/L drinking water health standard, especially in areas of high nitrogen input, well-drained soil, and less extensive woodland relative to cropland (Nolan et al., 1998). Shallow wells (less than 15 m in depth) screened in unconsolidated aquifers in areas of irrigated crops are nearly twice as likely to be contaminated with pesticide residues than shallow wells in nonirrigated areas (Barbash and Resek, 1996, p. 245). Obtaining representative results in monitoring should be done with caution, which could affect monitoring costs and extrapolation of those results for economic analysis and decision making, since the soil texture around monitored wells may not be the same as in the recharge zone, from where the contaminated water originated (Barbash and Resek, 1996, p. 245, citing Hallberg, 1995). Field-monitoring studies of pesticides in groundwater in Canada and the United States found their occurrence in the broad ranges of 4.5%–100% in monitoring wells, 18%–43% in irrigation wells, 2.5%–33.6% in domestic supply wells, 6.4%–94% in public water supply wells (Barbash and Resek, 1996, pp. 294–295).

Some pesticides and their breakdown products are known carcinogens and high levels of certain nutrients, such as nitrate, have acute health effects (see Part 1 of Chapter 6; also, USDA, 1987, p. 21). A partial list of pesticides found in groundwater under cropland is listed in Exhibit 6B.14. In the groundwaters of North America, monitoring studies have detected more than 160 pesticides and transformation products (chemicals resulting from degradation of pesticides) (Barbash and Resek, 1996, pp. 162–171), and many of these have also been detected in groundwaters of Europe (Barbash

EXHIBIT 6B.14 A PARTIAL LIST OF PESTICIDES FOUND IN GROUNDWATERS UNDER CROPLAND IN THE UNITED STATES WITH HIGHEST OCCURRING PESTICIDES INDICATED WITH PERCENT OF DETECTION FREQUENCY

Atrazine (28%)	Tebuthiuran	Terbacil	Napropamide
Desethylatrazine (24%)	Alachlor	Carbaryl	Pebulate
Simazine (11%)	Cyanazine	Diazinon	Pendimethalin
Prometon (10%)	Diethylanline	Alpha-HCH	Pronamide
Metachlor (6%)	Dieldrin	DCPA	Propanil
Metribuzin (2%)	Carbofuran	Ethelfluralin	Trifluralin
	EPTC	Linuron	

Source: U.S. Geological Survey (USGS), The Quality of Our Nation's Waters; Pesticides in the Nation's Streams and Ground Water, 1992–2001, USGS Circular 1291, 2000, 172.

and Resek, 1996, pp. 101–103). Nitrate from fertilizer and pesticides are not always detected coincidently in groundwater and, therefore, "may impose different costs on society" (USDA, 1987, pp. v, 30–31). In the United States, the Department of Agriculture estimated that over 19 million people on private wells and 53 million people on public water systems had some risk of exposure to agricultural chemicals in their drinking water (USDA, 1987, pp. 17–20). A partial of list of potential effects of groundwater contaminated by agricultural chemicals, which contribute to costs to individuals and society that are difficult to estimate, include (USDA, 1897, p. 21)

- Livestock poisoning and health problems from nitrate/nitrite
- Decreased crop quality or quantity from salts in fertilizers
- Methemoglobinemia (infant death and illness) from nitrate/nitrite
- Cancer from pesticides
- Miscellaneous health (cardiovascular, blood, kidney, liver, nervous system, and other) problems from pesticides and nitrate
- Damage to vegetation, waterfowl, and aquatic life in groundwater recharge areas and in surface water contaminated by groundwater discharge.

BEST MANAGEMENT PRACTICES

Implementing best management practices (BMP) for irrigated fields can mitigate some of the problems noted in the previous section on ecosystem effects. Many of the BMPs are similar for nonirrigated agriculture. Applying BMPs have a cost associated with them, but may be less costly than dealing with the other effects. These BMPs include but are not limited to (Seelig and Scherer, 1996; NCAES, 1988):

- Scheduling irrigation appropriately by accounting for the soil moisture and crop water use.
- Timing water applications to avoid water movement beyond the rooting zone.
- Adjusting water application amounts to meet varying crop demands at different growth stages.
- Applying irrigation water uniformly and accurately.
- Using the least amount of water possible to apply chemicals.
- When injecting chemicals into an irrigation system, using chemigation equipment protects the water supply.

- Calibrating the chemigation unit with each use to ensure accurate application of chemicals.
- Using a secondary containment structure where pesticides are stored near the irrigation well when chemigation is practiced.
- Using close-growing crops such as grass or small grains as cover strips to catch runoff and retain pesticides.

Best management practices focused on conditions with limited or restricted water supply for irrigation can still provide yields that could be attractive to farmers. Recognizing that the amount of water moves through the plant and is transpired directly, Schneekloth et al. (2001) show that depending on soil type, climatic conditions, crop prices, and production costs, even with reduced amounts of irrigation, yield may be profitable. For example, the following irrigation–yield relationships may result in the High Plains of the United States, assuming an aslit loam soil, average rainfall, and center pivot sprinkler irrigation (Schneekloth et al., 2001):

- Continuous corn – production increases by 50% with 5.1 cm of irrigation, doubles with 10.2 cm, and levels off at 3.5 times dryland production at about 52.4 cm.
- Soybean – production increases more than double with 5.1 cm of irrigation, nearly triples with 10.2 cm, and reaches 3.5 times dryland production at 15.2–20.3 cm.
- Winter wheat after soybean – production doubles with 5.1 cm and levels off at about 2.5 times dryland production with 15.2 cm of irrigation water.

In a constrained water situation, and assuming year 2000 prices, Schneekloth et al. (2001) show that winter wheat at 10.2 cm/unit area and soybean at 15.2 cm/unit area have higher net returns than that of corn at similar levels of irrigation, respectively.

Since the cost of BMPs varies based on the objective (e.g., reduce groundwater use, mitigate fertilizer and pesticide use), the soil type, climate, area of application, technology, and other factors, little general cost information is available. However, governments have provided some limited economic incentives to encourage farmers to use BMPs. These include tax credits (limited by amount), loans at low rates and over short time periods (1–10 years) for installation, and land rentals and payments for leaving land fallow. See for example, programs listed under Virginia (United States) Cooperative Extension (2000).

Management practices to mitigate the creation and use of saline groundwater include (UNFAO, 1992)

- Growing suitably tolerant crops
- Managing seedbeds and grading fields to minimize local accumulations of salinity
- Managing soils under saline water irrigation
- Operating delivery systems efficiently
- Irrigating efficiently
- Monitoring soil water and salinity and assessing adequacy of leaching and drainage

While installing drain tiles can reduce waterlogging, their expense relative to increased yield must be considered. Subsurface drainage systems may cost as much as 2001 US$ 988/ha, cited in one report (assuming clay soils and tile alignment on 15.24 m centers) (MAES, 2001). Corn yield in the same study indicated an average increase in yield of 314 kg/ha in Missouri, United States. Tile drainage systems may have a useful life of 50 years (UIUC, 2004). Draining soils in wetlands reduces wildlife habitat and ecological diversity. The United States has converted approximately 48.6 million hectares from wetlands to other uses through drainage and land-filling, mostly through agricultural drainage (USGS, 1997). Twenty-five percent of the farmland in the United States and Canada are drained (UMES, 2001).

Studies of pesticide effects on groundwater from different irrigation methods found that (Barbash and Resek, 1996, pp. 243–245)

- Sprinkler irrigation had the least downward movement of water and atrazine because of evaporative loss.
- Furrow irrigation produced the largest downward migration of water and atrazine.
- Drip irrigation had very slight downward movement of water and atrazine.
- Increased rates of water application result in pesticide residue concentrations being reduced in the soil and enhancing their downward transport particularly in more permeable soils.
- The studies did not evaluate the occurrence of transformation products of the pesticides.

INSTITUTIONAL FACTORS

Irrigated agriculture is one of the most heavily subsidized sectors by governments internationally (UNFAO, 2003a). Because of the growing demand for food, irrigated agriculture is a key target for government policy. As noted previously, countries such as India have worked to develop lending institutions that will support the small farmer. Tubewells have received government subsidies since the early 1980s in developing countries, such as Bangladesh and Nepal (Hartmann and Boyce, 1981; Kansakar, 2001). However, education of these farmers may also be critical. When groundwater levels decline to a point that small and marginal farmers do not have the economic capability to apply their pumping technology, poorer farmers are penalized and their lands may be removed from production (UNESCO, 2003a, p. 209). This circumstance suggests a real issue with economic assumptions that include perfect knowledge of an intermediate commodity, in this case, an input or factor of production, to use it in a way that maximizes welfare. The use of the groundwater resource in this case is one not of efficiency but of equity and having equal access to participate in the economy. Scale of use and distribution of the resource are both significant considerations, then. Thus, institutions should be developed to ensure that even small farmers understand the effect they have on the water table and how best to manage their water use relative to the larger aquifer use.

Sustainable agriculture (using groundwater or any water source) “requires the farmer to be more knowledgeable about his farm’s ecosystem and recognize its place in his life and society’s” (Guru and Horne, 2000, p. 28). Irrigated biofuels production is displacing land and energy for food production in some countries and this outcome may not be well understood in those places. More fully informed people at all levels of water use should be able to improve their water practices, and in the process provide a better balance in meeting the objectives of those uses (e.g., see UNESCO, 2003a, pp. 347–366). However, while international organizations are focused on consumption of groundwater for irrigation and its positive contribution to feeding the world, nations may desire to consider policies that address the open access to groundwaters that are being depleted and establish institutions, investing in social capital that will foster community organizations to promote access to and share critical information (Markandya et al., 2002, p. 25), that will help manage the resource for the long term and for the greatest benefit of human kind.

MACROECONOMIC CONSIDERATIONS

The agricultural sectors of developed countries contribute about 3% to their GDP and provide less than 5% of total employment. In Nepal, an example of a less developed country, nearly 40% of its gross domestic product and 80% of the employment are derived from the agricultural sector (Kansakar, 2001). Thus, government policies encouraging irrigation have a significant and positive effect on the economy, and potentially a large number of people experience a direct benefit from improved income and greater food availability. Because of the large effect of irrigated agriculture on national economy, losses of wetlands, polluted groundwaters, and depleted aquifers should be accounted as consumed assets in the net national product with the value of the remaining natural capital potentially being increased (Markandya et al., 2002, pp. 66–68). Policies supporting sustainable management of natural resources may address balancing ecosystem, economic, and social objectives relative to people’s needs (Markandya et al., 2002, p. 15). Macroeconomic policies could even include financial incentives for large users to use water efficiently, reducing current demand, and provide adequately for the needs of the future, ensuring sufficient supply (Markandya et al., 2002).

Macroeconomic policies regarding irrigation affect national income derived from agricultural trade. While water is expensive to transport relative to its value, it can be "traded" as input to food commodities. Water deficient countries can import "virtual water" by trading their products for food grown with other countries' water resources (UNESCO, 2003a, pp. 202–203). In effect, the exporting countries are shipping a portion of the production from their water use in irrigation, as well as a part of their natural endowment of rain-fed agricultural output, to external consumers. Both of these acts – exporting and importing of irrigatively grown food – are sufficiently important to be addressed at the highest levels of governments to ensure that their citizens acknowledge that each group (exporters and importers of virtual water) may be depleting national resources whose possession is comparatively advantageous at present. Depending on how much groundwater is coming out of storage from fossil aquifers receiving little recharge, the exporting countries may be trading away their own future food security, unless they focus policy development on efficient irrigation methods to mitigate derived demand for irrigation water and replenishment of diminished groundwater stocks and other alternative water sources, such as recycled water. By establishing such macroeconomic policies influencing efficient water use and future supply, countries exporting virtual water through food trade provide for their internal needs as well as generating income from global food demand.

SUMMARY

Use of groundwater is expanding for irrigated agriculture in response to increased demand for food. Groundwater provides an important input factor to the much-needed food in countries, which have growing populations. This activity is depleting aquifers around the world and potentially contributing to other negative effects on the supporting ecosystem. On a per capita basis, less land is being used and more fertilizer is being applied. Pesticide use has also grown and can be applied through irrigation systems, allowing residuals to reach groundwater. Small farmers have benefitted from low-cost technology to irrigate their crops with groundwater. However, small farmers may not understand appropriate groundwater management actions individually and collectively to ensure their investment in tubewells will provide for their sustenance over time and not just for a few growing seasons. Nations should consider developing their institutions to better inform farmers of the appropriate techniques to manage groundwater for irrigation and thereby maximize its capacity for the near and long terms. Since irrigated agriculture is expanding with positive effect on food supply as well as increasing biofuels production, national governments should consider developing balanced policies that account for ecosystem and economic dynamics. Furthermore, such policies could address national income from virtual water trading through food exports to water deficient countries, while promoting efficient irrigation water use to provide for future water supply in response to direct water need and derived demand from food consumption.

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7 Groundwater Quality Treatment and Waste Disposal

Groundwater containing contaminants may need treatment before use to meet its expected quality. Or, for continued use, groundwater may need special protection from wastes disposed in the subsurface "sink." Treatment is a "last resort" if other groundwater protection barriers are unsuccessful. Furthermore, groundwater may have naturally occurring constituents at high concentrations that minimize its use for certain purposes, such as drinking or industrial processes and irrigation. It may also have anthropogenic contaminants that make it unhealthful. These contaminants may reach the subsurface environment through leaching and percolating to groundwater, or may have been consciously and actively introduced underground, because the current economics of waste disposal indicate that this is the least-expensive disposal repository. In any case, groundwater may need to be treated before use, in particular, if no alternative sources of water with the expected or preferred amount and quality were available at the same or reasonable cost.

The major sources of groundwater quality problems in the United States (USEPA, 1996) and the European Union (EEA, 1999; indicated by*) include:

- Underground storage tanks
- Pesticide applications*
- Septic tanks
- Fertilizer applications*
- Landfills*
- Surface impoundments
- Aboveground storage tanks
- Land application
- Animal feedlots
- Shallow injection wells
- Mining and mine drainage
- Road salting
- Urban runoff
- Transportation of materials
- Pipelines and sewer lines
- Saltwater intrusion*
- Waste tailings
- Irrigation practices*
- Deep injection wells

Contaminants emanating from this range of sources may include: petroleum compounds, nitrate, chloride, metals, organic chemicals and pesticides, inorganic chemicals and pesticides, bacteria, viruses, protozoa, radionuclides.

The cost of treatment in economic terms translates into "abatement costs" for contaminants that can be compared with the damages from contaminants affecting the water quality, to determine the efficient result for a community or nation to obtain the quality of groundwater which it desires. Abatement costs may include not only the costs of purchasing, installing, and operating a particular technology at a treatment plant but also purchase and transaction costs of permits for land and construction, chemical use for treatment, and waste disposal from removal of the contaminants.

The cost of underground disposal should include the damages to the subterranean ecosystem or the future users of this subsurface zone.

First, groundwater treatment for immediate drinking water use is examined. Second, the best practices in the watershed are considered as important alternatives to water treatment for some contaminants. Subsequently, groundwater remediation for future use is discussed. Finally, an examination of groundwater and the subsurface as a "waste sink" is presented, which suggests increasing pressure and competition for the subterranean environment.

TREATMENT FOR DRINKING WATER

Household Treatment

Treatment of water to facilitate its use as household or community drinking water is the subject of much research and industry. Groundwater treatment can be done at the individual household level for highly mineralized water, referred to as "hard" water. Other processes can remove a range of contaminants at both the household and the community levels through a central water treatment plant. Household treatment of groundwater for drinking can range from water softening of highly mineralized water at the "point of entry" (POE) to a house, to more sophisticated "point of use" (POU) devices at faucets or on countertops for inorganic, organic, and radiologic constituents. In the United States, approximately 43 million people are served by individual household (domestic) water systems (USGS, 2008). Exhibit 7.1 provides information on a range of household water

EXHIBIT 7.1 HOUSEHOLD GROUNDWATER TREATMENT OPTIONS

Individual well-owner water treatment options (based on treatment objectives) (Water System Council, 2002)

1. Disinfection: treatment of the well to remove bacteria
2. Point of use: treatment device under a sink or on a countertop to filter contaminants from water used for drinking or cooking
3. Point of entry: treatment located where water is supplied to water pipes within a home
4. Multiple treatments: a combination of treatments to remove contaminants for all household purposes, often near the water storage tank

Specific types of treatment (Water System Council, 2002)

Activated carbon filter
A highly porous, absorbent material, usually made from coal or wood, is used to filter contaminants, such as excess chlorine, and to reduce soluble materials, such as organic chemicals and radon.

Activated carbon block filter
Activated carbon is molded into a cartridge filter with a much greater absorption capacity and speed than a granular carbon filter. Specialized media may be added to target specific contaminants.

Chlorination
Chlorination is added to water to destroy unhealthy bacteria and control microorganisms and to remove dissolved iron, manganese, and hydrogen sulfide. Shock chlorination of a private well uses concentrations of chlorine that are 100–400 times the amount found in municipal water supplies. The highly chlorinated water is held in the pipes for 12–24 h before it is flushed out and the system is ready for use again. (Also see *Disinfection*.)

EXHIBIT 7.1 (continued) HOUSEHOLD GROUNDWATER TREATMENT OPTIONS

Coagulation

Chemicals neutralize the electrical charges of fine particles (contaminants) in water, making it easier to remove the particles by settling, skimming, draining, or filtering.

Disinfection

Chemicals such as chlorine, iodine, ozone, or hydrogen peroxide are used to destroy disease-producing bacteria without eliminating all the microorganisms. The treatment may also involve steps such as distillation, microfiltration, ultrafiltration, boiling, or the use of ultraviolet light. (Also see *Chlorination.*)

Distillation

Organic and inorganic contaminants are separated from water through a combination of evaporation, cooling, and condensation.

Electrodialysis

An electric current is used to remove ions (an atom or group of atoms) from water through a semipermeable membrane (which allows select molecules to pass and blocks others).

Water softening to remove calcium and magnesium (Hardness)

The hardness of groundwater is measured by the amount calcium carbonate in it, which is reported as parts per million (ppm). Water is typically considered as hard when it has more than 120 ppm of calcium carbonate (Driscoll, 1986, p. 829).

Water softening can be accomplished by either lime softening or ion exchange.

Lime softening—applies lime to precipitate calcium carbonate and/or magnesium hydroxide from water, which after settling, is filtered out.

Ion exchange—can remove calcium and magnesium as well as ions of iron, manganese, strontium, and other inorganic constituents by passing water through a resin medium to be exchanged for sodium ions. The medium needs to be regenerated regularly and can last for many years. (Driscoll, 1986, pp. 802–803).

Oxidizing filter

A type of filter that changes the balanced state of the dissolved molecules, making them insoluble and, therefore, filterable.

Oxidizing chemical injection

Agents such as oxygen, ozone, chlorine, or peroxide are used to attract electrons, and thus, they can be removed from water.

Reverse osmosis

Pressure is used to force the water molecules through a semipermeable membrane (it allows select molecules to pass and blocks others). The pressure forces the molecules to flow in the reverse direction, moving from a concentrated solution to a dilute solution, thus, diluting the molecules in water. To make these devices effective, water may need to be pretreated with chlorine or oxidation.

More comprehensive descriptions of these and other treatment technologies are available from the following sources:

1. Water System Council, *Drinking Water Treatments* (Factsheet) (May 2002), URL:http://www.watersystemscouncil.org/upload/wellcare/in serttreat.pdf (accessed March 9, 2003).
2. Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1986, 1089.
3. U.S. Environmental Protection Agency (USEPA), http://epa.gov/ogwdw/safewater/standard (accessed April 5, 2003).

EXHIBIT 7.2 HOUSEHOLD TREATMENT OPTIONS FOR SOME SELECTED CONTAMINANTS

Contaminant	Treatment Options
Sand, silt, rust	Point of use: Cartridge filter, distillation
Algae	Point of use: Chlorination, ultraviolet light, reverse osmosis, distillation
Bacteria	Disinfection: Chlorination, ultraviolet light, ozone treatments, reverse osmosis
Viruses	Point of use: Ultraviolet light, distillation
Arsenic	Point of use: Reverse osmosis, distillation or cartridge-type removal devices
Calcium	Point of use: Ion exchange, reverse osmosis, distillation
Chromium	Point of use: Coagulation, ion exchange, reverse osmosis or lime softening
Iron	Multiple: Shock chlorination, water heater modification, activated carbon filter, oxidizing filter or oxidizing chemical injection (Testing should be done to determine the appropriate treatment for the conditions)
Nitrate	Point of use: Ion exchange, electrodialysis or reverse osmosis
Radium	Point of use: Ion exchange or reverse osmosis
Radon	Point of use: Aeration devices or granular activated carbon (GAC) filters
Sulfur and manganese	Point of use: Sulfur—distillation, reverse osmosis or ion exchange; manganese and hydrogen sulfide—shock chlorination, water heater modification, activated carbon filter, oxidizing filter or oxidizing chemical injection
TCE (trichloro ethylene)	Point of use: Packed tower aeration (GAC filter with reverse osmosis, distillation)
Benzene and other petroleum solvents	Point of use: GAC filters, reverse osmosis, distillation
Pesticides	Point of use: GAC filters, reverse osmosis, distillation

Sources:
1. Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1986, 827. With permission.
2. Water Systems Council, *Drinking Water Treatments* (Factsheet) (May 2002), URL: www.watersystemscouncil.org/upload/wellcare/insert treat.pdf (accessed March 9, 2003). With permission.

treatment options. Exhibit 7.2 matches the potential contaminants with the treatment options, while Exhibit 7.3 presents the costs for some treatment types. Importantly, the most economically efficient choice from among the options should be based on the objective being addressed: for example, choosing a faucet-mounted device for water used for drinking and cooking does not address any concerns about the dermal or inhalation exposure to the water. The costs can range from \$25 to \$12,000 (2002\$US) depending on the contaminant(s) of concern and the type of exposure that is to be controlled by the treatment option. The options that provide the most comprehensive response to a range of potential contaminants and address all major exposure pathways may be more expensive: installing a new well or connecting to a public water supply.

CENTRAL WATER SUPPLY TREATMENT

Central water supply treatment providing water to a community of known and accepted quality has a long history. Wells and springs serving many families and entire communities had existed in ancient times. Documented treatment of water dates back to Sanskrit and Egyptian times, of 2000–1400 BC (Baker, 1949). In the United States, in 2005, nearly 90 million people (32% of all people served by community water systems) received their groundwater supply from approximately 40,000 central

EXHIBIT 7.3 HOUSEHOLD TREATMENT COSTS

Treatment System	Estimated Costs[a] (1996$US, Unless Otherwise Noted)
Water softening	$500–$1500
Activated carbon filtration	Faucet-mounted: $25–$50
	Under the sink: $50–$300
	Whole house: $500–$800
Distillation	Countertop: $300–$350
	Automatic: $600–$800
Reverse osmosis	Single tap: $400–$500
Bottled water	$7–$15 per week for a family of four persons (operation and maintenance costs only)
New well	Steel-cased well with submersible pump, average depth 217 ft: $6250
	PVC-cased well with submersible pump, average depth 217 ft: $5700 (2000$US)
Public water system	$12,000 or more per household hookup depending on the distance to water main, along with monthly water use payments

Sources:

1. Water Systems Council, *Drinking Water Treatments* (Factsheet) (May 2002), URL: http://www.watersystemscouncil.org/upload/wellcare/insert treat.pdf (accessed March 9, 2003). With permission.
2. Robillard, et al., *Water Softening Factsheet* 141, Pennsylvania State University, Cooperative Extension Service, 2003, URL: http://www.age.psu.edu/extension/factsheets/F%20141.pdf (accessed March 8, 2003).
3. National Ground Water Association, Consumer price index annual adjustments for household well drilling costs, 2003, January 1992 to January 2001 (unpublished).

[a] Estimated costs are one-time capital costs and do not include operation and maintenance costs, unless otherwise noted.

water systems (USEPA, 2006a), and the quality of the water from these systems in the United States has been regulated under the Safe Drinking Water Act standards described in Chapter 6. Significantly, many European countries have very large populations relying on central water systems supplied by groundwater: in Austria, Denmark, France, Germany, Hungary, Luxembourg, Netherlands, and Switzerland, 99%, 99%, 62%, 72%, 96%, 69%, 68%, and 83% of the centrally supplied population use groundwater sources, respectively. These centrally supplied systems typically treat the groundwater to ensure that it meets the national and local standards for drinking water quality.

Removal of contaminants can be accomplished through the use of different treatment processes applied to the larger volumes in municipal systems. In the United States, central water systems serve communities ranging in size from 25 to millions of people. In many very small central water systems, historically, groundwater has been considered clean enough that it is often untreated after leaving the wellhead. With the more frequent incidences of microorganisms contaminating groundwater, treatment may be needed more often. Larger groundwater systems typically provide some level of treatment depending on the contaminants needing to be removed and their concentration. Exhibit 7.4 provides an overview of the treatment steps of a central water treatment system. It also gives the costs of several treatment plants.

Treatment costs for central water systems may vary based on the volume of water and the contaminants to be treated. Exhibit 7.5 displays the range of costs for capital and operation and maintenance costs for a range of specific treatment technologies at the central water treatment plants.

Economies of scale can be clearly observed from the results reported in Exhibits 7.5 and 7.6 for different technologies. For example, for the Chlorination technology, the capital costs for the 38 m^3/day plant are $3857/1000 m^3, while the capital costs for a 37,854 m^3/day plant are $1849/1000 m^3. Likewise, the scale is significant for the operation and maintenance costs of these technologies: for the 38 m^3/day

EXHIBIT 7.4 CENTRAL WATER TREATMENT PLANTS AND COSTS

Principal Water Purification Stages at Central Water Treatment Plants:

1. Primary treatment—Pumping from aquifers or rivers, and screening for larger objects (stones, paper, large organic matter)
2. Secondary treatment—Removal of fine solids and most of the contaminants through coagulation, flocculation, filtration, and membranes
3. Tertiary treatment—Polishing, pH adjustment, carbon treatment to remove taste and odors, disinfection, and temporary storage sufficient for disinfectants to be effective.

Selected Water Treatment Plant Costs:

Municipality	Treatment Identified	Plant Size (m^3/Day)	Cost (for Year Listed)	Year	Cost per m^3/Day
Tampa Bay, Florida	Reverse osmosis	12,870	US$8,100,000	2007	US$629
Seward, Nebraska	Reverse osmosis	15,140	US$4,300,000	2004	US$284
Longmont, Colorado	Secondary	113,560	US$40,200,000	2006	US$354
Clearwater, Florida	—	227,125	US$79,000,000	2000	US$347
Salt Lake City, Utah	Conventional	264,980	US$135,000,000	2003	US$509

Sources:

1. American Water Works Association (AWWA), *Water Treatment Plant Design*, 4th edn, McGraw-Hill Professional, New York, 2004, 896.
2. Water Industry News (WIN), Tampa Bay water board approves contract for regional surface water treatment plant to US Filter/CDM, 2000, URL: http://waterindustry.org/New%20Projects/usfilter-1.htm (accessed February 11, 2007).
3. Salt Lake City (Utah) Department of Public Utilities (SLC), *Water District Breaks Ground for New Water Treatment Plant*, 2003, URL: http://www.ci.slc.ut.us/Utilities/NewsEvents/news2003/news6132003.htm (accessed February 11, 2007).
4. Olasson Associates, *Seward Water Treatment Plant*, 2004, URL: http://www.oaconsulting.com/project_indi.asp?ID=107 (accessed February 11, 2007).
5. Black Veatch Holding Company (B&V), *Colorado Water Treatment Plant Earns Design-Build Award*, 2006, URL: http://www.bv.com/wcm/press_release/10232006_5201.aspx (accessed February 11, 2007).
6. Clearwater Public Utilities, Florida (CPUFL), Reservoir No. 1 Project, 2007, URL: http://www.clearwater-fl.com/gov/depts/pwa/public_utils/projects/reservoir_1/FAQwtp.asp (accessed February 11, 2007).

plant, the cost is \$31.70/m^3 and for the 37,854 m^3/day plant, the cost is \$0.07/m^3. While calculating the abatement costs, the economies of scale must be considered when relating the cost estimates to the population affected by contaminants.

Exhibit 7.5 also shows that some technologies may be more expensive than others to treat the same contaminant. Coagulation-assisted microfiltration is the most expensive technology at all design flows. On the other hand, enhanced lime softening is the least expensive at smaller design flows, whereas chlorination is the least expensive at larger flows. This circumstance points out the reason that it is important not to use only one technology, but rather let the economics of the situation indicate, in part, the appropriate technology, with everything else being equal.

EXHIBIT 7.5 COSTS OF DIFFERENT TREATMENT TECHNOLOGIES AT CENTRAL WATER TREATMENT PLANTS

The U.S. Environmental Protection Agency carried out an extensive review of costs associated with a range of central treatment plants that could provide arsenic removal. The costs were derived from industry sources and modeling. While these treatments could also remove other contaminants, the costs presented do not consider treatment of other contaminants and do not include land purchase costs. However, the costs include housing the treatment plant, waste disposal, and permit. The results of this examination are presented as follows

Costs Based on Water Treatment Plant Flow (Plant Size) in Cubic Meters/Day (m^3/day)[a] with Estimated Costs in Thousands (1000s) of 1995$US

Selected Technology	38		380		3785		37854	
	Capital[b]	O&M[c]	Capital[b]	O&M[c]	Capital[b]	O&M[c]	Capital[b]	O&M[c]
Chlorination	$14.6	$1.2	$14.6	$1.6	$14.6	$5.8	$70.0	$27.6
Enhanced coagulation/filtration	$7.2	$0.3	$8.6	$1.0	$18.1	$14.0	$864.7	$157.4
Coagulation-assisted microfiltration	$140.0	$22.0	$460.0	$33.0	$2,100.0	$66.0	$11,400.0	$200.0
Enhanced lime softening	$7.9	$0.6	$12.9	$3.4	$33.1	$30.2	$1,235.0	$275.6
Activated alumina	$15.4	$6.0	$61.7	$23.0	$430.5	$200.5	$4,213.1	$1,917.1
Anion exchange	$23.0	$5.8	$68.6	$12.1	$349.6	$52.2	$3,228.4	$390.0
Greensand filtration	$12.0	$8.0	$90.0	$13.3	$590.0	$66.3	$4,000.0	$596.6

[a] The relationship between the treatment plant flow and the approximate population served is: 38 m^3/day: 100 persons; 380 m^3/day: 1000 persons; 3785 m^3/day: 10,000 persons; 37,854 m^3/day: 100,000 persons.

[b] Capital costs are one-time treatment plant costs estimated for design flow and technology specified.

[c] O&M are operation and maintenance costs on annual basis estimated for average flow.

Definitions

Chlorination: Chlorine is added to water to remove dissolved arsenic, as well as other inorganic contaminants such as iron, manganese, and hydrogen sulfide, and to destroy unhealthy bacteria and control microorganisms.

Enhanced coagulation/filtration: A treatment process that changes the physical or chemical properties of the colloidal or suspended solids, and enhances agglomeration that subsequently to allow the solids to settle out or be filtered out. This process is enhanced by increasing coagulant dosage, reducing pH, or both.

Coagulation-assisted microfiltration: It is a coagulation treatment process, except that microfiltration is used rather than a conventional gravity filter. Removal can be adjusted by changing the pH.

Enhanced lime softening: This is the typical lime softening process (applying lime to the water), except for adjusting the pH to greater than 10.5 by increasing the lime dosage and possibly increasing the soda ash dosage.

(*continued*)

EXHIBIT 7.5 (continued) COSTS OF DIFFERENT TREATMENT TECHNOLOGIES AT CENTRAL WATER TREATMENT PLANTS

Activated alumina: This is a physical/chemical process in which ions in the water are sorbed to the oxidized activated alumina in a bed.

Anion exchange: A physical/chemical process in which contaminant ions in the water are exchanged for ions from a solid resin media.

Greensand filtration: Glauconite sand is coated with manganese oxides, and exchange ions with the contaminant ions, as water passes through the sand.

Source: U.S. Environmental Protection Agency (USEPA), *Technologies and Costs for Removal of Arsenic from Drinking Water*, EPA-815-R-00-010/December 1999, URL: www.epa.gov/ogwdw/ars/treatments_and _costs.pdf (accessed April 5, 2003).

DESALINATION

As noted in Chapter 3, groundwater brines, in the past, have had economic value in the production of chemicals. As climate change may lead to less precipitation in some areas resulting in less groundwater recharge, other potential water sources may be utilized, such as brackish and saline groundwater, in water-short areas (Walha et al., 2007). For example, the Texas (USA) Water Development Board identified 3.3 trillion cubic meters of brackish groundwater in Texas that could be desalinated (TWDB, 2008). As many as 60% of the community water systems in the United States overlie saline and brackish groundwaters. Typically, brackish waters contain 1000–10,000 ppm of total dissolved solids, with saline waters having greater than 10,000 ppm of total dissolved solids. As treatment technology, such as reverse osmosis or nanofiltration, has demonstrated lower costs for the production of high-quality water by removing drinking water contaminants effectively, brackish groundwater is now attractive as an alternative water source.

Desalination of seawater and saline and brackish waters in deep geological formations is considered as the "backstop" technology for water supply (Frederick, 1995), except in places that must actively seek other water sources. The technologies for desalination include reverse osmosis, mechanical vapor compression, distillation, nanofiltration, and electrodialysis reversal. The cost ranges for these technologies are from \$0.45 to \$6.56/m^3 for seawater and \$0.25 to \$0.70/m^3 for brackish water from underground sources. (Younos, 2005) Since the 1960s to 2005, seawater desalination costs have fallen by 60% (Frederick, 1995; Younos, 2005). This cost, when compared with the average drinking water supply costs of water systems to consumers in the United States in 2004 was US\$0.53/m^3 (USEPA, 2004a), and in 2005, in Germany, it was \$0.68/m^3; in the United Kingdom, \$0.46/m^3; and in France, \$0.42/m^3 (UKTI, 2007). For seawater desalination by reverse osmosis, capital and power costs are 37% and 44%, respectively, while for brackish water, they are 54% and 11%, respectively (see Exhibit 7.6). Clearly, power costs are a major factor in removal of a greater concentration of dissolved solids in seawater (Younos, 2005). Desalination is discussed further under "Waste Releases to Groundwater and the Subsurface Environment" in conjunction with waste concentrate disposal from treatment of brackish and saline groundwater.

Large capacity plants do exhibit economies of scale (Younos, 2005). Capital costs for seawater desalination plants using reverse osmosis in early planning stages in 2003 in California ranged from \$70 million for a 45,425 m^3/day plant proposed for Los Angeles, to \$272 million for a 189,270 m^3/day plant proposed for San Diego. Thus, the economies of scale can be given as \$1541/m^3/day capacity at the smaller Los Angeles plant versus \$1437/m^3/day capacity at the larger San Diego plant.

EXHIBIT 7.6 CENTRAL TREATMENT PLANT AND PRODUCTION COSTS FOR DESALINATION BY REVERSE OSMOSIS

	Brackish Water (US\$ per m^3)	Seawater (US\$ per m^3)
Production costs		
Average	\$0.34	\$1.16
Range	\$0.18–\$0.70	\$0.45–\$6.56
Cost factors	(Percent of costs)	(Percent of costs)
Fixed costs	54	37
Electric power	11	44
Other O&M	35	19

Source: Younos, T., *J. Contemp. Water Res. Edu.,* 132, 39, 2005.

The drinking water production costs for the two proposed facilities were \$0.83/m^3 and \$0.72/m^3 for the Los Angeles and San Diego plants, respectively (CEC, 2003).

SUBSURFACE DISPOSAL AND RELEASE OF DRINKING WATER TREATMENT RESIDUALS

Drinking waters often contain naturally occurring constituents, which, in high concentrations, may be harmful to human health, as indicated in Chapter 6. Removal of these high concentrations results in wastes that must be disposed. Constituents that may be treated include: arsenic, barium, cadmium, chromium, lead, mercury, silver, radium-226 (Ra-226), radium-228 (Ra-228), gross alpha particle activity, beta particle and photon radioactivity, and uranium. For solid wastes, disposal options include solid-waste landfill, hazardous-waste landfill, or radioactive-waste landfill, depending on the concentration of the constituents and whether they are radioactive. For liquid wastes, disposal options are discharge to waters (which requires a governmental permit), release to a waste treatment plant (which requires a permit), and injection into deep geologic strata (also requiring a permit) (USEPA, 2006a,b,c). Thus, residual disposal is an additional cost apart from the treatment of drinking water.

WATERSHED MANAGEMENT

Watershed or river basin management has emerged as an integrative approach to improve water quality with regard to ground and surface waters, their interaction, and managing contaminant sources affecting both, within the catchment. As groundwater and surface water are hydrologically connected in a watershed and contaminants can flow from one resource to the other, it is necessary to examine the dynamic relationships among these factors. Nonpoint sources of contaminants, sources not originating from one defined point, and/or spread across large areas, should be considered for their variable inputs of contaminants. Furthermore, whether one source is more cost-effectively controlled should be carefully evaluated before major expense is incurred in controlling any particular source of contaminants in a watershed. This approach will require modeling of the water flow and contaminant movement in the watershed. Likewise, the most effective management of point sources needs to be considered in the same way, as well as between the point and non-point sources. Research is needed to begin to better understand the tradeoffs among the contaminant control strategies in watersheds and the most economically efficient approaches. Sometimes, the laws that recognize only a portion of the water resource, either groundwater or surface water, obstruct a comprehensive evaluation and efficiently targeted water quality improvement actions from occurring.

WASTE RELEASES TO GROUNDWATER AND THE SUBSURFACE ENVIRONMENT

Groundwater and its subsurface environment receive many types of waste releases, potentially affecting their quality at a particular site or, if left unaddressed for a long time, even under a large area. As noted previously, billions of pounds of agricultural chemicals and pesticides are applied to the ground each year, some of which percolate through the subsurface to groundwater. The unused portion of these chemicals is a residual waste. Past physical, chemical, and biological wastes that were considered properly disposed in the ground continue to be the sources of contamination to groundwater around the world (Sampat, 2000). Deep injection of wastes is expected to increase, partly in response to concerns about global warming: disposal of both carbon dioxide (CO_2) emissions and desalination wastes. There are numerous small private and local wastewater systems that treat and discharge wastewater to the subsurface and groundwater. These demands, along with the ever increasing demands for groundwater, especially in areas of drought, present an enormous pressure and competition for groundwater and the subsurface—at times in conflict, where the same groundwater may be used for human and animal water supply as well as being a sink for wastes!

ONSITE WASTEWATER DISPOSAL

Many small and individual water systems serve populations whose domestic waste is treated by onsite or near-site septic systems. Exhibit 7.7 describes an onsite wastewater disposal (septic) system in general terms. A typical residential septic system may release 1893 liters per day of sewage, on average, to the subsurface if it is working properly (Lucas, 2007). In the United States as of 2000, approximately 15 million homes have septic systems (USEPA, 2003c; USDOC, 2003; NPR, 2007), of which as many as up to 60% may not work properly, discharging untreated domestic wastewater to the subsurface and groundwater (Lucas, 2007) that is potentially used as a drinking water source.

Properly maintained onsite septic systems may be financially beneficial to homeowners in terms of saving money. Typical maintenance includes a regular inspection and pumping. These maintenance costs are less than the cost of replacing a failed system. Exhibit 7.8 describes the lifecycle costs of a septic system.

UNDERGROUND INJECTION

The underground injection control (UIC) program in the United States was briefly presented in Chapter 3, with the mention that the program is designed to place hazardous wastes into deep geologic zones below the underground sources of drinking water. In both the United States and the European Union, disposal of hazardous substances into groundwater is prohibited. Exhibit 7.9 describes the UIC program in the United States.

Nearly one million shallow injection wells in the form of Class V injection wells exist in the United States alone. Some UIC wells commonly used and permitted by regulation are septic tanks for domestic wastewater and cisterns to collect runoff from roofs. The UIC wells that are not permitted are floor drains in service station bays that allow wastewater containing oils and other chemical products or wastes to enter the subsurface and intersect the water table below, and dry cleaners, as well as septic systems used by smaller commercial operators that dispose chemicals from their production or service processes. In these industries requiring chemical disposal, the chemicals should be treated, recycled, or returned to the manufacturer, if such arrangements can be made. While this would add cost, it protects the community water supply. However, stormwater drains exist extensively for the control of overland flow from storm events and may drain into cisterns (rather than sewer lines) without treatment. These waters, while recharging groundwater, may have contaminants that may not expeditiously be broken down or degraded in the subsurface, and could reach nearby water-supply wells. With greater population densities, there is an increasing

EXHIBIT 7.7 ONSITE WASTEWATER DISPOSAL (SEPTIC) SYSTEM DESCRIPTION

A typical septic system has four main components: a pipe from the home, a septic tank, a drainfield, and the soil. Microbes in the soil digest or remove most of the contaminants from the wastewater before it eventually reaches groundwater.

PIPE FROM THE HOME

All household wastewater exits through a pipe to the septic tank.

SEPTIC TANK

The septic tank is a buried, watertight container typically made of concrete, fiberglass, or polyethylene. It holds the wastewater long enough to allow solids to settle out (forming sludge) and oil and grease to float to the surface (as scum). It also allows partial decomposition of the solid materials. Compartments and a T-shaped outlet in the septic tank prevent the sludge and scum from leaving the tank and traveling into the drainfield area. Screens are also recommended to prevent the solids from entering the drainfield. Newer tanks generally have risers with lids at the ground surface to allow easy location, inspection, and pumping of the tank.

DRAINFIELD

The wastewater exits the septic tank and is discharged into the drainfield for further treatment by the soil. The partially treated wastewater is pushed along into the drainfield for further treatment every time new wastewater enters the tank. If the drainfield is overloaded with too much liquid, it will flood, causing sewage to flow to the ground surface or create backups in plumbing fixtures and prevent treatment of all wastewater. A reserve drainfield, required by many states, is an area suitable for a new drainfield system if the current drainfield fails. This area should be treated with same care as the septic system.

SOIL

Septic tank wastewater flows to the drainfield, where it percolates into the soil, which provides final treatment by removing harmful bacteria, viruses, and nutrients. Suitable soil is necessary for successful wastewater treatment.

Sources:

1. Abstracted from U.S. Environmental Protection Agency (USEPA), *Homeowner's Guide to Septic Systems-Short Version,* 2003c, URL: http://www.nesc.wva.edu/NSFC/pdf/homeowner_guide_long.pdf (accessed February 11, 2007).

need to dispose of stormwater and wastewaters associated with increased use of chemicals in all kinds of products. These waters accumulating nonpoint sources of pollution can have a detrimental effect on groundwater. Users of groundwater near these drains may have to incur the cost of treatment which may be an additional cost that they did not previously have.

The economic significance of the UIC program is that the governments give the right of discharge to waste producers through access to deep geologic formations for the largest volume of controlled waste disposal. The technical expectation is that the disposal permanently remains in the formations below drinking water aquifers. This disposal is modeled and no major incidents of

EXHIBIT 7.8 SEPTIC SYSTEM COSTS

The price of a septic system depends on house size (number of bedrooms), soil suitability, local labor, and material costs. The price may range from $3000 to $75,000. The main costs of a septic system are (1) installation cost, (2) maintenance and repair costs, and (3) replacement costs if the system fails.

Installation Costs

System Type	**Cost**
Standard, gravity-fed tank and trench system	$3,000–$20,000 (depending on the location)
Cluster system (each home with septic tank share common drainfield)	$5,000–$8,000
Engineered systems (mounds, sand/peat filters, aerobic systems, and constructed wetlands)	$6,000–$15,000
Evapotranspiration system	$44,000
Maintenance Costs	
Standard, gravity-fed tank and trench systems with 1–3 years of regular inspection and pumping	$75–$150
Typical annual costs of drainfield or mound system	$30–$500 if replacing pumps in mound systems
Annual costs of constructed wetlands or sand and peat filters	$50–$1,700, depending on the discharge method and monitoring requirements
Annual costs for multiple-household systems	$200–$1500 per household
Lifetime costs over 20 years:	
Individual home systems	
Trenches and mounds	$6,300–$13,000
Alternative treatment systems	$13,500–$32,000
Multi-household systems	
Trench or mound systems	$18,500–$25,000
Alternative treatment systems	$18,000–$44,500

Sources:

1. Abstracted from Laundry Alternative Inc., (LAI), *Septic System Price*, 2005, URL: http://www.laundry-alternative.com/septic_system_price.htm (accessed February 11, 2007)
2. Abstracted from Stony Brook-Millstone Watershed Association (SBMWA), *Funding for Septic Systems*, 2004, URL: http://www.thewatershed.org/images/uploads/Funding%20brochure.pdf (accessed February 11, 2007).

migration of wastes to the aquifers used as public water sources have occurred in the United States. Only the waste concentrations are monitored as they are injected; no monitoring of the formations above the injection zone takes place, except that many water-supply wells exist in shallower formations and the water from them is monitored regularly under the Safe Drinking Water Act and State drinking water laws. Exhibit 7.10 compares the distribution of major toxic substances disposal in the United States between the years 1987 and 2001, including underground injection, as well as other land disposal methods that may use the subsurface as an intentional or unintentional disposal path and sink. Notably, underground injection as a method for disposal of toxic chemicals in the United States appears to be declining, as indicated in Exhibit 7.10. However, nontoxic wastes and small unreportable quantities of toxic wastes that are disposed by underground injection are not accounted for. The U.S. EPA reported that underground injection wells are used to dispose over 34 million cubic meters of hazardous waste every year, and over 7.6 million cubic meters of brine from oil and gas operations every day in the United States (USEPA, 2003d).

EXHIBIT 7.9 THE UNDERGROUND INJECTION CONTROL PROGRAM IN THE UNITED STATES

The UIC Program is very significant in managing the waste disposal, because it controls the largest volume of waste disposed in land or water. In 1988, of the 5.6 billion pounds of waste disposal reported by the industry sources to the Toxic Release Inventory (required under Section 313 of the Emergency Planning and Community Right-to-Know Act – EPCRA), 19% were disposed by underground injection through wells into the subsurface. The top chemical releases via underground injection were: ammonium nitrate, hydrochloric acid, ammonium sulfate, sulfuric acid, and carbon disulfide.

The UIC Program works with State and local governments to regulate injection wells to prevent them from contaminating drinking water resources. The EPA defines the five classes of wells according to the type of waste that they inject and where the waste is injected.

Class I wells are technologically sophisticated wells that inject large volumes of hazardous and nonhazardous wastes into deep, isolated rock formations that are separated from the lowermost underground source of drinking water (USDW) by many layers of impermeable clay and rock.

Class II wells inject fluids associated with oil and natural gas production. Most of the injected fluid is brine that is produced when oil and gas are extracted from the earth (about 10 barrels for every barrel of oil).

Class III wells inject super-hot steam, water, or other fluids into mineral formations, which is then pumped to the surface and extracted. Generally, the fluid is treated and reinjected into the same formation. More than 50% of the salt and 80% of the uranium extraction in the United States is produced in this way.

Class IV wells inject hazardous or radioactive wastes into or above the underground sources of drinking water. These wells are banned under the UIC program because they directly threaten the quality of underground sources of drinking water.

Class V wells use injection practices that are not included in the other classes. Some Class V wells are technologically advanced wastewater disposal systems used by industry, but most are "low-tech" holes in the ground. Generally, they are shallow and depend on gravity to drain or "inject" liquid waste into the ground above or into underground sources of drinking water. Their simple construction provides little or no protection against possible groundwater contamination, and hence, it is important to control what goes into them.

Source: EPA, Office of Water, Office of Ground Water and Drinking Water, Underground Injection Control, Internet Web site: www.epa.gov/ogwdw. October 9, 1999.

SUBSURFACE RELEASES AND MODIFICATIONS ASSOCIATED WITH GLOBAL CLIMATE CHANGE

Residual releases to the subsurface and groundwater are projected to be associated with responses to brackish and saline groundwater treatment in areas with no other lower-cost alternative water source and to global climate change. These releases include injection and sequestration of CO_2 in deep geologic strata and desalination wastes that may result from the need to find alternative water sources because of saltwater intrusion into coastal aquifers, owing to sea-level rise as well as in arid inland locations requiring the use of alternative brackish or saline groundwaters as water supplies. Significant assessments and technology research are being carried out to address these issues.

Carbon Dioxide

Current global emissions of CO_2 are approximately from 22.6 (IPCC, 2005, p. 241) to 25 Gt (Greenblatt, 2006) (1 gigaton = 1 billion metric tons or 1 trillion kilograms), some of which may

EXHIBIT 7.10 DISTRIBUTION OF TOXIC SUBSTANCES RELEASED AND REPORTED IN THE UNITED STATES FOR THE YEARS 1987 AND 2001

In the United States, all major releasers of toxic chemicals to the environment must report those releases to the Environmental Protection Agency each year under the Emergency Planning and Community Right-to-Know Act of 1986. The list of chemicals required to be reported was expanded under the Pollution Prevention Act.

	1987		**2001**	
Total releases	3.2 million metric tons		2.8 million metric tons	
Number of chemicals	253		650	
	1987		**2001**	
Percent distribution by receiving media or process	Air	37%	Other onsite land releases	54%
	Underground injection	19%	Air emissions	27.3%
	Offsite	19%	Transfers offsite to disposal	9.4%
	Land	10%	Surface water discharge	3.6%
	Public sewage	9%	UIC Class I wells	3.1%
	Surface water	6%	UIC Class II–V wells	0.4%
		—	Onsite RCRA Subtitle C landfills	2.2%
		100%		100%

These results indicate an 84% decline in underground injection disposal of toxic chemicals in the United States over the period from 1987 to 2001. This outcome may also reflect changed accounting or improved reporting. The UIC wells may also be used for disposal of wastes not considered toxic, which were not considered in the reports of 1987 and 2001. This may include stormwater disposal and wastewaters carrying chemicals disposed through septic systems.

Sources:

1. U.S. Environmental Protection Agency (USEPA), 1990. Toxics in the Community. EPA 560/4-90-017. Washington, DC, 364p.
2. U.S. Environmental Protection Agency (USEPA), Toxic Release Inventory Program URL: http://www.epa.gov/tr:/

be capable of being stored deep underground, depending on the location of the source relative to geologic formations. Globally, 35% of CO_2 emissions are from electricity and heat production, and 21% each from manufacturing/construction and transportation (IPCC, 2005, p. 83). The benefits of addressing CO_2 emissions may include inhibiting global rise in temperatures and associated losses in biodiversity and sea-level rise affecting wetlands and coastal lands (IPCC, 2002). Major costs for the capture and deep storage of CO_2 emissions—a "greenhouse" gas—range widely. The capital costs of capture and compression for 907,200 metric tons of CO_2 in Algeria in 2005 were $100 million (USDOE, 2005a). "Using present technology, estimates of sequestration costs are in the range of $110–$330/metric ton of carbon emissions avoided" (USDOE, 2005b). Candidate geologic zones for CO_2 storage and their estimated potential capacities are given in Exhibit 7.11.

The economic damages due to underground injection of CO_2 have been estimated at $0.002/kilowatt-hour for coal-fired power production (Smekens and van der Zwaan, 2004, p. 7), responsible for 25% of the CO_2 volume (equivalent to 2.27 billion metric tons/year) produced in the United States (NRDC, 2007). Other specific environmental effects in the subsurface environment from underground injection and storage of CO_2 may include (Smekens and van der Zwaan 2004, pp. 4–6):

EXHIBIT 7.11 CANDIDATE GEOLOGIC ZONES FOR CO_2 STORAGE AND POTENTIAL CAPACITIES

	U.S. (Gt)	Global (Gt)
Depleted oil and gas fields	98	675–900
Unminable coal seams	7	15–200
Deep (800+ meter) saline aquifers	500	1,000–10,000
Total	605	1,700–11,000

Source: Greenblatt, J., Driving a wedge through global warming: Existing technologies to bridge the gap between business-as-usual and stable global emissions, in *Annual Meeting, Committee on Environmental Improvement*, American Chemical Society, San Francisco, CA, September 9, 2006, URL: http://membership.acs.org/c/cei/Greenblatt.pdf (accessed March 23, 2007).

- Acidification of groundwater, potentially affecting groundwater supplies of drinking water if the CO_2 migrates from the deep storage location, and also having potential effects on aquatic life habitat
- Modification of the hydrodynamic properties of underground geological layers, affecting the water extraction potential of certain sources
- Loss of integrity of deep geologic strata
- Dissolution of deep geologic strata
- Well “blowouts,” which could be catastrophic for human and animal life in the vicinity
- Slow or rapid release of CO_2 from geologic formations, thus reintroducing CO_2 to the atmosphere.

The costs of deep underground injection of wastes potentially affecting water supply and other ecological purposes related to the economy should be examined in the future. The costs of disposal do not equate to value of the subsurface environment: if only costs of disposal are considered, then the value of the subsurface for its disposal capacity and other uses/purposes displaced is considered as zero, which may not be equitable either in the near-term or long-term to current or future users of this inner-earth zone. Migration of CO_2 across the boundaries is also a factor in evaluating the effects of underground storage (Rubin, 2005). Measurement, monitoring, and verification at an injection site are important for ensuring that environmental factors are addressed, including the steps of site characterization, simulation, modeling, injection array design and placement, baseline monitoring, operational monitoring during injection, and array monitoring during and after injection. The cost estimates for CO_2 capture and storage (CSS) are presented in Exhibit 7.12. Enhanced oil recovery (EOR) or gas recovery (EGR) using injected CO_2 resulting from electrical production may be balanced against a portion of the cost of capture and storage.

These costs incurred for the indicated investments alone will not ensure by themselves that no leakage or other damage would occur. Potential leakage may be significant in the long term* (Rubin, 2005) and needs more research. Exhibit 7.13 provides a perspective of the types of monitoring that may be necessary to verify successful subsurface disposal of CO_2. Additionally, these costs do not include any risk premium for deleterious effects that might be projected.

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* Rubin (2005) estimated the potential leakage as up to 10% in 100 years and up to 40% in 500 years.

EXHIBIT 7.12 COST ESTIMATES FOR CO_2 CAPTURE AND STORAGE (CCS)

- Groundwater-related costs for a large-scale demonstration project using low-cost CO_2 for the capture of 90,718–5,443,108 metric tons/year (Friedman, 2005)

Activity	Cost Range	Frequency
Detailed predrill assessment	\$2–\$4 million	Once
Injection wells (1–2) and monitoring wells (3–8)	\$3–\$8 million	Once
Monitoring (multiple methods)	\$2.2–\$6.4 million	Annually
Analysis and modeling	\$5–\$7 million	Annually
Post-injection sampling/recompletion	\$3–\$8 million	Once

- CO_2 capture, storage, and monitoring costs (400–800 MW coal power plant net with capture 300–700 MW) (IPCC, 2005)

Capture with current technology:	2002\$US 21–32/metric ton CO_2
Storage depending on geologic conditions:	2002\$US 0.5–7.3/metric ton CO_2
Monitoring depending on geologic conditions:	2002\$US 0.1–0.3/metric ton CO_2

- Estimated CCS cost for new power plants using current technology (IPCC, 2005; Rubin, 2005; USDOE, 2005c)

Power Plant System	Natural Gas Combined Cycle Plant (2002\$US)	Pulverized Coal Plant (2002\$US)	Integrated Gasification Combined Cycle Plant (2002\$US)
Reference plant production cost[a] (without capture)—IPCC	0.03–0.05	0.04–0.05	0.04–0.06
Added cost of CCS with geological storage—Rubin	0.01–0.03	0.02–0.05	0.01–0.03
Added cost of CCS with EOR storage—Rubin	0.01–0.02	0.01–0.03	0.00–0.01
USDOE power plant including geologic storage	0.06–0.09		

- Cost of CO_2 Avoided

	(2002\$US/ton)	(2002\$US/ton)	(2002\$US/ton)
Reference plant[a] with CCS (geological storage)	\$40–\$90	\$30–\$70	\$15–\$55
Reference plant[a] with CCS (EOR storage)	\$20–\$70	\$10–\$45	\$(−5)–\$30
USDOE power plant including geologic storage		\$50–\$200	

Sources:

1. Rubin, E.S., IPCC special report on carbon dioxide capture and storage, *U.S. Climate Change Science Program Workshop*, Washington, DC, November 14, 2005, URL: www.climatescience.gov/workshop2005/presentations/breakout_2ARubin.pdf (accessed March 23, 2007).
2. United States Department of Energy (USDOE), *The Cost of Carbon Dioxide Capture and Storage in Geologic Formations*, 2005c, URL: www.netl.doe.gov (accessed March 23, 2007).

[a] Reference power plant assumptions: 400–800 MW without capture, 300–700 MW net power output with capture, 90% efficiency of CO_2 recovery.

EXHIBIT 7.13 MEASUREMENT, MONITORING, AND VERIFICATION OF SUBSURFACE CO_2 DISPOSAL

The following techniques have been identified for use in monitoring the subsurface disposal of CO_2:

CO_2 fate and transport models

- Reservoir models (target formation to vadose zone)
- Geochemical models
- Geomechanical models
- CO_2 equation of state at reservoir conditions

Plume tracking

- Surface to borehole seismic monitoring
- Micro-seismic monitoring
- Cross-well tomography
- Reservoir pressure monitoring
- Observation wells/fluid sampling

CO_2 leak detection

- Vadose zone soil/water sampling
- Air sample/gas chromospectrometry
- Infrared-based CO_2 in air detectors
- Vegetation growth rates
- CO_2 tracers, natural and introduced
- Subsurface monitoring wells

Land surface deformation

- Satellite and air plane-based monitoring

Mitigation

- De-pressure target formation

Sources:

1. Benson, S.M. and Myer, L., *Presentation to the IPCC Workshop for Carbon Capture and Storage*, November 18–21, 2002, Regina, AB, Canada, URL: http://arch.rivm.nl/env/int/ipcc/docs/css2002/ccs02–10.pdf (accessed April 6, 2007), pp. 3–8.
2. United States Department of Energy (USDOE), *Carbon Sequestration Technology Roadmap and Program Plan*, 2006, URL: http://www.netl.doe.gov/publications/carbon_seq/2006%20Sequestration%20Roadmap%20FINAL.pdf (accessed April 6, 2007), p. 27.

Alternatives to subsurface disposal of CO_2 include (USEPA, 2006a; USDOE, 2007a)

- Promoting more forest growth
- Increasing the carbon content in the soils and development of humus
- Injection into oceans
- Stimulating photosynthesis of oceans through addition of iron particles

These alternatives may have ecosystem effects that need further research to examine their potential success, cost, and external impacts.

Sea-Level Rise and Saltwater Intrusion

With sea-level rise resulting from global climate change, groundwater sources of water supply will be affected by saltwater intrusion. Three-fourths of the population of the United States live within 200 km of the coast (USGS, 2007). Saline water intrusion is also a problem in the coastal zone of Europe (EEA, 2003), and along Asian and African coasts where cities pump significant quantities of groundwater (Howard and Gelo, 2003). A cost of saltwater intrusion includes the closure of near-coast wells and the drilling of new wells, importation of water from wells or water sources more distant from the coast (EEA, 2003, p. 20), or desalination of groundwater turned brackish from saltwater intrusion, such as at Cape May, New Jersey. The cost of well drilling and installation is examined in Chapter 4.

Additionally, a projected 20% of coastal wetlands may be lost by 2080 due to sea-level rise (IPCC, 2002).

Inland Brackish and Saline Water Intrusion

Inland areas where intensive pumping of fresh groundwater have led to brackish and saline water intrusion (for example: EPWU, 2007) may pursue alternative water supplies. Inland southwestern United States communities have experienced similar brackish water intrusion to their freshwater aquifers from pumping for water supply (Sheng and Devere, 2005). El Paso, Texas has been producing brackish groundwater for treatment to meet drinking water standards and fulfill its water supply demand. Arid regions may receive less precipitation as a result of climate change and thus less recharge (IPCC, 2008), indicating a need to pursue alternatives for water supply, such as inland brackish water sources.

Desalination Wastes

Coastal areas already using groundwater to an extent that is depleting their historically used aquifers and causing saltwater intrusion and future subterranean saltwater advances from sea-level rise may already have turned to desalination of seawater, removing salts through thermal or membrane technologies. The concentration of dissolved salts in ocean water is approximately 35,000 parts per million (ppm), whereas typical freshwater from wells used for drinking is 1000 ppm or less (USGS, 2003). In addition, the brackish and saline waters from interior continental locations may be used as water sources in the arid regions where those waters may be the only ones available and must be desalinated before use by people. The cost of water from desalination with reverse osmosis and other technologies was discussed earlier and averages \$0.34/m^3 for brackish water and \$1.16/m^3 for seawater (Younos, 2005; USGS, 2003). The discharged wastewater from desalination plants includes (CCC, 1993)

- High salt concentrations in the range of 46,000–80,000 ppm
- Higher temperatures than ocean waters (about 5E F increase at the point of discharge)
- Turbidity levels above ocean water
- Oxygen levels below those of ocean waters for some technologies
- Chemicals from pretreatment of the feedwater which may include biocides, sulfur dioxide, coagulants (e.g., ferric chloride), CO_2, polyelectrolytes, antiscalants (e.g., polyacrylic acid), sodium bisulfite, antifoam agents, and polymers
- Chemicals used in flushing the pipelines and cleaning the membranes in plants using reverse osmosis technology (which may include sodium compounds, hydrochloric acid, citric acid, alkalines, polyphosphate, biocides, copper sulfate, and acrolein)
- Chemicals used to preserve membranes of reverse osmosis technology (e.g., propylene glycol, glycerine, or sodium bisulfite)

- Organic chemicals and metals contained in feedwater that become concentrated in the desalination process
- Metals that are picked up by the brine in contact with plant components and pipelines.

At coastal locations, these wastewaters are usually discharged back into the ocean. Higher salinity in ocean waters that receive discharge from desalination plants affect the embryo development of certain aquatic life in those coastal areas (CCC, 1993); however, appropriately sized and placed diffusers used in conjunction with this discharge can minimize the marine impact (USNOAA, 2005). However, disposal of desalination wastes through injection into deep geological strata is an alternative (TWDB, 2006). The capital costs for a 37,854 m^3/day deep injection desalination waste disposal facility may range from \$3.3 to \$10.8 million, with operating costs of \$300,000–\$400,000 per year (Foldager, 2003, p. 48). Deep injection of oilfield brine as a waste product of oil production has already been carried out (Manning and Thompson, 1995, p. 114).

REMEDIATION OF CHEMICAL RESIDUALS IN GROUNDWATER

Past chemical and biological disposal practices (most of them prior to the late 1970s) often assumed that such wastes could be applied on the land or buried underground and be held at that location without causing any harm or costs to other people or property. The advent of extensive groundwater monitoring throughout the United States in the 1970s revealed groundwater contamination in places never imagined such as Love Canal, New York; Bridgeport, New Jersey; and Riverside, California. Scientists began to realize that contaminants are not bound in the subsurface, but migrate and can be carried by groundwater movement. At that time, over 30,000 sites of potential uncontrolled hazardous waste disposal were identified in the United States through activities under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), otherwise known as "Superfund." Other active waste disposal sites that involved contaminated groundwater were identified under the Resource Conservation and Recovery Act (RCRA). In addition, other abandoned waste sites have been identified around the world. For example, please see Exhibit 1.7, Examples of Groundwater Contaminated Areas, and Sampat (2000).

Though many of the sites are not considered as locations of extensive contamination, more than 85% of the nationally listed sites in the United States had contamination that affected groundwater quality and, thereby, its use for drinking water (USEPA, 1991). By the end of 2000, the National Priorities List (NPL) had 1450 sites for cleanup. Dense nonaqueous phase liquids (DNAPLs), chemicals that sink in water, have been a continuing source of contamination at approximately 60% of these sites (USEPA, 1993). Perhaps, as many as 8–10 sites involve injection of wastes through shallow wells into the subsurface and contaminated groundwater (Paque, 2003). The most commonly found contaminants in groundwater at NPL sites are volatile organic and inorganic chemicals. Exhibit 7.14 lists the most commonly found contaminants at NPL sites with contaminated groundwater.

The costs of remediating groundwater contamination are considerable. The average cost of remediating an uncontrolled hazardous waste site is estimated to be \$10 million (USEPA, 2003b). Some of these costs include

- Sampling the contaminated materials and the surrounding soil, air, and water
- Installing security measures
- Disposing contaminated containers and debris
- Excavating and disposing contaminated soil, wastes, and debris
- Pumping contaminated liquids from overflowing lagoons
- Draining or skimming off contaminants
- Controlling detonation or explosions of ordnance

EXHIBIT 7.14 MOST FREQUENTLY-FOUND CONTAMINANTS IN GROUNDWATER AT NATIONAL PRIORITY LIST (SUPERFUND) SITES IN THE UNITED STATES

Organic Contaminants

- Trichloroethylene
- Tetrachloroethylene (TCE) or (perchloroethene, “PCE”)
- Chloroform, benzene
- Toluene
- 1,1,1-Trichloroethane
- Polychlorinated biphenyls (PCB)
- 1,2-Trans-dichloroethylene
- 1,1-Dichloroethane
- 1,1-Dichloroethene
- Vinyl chloride
- Xylene
- Ethylbenzene
- Carbon tetrachloride
- Phenol
- Methylene chloride
- 1,2-Dichloroethane
- Pentachlorophenol (PCP)
- Chlorobenzene
- Benzo (a) pyrene

Inorganic Contaminants

- Lead
- Chromium
- Arsenic
- Cadmium
- Mercury
- Copper
- Zinc
- Nickel
- Cyanide
- Barium

Other inorganic contaminants that are radiologic have been identified at Superfund sites, such as uranium, tritium, thorium, technetium-99, strontium-90, radon, radium, plutonium, iodine, cobalt-60, cesium-137, and americanium-241.

Source: U.S. Environmental Protection Agency (USEPA), *Common Contaminants Found at Superfund Sites*, 2003a, URL: http://www.epa.gov/superfund/resources/chemicals.htm (accessed April 5, 2003).

- Applying alternative treatment technologies
- Restoring the site
- Relocating threatened individuals or finding them temporary shelter
- Providing alternate water supplies
- Installing decontamination devices

In situations where the contamination of aquifers is extensive or deep, cleanup of groundwater may not be economically or technically possible. However, where remediation is practical, it can occur in the subsurface, called “in-situ” cleanup, or at the ground surface nearby, referred to as “ex-situ” remediation. In-situ technologies include bioremediation, chemical treatment, permeable reactive barriers, phytoremediation, physical extraction, and barriers or capping. Ex-situ remediation comprises pumping groundwater to the ground surface and treating it, referred to as “pump and treat.” These ex-situ technologies include advanced oxidation processes, chemical treatment, bioremediation, physical separation, air stripping, and thermal treatment (FRTR, 2009). Exhibit 7.15 provides a brief description of the technologies. Exhibit 7.16 reviews the costs of different technologies.

As Exhibit 7.16 indicates, the cost to treat contaminated groundwater is highly variable, depending on the contaminant and the technology. The cost and effectiveness of groundwater remediation are also affected by many other factors. Natural subsurface characteristics include the geology of the location and depth of the water table. More permeable subsurface conditions may facilitate pumping groundwater or subsurface treatments at lower costs. Greater depth to reach water will increase the pumping costs. The contaminant factors are obviously important. The contaminant type and concentration will determine the technologies that can be applied most effectively. Furthermore, the remediation goal will also influence technology selection. Often groundwater is used as a drinking water source, and hence, the goals may be driven by the maximum contaminant levels set for that use.

EXHIBIT 7.15 BRIEF DESCRIPTION OF REMEDIAL TREATMENT TECHNOLOGIES

Ex-situ Technologies

Advanced Oxidation Processes—Combines oxygen from the oxidizing agents with the contaminants, and transforms it to different substances and may use ultraviolet radiation and strong oxidizing agents (hydrogen peroxide or ozone) to improve efficiency.

Other chemical treatments (oxidation, reduction, precipitation, etc.)—Chemicals break-down contaminants through oxidation or reduction, and other chemicals may be added to transform them to solids to be precipitated, coagulated, or flocculated.

Bioremediation—Uses microorganisms to destroy or stabilize contaminants and may add nutrients, oxygen, or other chemicals to enhance the action of the organisms.

Physical Separation (filtration, adsorption, ion exchange, etc.)—Uses activated carbon or resins to remove the contaminants from groundwater.

Air Stripping—Once pumped to the ground surface, the contaminated groundwater flows through a media that allows the contaminants to volatilize into the air.

Thermal Treatment—Heat is applied to the contaminated groundwater to destroy or remove the contaminants.

In-situ Technologies

Bioremediation—Treating contaminated groundwater in place underground by introducing microorganisms as well as chemicals that may stimulate those organisms to degrade or stabilize the contaminants.

Chemical Treatment—Injecting chemicals that treat the contaminants in groundwater in place.

Permeable Reactive Barriers—Creation of a zone for contaminated groundwater to move through, which will treat the water using other chemical, physical, or microbiological technologies.

Phytoremediation—Plants roots draw the contaminants out of the groundwater, which may serve as a food source or may be concentrated in their cell structure and then harvested and disposed as a hazardous waste.

Physical Extraction (skimmers, in-situ pump and treat methods, stream stripping, etc.)—Removal of contaminants through air stripping in wells and injecting steam to enhance the movement of contaminants

Barrier, Containment—In cases where other approaches are too costly or infeasible, a barrier to contain the contaminants in place may be constructed, using a range of materials depending on the type of containment, such as grout, plastic, ice, or steel, which can be placed over (capping), under, or around the contaminated zone.

Sources:

1. Federal Remediation Technology Roundtable (FRTR), Glossary, 2009, URL: http://www.frtr.gov/glossary/aterms.htm (accessed January 7, 2009).
2. Driscoll, F.G., *Groundwater and Wells*, Johnson Screens, St. Paul, MN, 1986, 1089.

If the institutions (governments, water suppliers, or public) decide that drinking water is no longer a goal for the resource, then alternative target levels may be set. The volume of groundwater contaminated and the time within which the remediation is expected to occur will determine the extent of technology deployment: large volumes and short timeframes will probably require greater inputs to be applied, increasing the cost of remediation.

EXHIBIT 7.16 COSTS OF GROUNDWATER TREATMENT

In-situ/Ex-situ	Technology	Contaminants Treated	Approximate Unit Cost
Ex-situ	Advanced oxidation processes	VOCs, SVOCs, DNAPLs, LNAPLs, pesticides, pathogens, metals, creosote, TPH, MTBE	\$0.03–\$2.64 per 1000 L[a]
Ex-situ	Other chemical treatments (oxidation, reduction, precipitation, etc.)	VOCs, SVOCs, pesticides, PCBs, TH, metals, explosives, nitrate	Highly variable, but generally under \$26 per 1000 L[a]
Ex-situ	Bioremediation	VOCs, SVOCs, pesticides, metals, TPH, nitrate, perchlorate, MTBE, pathogens, radionuclides, LNAPL	Generally under \$0.79 per 1000 L[a] for mature technologies
Ex-situ	Physical separation (filtration, adsorption, ion exchange, etc.)	VOCs, SVOCs, DNAPLs, pesticides, metals, TPH, nitrate, explosives, perchlorate, MTBE, arsenic, radionuclides, PCBs	Generally under \$1.32 per 1000 L[a]; some proprietary technologies may cost more
Ex-situ	Air stripping	VOCs, SVOCs, LNAPLs, TPH, MTBE	\$0.01–\$1.85 per 1000 L[a]
Ex-situ	Thermal treatment	VOCs, SVOCs, PCBs, pesticides, TPH, pathogens, explosives, perchlorate, radionuclides	Highly variable based on type of technology, SC WO costs approximately \$80–\$130 per cubic meter[a]
In-situ	Bioremediation	VOCs, SVOCs, PCBs, DNAPLs, LNAPLs, pesticides, petroleum hydrocarbons, metals, radionuclides, nitrate, perchlorate, MTBE, coal tar, creosote	\$10–\$933 per cubic meter[b]
In-situ	Chemical treatment	VOCs, SVOCs, PCBs, DNAPLs, LNAPLs, pesticides, pathogens, TPH, MTBE, metals, radionuclides	Variable with technology, in-situ chemical oxidation through recirculation (ISCOR) costs approximately \$77 per cubic meter[b]
In situ	Permeable reactive barriers	VOCs, SVOCs, DNAPLs, pesticides, pathogens, metals, TPH, BTEX, radionuclides, nitrate, arsenic, PCBs, creososte	Installation costs \$59–\$370 per 1000 L[a]
In-situ	Phytoremediation	VOCs, SVOCs, PCBs, NDNAPL, pesticides, pathogens, metals, TPA, radionuclides, explosives, MTBE, nitrate, arsenic, perchlorate	\$11–\$39 per metric ton[b]
In-situ	Physical extraction (skimmers, in-situ pump and treat methods, stream stripping, etc.)	VOCs, SVOCs, DNAPL, LNAPL, petroleum hydrocarbons, pesticides, creosote, coal tar, MTBE, nitrate, metals, arsenic	Varies with technology, but generally \$8–\$268 per cubic meter[b]

EXHIBIT 7.16 (continued) COSTS OF GROUNDWATER TREATMENT

In-situ/Ex-situ	Technology	Contaminants Treated	Approximate Unit Cost
In-situ	Barrier, containment	VOCs, SVOCs, PCBs, DNAPL, LNAPL, coal tar, metals, petroleum hydrocarbons, nitrate, radionuclides, arsenic	Generally installation costs range from \$54–\$377 per square meter of the barrier[c]

Source: Van Dueren et al., *Remediation Technologies Screening Matrix and Reference Guide*, Version 4.0, 2002, URL: http://www.frtr.gov/matrix2/section1/toc.html (accessed February 18, 2003).

[a] Of influent media.

[b] Of subsurface media.

[c] Volumetric costs not available.

A technology not listed earlier is that of replacing the contaminated groundwater resource with another water source, either ground or surface water, and even bottled or mobile tank-delivered water. The costs for installing a new well for a single home or a community have been addressed in Chapter 4. In addition, the costs of delivering water from an alternative source should also be considered. Delivery costs include those of installing a transmission line and then maintaining it. In 2000, estimates of water distribution pipe costs in the United States ranged from US\$137,950/km for small communities serving 3,300–10,000 people, to US\$1,068,200/km for large urban communities serving more than 500,000 people (USEPA, 2002, p. 65).

WATER RECLAMATION AND REUSE

Many communities and countries around the world have reached or are expected to reach the limits of their water resources (USEPA, 2004a,b). Increasing demand in population centers contributes to greater demand on all other economic sectors and their derived demand for water: domestic, commercial, industrial, and agricultural. In 2004, an estimated 6.4 million m^3 of water was reused in the United States. Likewise, wastewater reclamation and reuse projects are active in the European Union focusing on applying treated wastewater for irrigated agriculture (EU, 2009). Water reuse often begins with reclamation, defined as the treatment of wastewater to meet particular water quality criteria for further use in another beneficial application. Thus, reuse is the actual deployment of treated wastewater for beneficial uses, such as irrigation or industrial cooling (Asano et al., 2007). Water reclamation in areas of limited water supplies a “new” water source. Water reuse is often cost-effective when (USEPA, 2004a,b):

- Considering obtaining the needed water supplies from distant sources
- Ground or surface water supplies are being depleted or have limited availability
- Treating a raw water supply source of lower quality
- Wastewater must be treated to stricter discharge standards

Health concerns are addressed with the reuse, such as ensuring that the application for the intended use satisfies the customer requirements, and preventing (1) improper system operation, (2) cross-connections with potable water lines, and (3) improper use of nonpotable water.

Exhibit 7.17 highlights the water reuse applications that are found to be beneficial as well as the factors affecting groundwater recharge applications.

EXHIBIT 7.17 SOME BENEFICIAL WATER REUSE APPLICATIONS

1. Reuse systems provide reclaimed water for various nonpotable purposes including:
   - Irrigation of public areas and golf courses
   - Irrigation of residential landscaped areas and maintenance activities
   - Irrigation of landscaped areas of commercial, and industrial developments
   - Irrigation of agricultural land
   - Washing of vehicles, laundry, windows
   - Commercial mixing water for pesticides, herbicides, and liquid fertilizers
   - Decorative water features, such as fountains, reflecting pools, and waterfalls
   - Dust control and concrete production for construction projects
   - Fire protection through reclaimed water fire hydrants
   - Toilet flushing in commercial and industrial buildings
   - Industrial cooling and processing
   - Soil conditioning
   - Additional water for wetlands and streamflow augmentation
   - Aquifer recharge through injection or recharge basins
2. Factors affecting engineered groundwater recharge

Factor	**Recharge Basins**	**Vadose Zone Injection Wells**	**Direct Injection Wells**
Aquifer type	Unconfined	Unconfined	Unconfined or confined
Pretreatment requirements	Low technology	Removal of solids	High technology
Estimated major capital costs (2004US$)	Land and distribution system	\$25,000–\$75,000/well	\$500,000–\$1,500,000/well
Capacity	100–20,000 m^3/hectare-day	1000–3000 m^3/d/well	2000–6000 m^3/d/well
Maintenance requirements	Drying and scraping	Drying and disinfection	Disinfection and flow reversal
Estimated life cycle	>100 years	5–20 years	25–50 years
Soil/aquifer treatment	Vadose zone and saturated zone	Vadose zone and saturated zone	Saturated zone

Sources:

1. U.S. Environmental Protection Agency (USEPA), *Drinking Water Costs & Federal Funding*, EPA 816-F-04–038, 2004a, URL: http://epa.gov/ogwdw/sdwa/30th/factsheets/pdfs/fs_30ann_dwsrf_web.pdf (accessed August 16, 2007).
2. U.S. Environmental Protection Agency (USEPA), *Guidelines for Water Reuse*, EPA/625/R-04/108 450p, 2004b, URL: http://www.epa.gov/ord/NRMRL/pubs/625r04108/625r04108.pdf (accessed January 7, 2009).

An equation for reclaimed water service which includes the cost factors for providing reclaimed water (USEPA, 2004a,b), can be given as:

$$\begin{aligned}\text{Total reclaimed water service} = {} & [\text{reclaimed water treatment} - \text{treatment to permitted} \\ & \text{disposal standards}] + \text{additional transmission} \\ & + \text{additional distribution} + \text{additional storage}\end{aligned} \tag{7.1}$$

Many examples of costs of delivering reclaimed wastewater exist (USEPA, 2004b). One example is San Marcos, Texas, in which the analysis found that the cost of:

- Treated and delivered reclaimed water was \$0.07–\$0.14/m^3
- Alternative water supplies in the region was \$0.11–\$0.24/m^3
- The reclaimed water charge established by the city was \$0.18/m^3

The charges for the use of reclaimed water have a wide range. During 2001–2002, for selected communities in six states in the United States (Texas, Colorado, Nevada, Florida, Illinois, and Hawaii), the range of reclaimed water charges for metered usage was \$0.03–\$2.69/m^3 (USEPA, 2004b).

The U.S. Environmental Protection Agency found the following benefits calculated as financial credits of reclaimed water projects in California (USEPA, 2004b):

- Water supply, \$0.24–\$0.89/m^3
- Water supply reliability, \$0.08–\$0.11/m^3
- Effluent disposal, \$0.16–\$1.62/m^3
- Downstream watershed, \$0.32–\$0.65/m^3
- Energy conservation, \$0.00–\$0.19/m^3

Internationally, reclaimed water use is significant in countries with arid climates that rely heavily on groundwater. In a survey of 23 northern African, Middle Eastern, and central Asian countries for the years 1990–1991, water reclamation was found to range from 0.002% to 15%. The three countries with the greatest use of reclaimed water at that time were: Israel, 10%; Cyprus, 11%; and Kuwait, 15% (USEPA, 2004b). In 2009, because of aquifer depletion and limits on water resources, Australia, Singapore, and Spain also reuse significant amounts of water.

ECONOMIC CONSIDERATIONS FOR GROUNDWATER IN TREATMENT AND DISPOSAL

From an economic standpoint, alternative technologies must be evaluated for the same objective or goal. Treating groundwater for drinking water purposes only as compared to groundwater for all uses, including drinking water, are vastly different objectives. The risk of contamination from residuals, disposal in using the subsurface as a waste sink may have perverse effects on the treatment approach and should be considered in the evaluation. The result is considerably different costs. Thus, fundamentally, an economic approach requires alternatives to be methodically evaluated. Different goals may have different, or, conversely, similar alternatives. Some technologies remove more contaminants than others. The economic efficiency evaluation requires that we determine the alternative that provides groundwater of an accepted quality at least cost. Thus, we must consider the initial costs for installing the treatment or disposal technique and the expenses of operating and maintaining the equipment or plant in the future. These costs can be subsequently incorporated into the price of groundwater delivered to the consumer who can decide how much water to purchase and use. If a community uses a large volume of water, its leaders have to decide the most efficient way to access, treat, and deliver that water: many small wells and treatment plants, or larger wells with a large treatment plant. The technology costs mentioned earlier suggest economies of scale, with smaller units having higher costs per unit of water treated and delivered.

With regard to global warming and its effects, a consensus of scientists and nations indicate that this phenomenon has already started and that an immediate response is necessary (IPCC, 2001). Relative to related groundwater effects, the potential capability of the subsurface to store CO_2 is perceived to be a significant benefit for all humankind, and major research is being carried out to successfully implement this (USDOE, 2007b). The locations of storage will need to be evaluated on a case-by-case basis to determine whether substantial costs would be incurred into the future, if deep geologic storage of this greenhouse gas occurs on a scale larger than that in this first decade of the twenty-first century. The data suggest that rising temperatures are related to increased severity of droughts as a result of elevated evaporation and water consumption (ADEWR, 2003), and that the land area affected by serious drought may be extensive (USNCAR, 2005), which have implications for reduced groundwater recharge and lower water tables, implying less groundwater for supply. In 2001, the Intergovernmental Panel on Climate Change concluded that the rising temperatures over the twentieth century were statistically significant and that the ocean levels, as measured by tidal gage data, had increased to 0.1–0.2 m—and are expected to rise as much as 0.9 m by 2100 (IPCC, 2001). This fact indicates that the coastal aquifers may already have been affected, and issues related to the use of near-coastal wells and activities in the coastal areas may emerge as costs to be mitigated, including the use of deep geologic storage of CO_2. These activities, such as deep well injection of CO_2 emissions and management of groundwater resources in coastal, arid and drought-stricken areas, suggest a significant need for investment in the subsurface and groundwater protection and supply, as well as for research and practice of using these subterranean resources sustainably, while balancing the benefits with costs.

With regard to deep geologic disposal, a nation or jurisdiction holds the subsurface rights in trust for its people, to ensure adequate consideration of the subterranean environment in decision making at all levels, including public and private entities. The possibility of initial and ongoing charges for use of this public trust space, such as disposal tax or fee based on volume, may reflect the economic value of its capacity and the other uses and purposes to which it is currently or could be engaged, including ecosystem support. Without such charges, the value of this space is equated to be zero, promoting its exploitation until some adverse consequence is observed. Waiting until the occurrence of such observation may result in deleterious to catastrophic effects which may seem obscure at this time.

From an environmental perspective, if a homeowner, community, or corporation must treat its groundwater because of a contaminating activity degrading the quality of its water supply, the expense of treatment is a "damage cost." However, who would pay this cost and what are the key environmental economic issues? The costs may be greater than simply treating the groundwater. In situations where people have become ill, the costs may be greater. Furthermore, if the groundwater quality (or watertable levels) changes, then for what purpose can a property owner use his or her land? This is also considered as a cost with a different set of benefits. An efficient resolution is to compare the abatement costs of the contaminating entity with the damage costs of the recipients of the unwanted contamination. These considerations will be addressed in the subsequent chapters. Taking a watershed or river basin approach to allow a holistic view of actions, effects, benefits, and damages for water-related results will enable an evaluation of alternatives with a more balanced potential for acceptable outcomes.

SUMMARY

Groundwater users may have a preference for high-quality water. If groundwater is used for drinking and other purposes resulting in its contact with the body, then the consumers may expect that the quality meets the public health standards for drinking water. If the quality does not meet the users' requirements, then treatment may be necessary. For people using individual wells, a range of treatment options are available, including POE to the household (such as a water softening unit) that treats water for all water uses in a house, or POU that treats only water for that tap. The costs vary according to the technology used and the volume of water needing treatment. Most groundwater users are supplied water through a central water supplier that can provide treatment for an entire community and spread the costs of that treatment over many more units of groundwater. If groundwater becomes contaminated with wastes that are not properly disposed, remediation of groundwater can be carried out in places below or above the ground once pumped to the surface. The treatment costs may vary based on the contaminant, extent of contamination, the subsurface environment, and the remedial goals. Water treatment and desalination produce wastes, which must also be managed and disposed if they cannot be recycled. Brackish groundwater desalination and water reclamation and reuse are significant in regions with limitations on groundwater availability.

Concerns about global climate change also present challenges to groundwater use, with associated responses that involve disposal of "greenhouse" gases and desalination waste in deep geologic strata, suggesting a greater competition for use of the subsurface environment. Efficiency as an economic goal indicates that we should evaluate alternatives of technology and scale, and select the least-cost approach that provides the quality of groundwater which the community desires. Environmental and public health effects of poor quality groundwater may increase the overall cost of its contamination beyond treatment alone. A watershed approach to waste treatment and disposal affecting groundwater may provide an opportunity to consider the costs and benefits in a holistic setting and a balance among people's needs and resource uses. To promote the efficient use of the public trust subsurface environment, particularly for disposal, its value should not be equated to zero, and public charges for its use might facilitate its best use, especially where significant risk is associated with the disposal.

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Part IIb

Reprise

Groundwater Flow, Supply, Habitat, and Sink—Guided by Law, Used Based on Cost and Necessity

SUMMARY

Several points from Part II are summarized here because of their significance:

- Groundwater is nearly ubiquitous in the subsurface portion of the ecosystem under the ground surface of continents and islands.
- Groundwater exists in a complex subsurface environment, is mobile, and travels slowly, but, in some cases, long distances across many boundaries.
- Managing groundwater on an aquifer basis in a watershed recognizes the groundwater flow component of the hydrologic cycle and provides a holistic approach to addressing water issues.
- It represents the largest freshwater source of water supply.
- Many organisms live in and rely on groundwater and the subsurface as their habitat.
- The largest uses of groundwater are for water supply for human beings (in some cases, their only water source) and other life forms (for some, their only habitat) and for irrigation (the largest use) to supply food—in many locations, of necessity, the only affordable source.
- Groundwater is a significant resource input to the economies of communities and nations around the world, supplying at least half the world's population with water.
- Aquifers are under stress from depletion and contamination around the world, which will most likely increase with climate change.
- Groundwater is vulnerable to contamination and is expensive to clean up.
- Not as readily recognized is the use of groundwater and the subsurface as a waste sink.
- Laws provide the basis for use of groundwater relative to who may access and use it, which provides the basis for economic transactions affecting groundwater.
- Laws in some countries and jurisdictions treat groundwater as a separable water source, but other countries recognize its role in the larger hydrologic cycle, such as in maintaining the baseflow of streams.
- In some locations, groundwater is easily accessed but this is more difficult in other places—this affects the cost to produce it, typically through wells.
- Aquifers around the world are being depleted—used up faster than they are recharged—but have been instrumental through irrigation in ensuring food supply in many countries, especially some densely populated countries.
- Because of their many purposes and uses, groundwater and its subsurface environment should be valued as some pecuniary amount significantly greater than zero.

INDICATORS OF COMPETITION FOR GROUNDWATER AND THE SUBSURFACE ENVIRONMENT IN THE UNITED STATES

Below are some indicators of competition for groundwater and the subsurface environment in the United States. Resources are used from the ecosystem, transformed to products, and returned as waste. This circumstance is true for groundwater and the subsurface environment as well. This list gives some selected statistics to show a level of competition for the subterranean zones of the earth in the United States only, with an emphasis on groundwater. It is only a partial list to be expanded by others, but is an indicator of the future challenge and opportunity posed by this portion of the ecosystem. Certainly, many other uses of the subsurface may be identified, and therefore also compete for this portion of the ecosystem.

SUPPLY AND PRODUCTION

Maintenance of stream baseflow: 1.862 billion m^3/day (492 billion gal/day) from groundwater discharge (USEPA, 1996)
Household domestic water: 15,131,691 wells (approx., WSC, 2006)
    13.4 million m^3/day (USGS, 2004)
Public water supply: 262,000 wells (est.) (USEPA, 2002)
    60.6 million m^3/day (USGS, 2004)
Irrigation: 401,193 wells in 2003 (USDA, 2003)
Oil: 336,088 wells (USGS, 2004)
    4,964,000 barrels/day produced in 2007 (USDOE, 2009c)
    5.0 million m^3/day of water use in 2005 for oil refining (ANL, 2008)
    5.7 million m^3/day of water use in 2005 for oil exploration & production (expected to decrease over time with declining domestic production) (ANL, 2008)
Natural gas: 452, 768 wells in 2007 (USDOE, 2009)
    696.3 trillion m^3 produced in 2007 (USDOE, 2009a)
    5.5 million m^3/day of water use in 2005 for processing, transport, plant operation (ANL, 2008)
    0.038 million m^3/day of water use projected by 2030 for tight sands and gas shale production (ANL, 2008)
Geothermal power: 141 units (Lund et al., 2000)
Geothermal heat pumps: 450,000 units, increasing at 50,000 units annually (Lund et al., 2000)
Coal: 1400 active mines (NMA, 2006)
    1,053,604,357 metric tons produced in 2006

TRANSMISSION

321,900 km of oil pipelines (AOPL, 2007)
492,500 km of natural gas pipelines (USDOE, 2009b)
3,380,000 km of water distribution lines (est.; USEPA, 2002)
1,000,000 km of sewer lines (est.) (Vipulanandan, 2008)
[Unknown] miles of CO_2 pipeline

STORAGE

Underground storage tanks: 1,200,000 (est., USEPA, 1996)
Oil (proved reserves): 29,920,000,000 barrels (USDOE, 2007a)
Natural gas (proved reserves): 5788 billion m^3
    Active storage sites: 394 sites with 234 billion m^3 in 2005 (USDOE, 2006)
Coal (proved reserves): 250 billion metric tons (USDOE, 1997)
Aquifer storage and recovery: 70 sites with 1–300 wells/site (ISWD, 2007)

WASTE SINK

Hazardous waste: 272 wells (USEPA, 2006)
Solid waste: 418 land disposal facilities subject to groundwater monitoring (USEPA, 1996)
Heating/air conditioning return flow: 35,000 wells (est., USEPA, circa. 2000)
Oil and gas brine: 167,000 disposal wells (USEPA, 2006)
  7.571 million m^3 injected/day (est., USEPA, 2006)
Shallow waste injection: 500,000–1,000,000 wells (USEPA, 1996, 2006)
Domestic wastewater septic systems: 19.5 million (est.) (Rail, 2000)
Abandoned waste National Priority List sites: 700 sites affecting groundwater (USEPA, 1996)
Releases from leaking underground storage tanks: 278,000 releases (USEPA, 1996)
Power plants and stationary sources annual release of CO_2: 3.447 billion metric tons/year (USDOE, 2007b)
Carbon dioxide disposal potential underground: 3175 billion metric tons of CO_2 (USDOE, 2007b)

It is on the basis of this expanding level of competition that groundwater and the subsurface environment need the careful and full consideration of thorough economic analyses. The remainder of this book is devoted to that topic.

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Part III

Economic Fundamentals

Part III provides some fundamental discussions of microeconomic and macroeconomic processes that relate to the use of groundwater and the disposal of residuals in the subsurface. Chapter 8 describes microeconomic processes important to understanding the marginal analysis of economic production and resource use. Chapter 9 covers important topics related to valuing groundwater in different approaches to provide insight to its cost, price, benefit, and value. Chapter 10 considers aggregate economic activity at the macroeconomic level and considerations relative to groundwater as an asset.

8 Microeconomics and Basic Economic Relationships

Water is an essential input for human life, agriculture, and several manufacturing industries. In other words, life and production of such things as food and beverages, petroleum, lumber and wood products, paper, chemicals, and electronic equipment (Hanemann, 2005, p. 20) would not be possible without water in certain quantities, qualities, and times. Water is thus defined as an "essential" economic commodity. Therein lies the motivation to supply water to ensure production that meets the necessary requirements of life.

Consumer demand drives producers to supply goods. Requirements for food has impelled demand for water to irrigate croplands—in the United States, Mexico, South America, and around the world. Demand for irrigation water stimulated water equipment producers to provide well casing and small pumps for farmers to increase food production in India, China, and elsewhere. Other than information on depth of the falling groundwater tables in these areas, the impact of millions of wells on aquifer depletion was not widely recognized but could have been anticipated and projected. These circumstances in which groundwater can have substantial ecosystem, health, and survival implications also affect economic relationships locally, nationally, and globally.

As we have observed, groundwater supplies fundamental human, animal, and plant needs to quench thirst for bodily functions. It contributes substantially to food production and foreign trade. Groundwater is also becoming scarce in many locations and so should receive attention in markets that rely on it as a critical factor of production. The basic economic relationships begin at the individual level but build up to national and international considerations.

The field of microeconomics provides tools to evaluate how scarce resources might be allocated in an efficient way in the market among a range of uses, given certain assumptions and limitations. Economics tools allow the assessment of alternative policies to anticipate and project their effects. The scarcity of both water and the effective means to produce and safeguard it are growing (Young, 2005, p. 16). In this chapter, which takes a neoclassical microeconomics perspective, we first consider the "individual" demand in relation to the "product" a firm produces. Simple equations provide insight into these relationships. Second, we will contemplate basic supply and demand for groundwater. A particular focus will be on specific decisions that producers make and their "production function." Third, a look at some financial considerations that affect groundwater production will be covered. Finally, we will consider some connections to macrolevel relationships at the national and international scale.

ECONOMIC UTILITY, PRICE, AND PRODUCT

The usefulness of a product or service, such as groundwater for water supply, to human beings is a driver of demand for that product or service. People have multiple needs which mean that they must decide how much among a range of products and services will satisfy those needs. Economists think in terms of an individual's "utility" for a product or service and whether a person has a requirement to be satisfied by the features or qualities of the good that are useful to him or her. "Utility," when acted on, generates a demand by that person for a product or service offered by a firm. The basic economic relationship at the individual-firm level in the market for products, referred to as the "basic market equation," is (Samuelson, 1964, pp. 430–431, 518–525; Daly and Farley, 2004, pp. 126–129):

$$\mathrm{MU}_{\mathrm{w}n}/\mathrm{MU}_{\mathrm{c}n} = P_{\mathrm{w}}/P_{\mathrm{c}} = \mathrm{MPP}_{a\mathrm{c}}/\mathrm{MPP}_{a\mathrm{w}} \tag{8.1}$$

where

$\mathrm{MU}_{\mathrm{w}n}$ is the marginal utility of good "w" (water, in this case) to person n, that is, the increment of satisfaction from having or using one additional unit of good "w" to person n; this added unit could be one more cup of water. Having a utility for more water is a fundamental basis for consumer demand for that additional water.

$\mathrm{MU}_{\mathrm{c}n}$ is the marginal utility of good "c" (cup or container for water) to person n; for example, the added satisfaction of owning one more cup, and thus the demand for more cups.

P_{w} is the price of water in the market, which may range from \$0.00008 up to \$0.50 and more per 0.236 L.

P_{c} is the price of a cup in the market, which could be under \$1 to several dollars and higher.

$\mathrm{MPP}_{a\mathrm{w}}$ is the marginal physical product of using one more of input factor a to produce an extra quantity of good "w" (water). Production is the basis for supplying water in response to a demand for more water.

$\mathrm{MPP}_{a\mathrm{c}}$ is the marginal physical product of applying one more input of a to manufacture or create more of good "c," more cups to hold water. Again, this reflects production to supply more cups because of a demand for them.

In a competitive market, so many people are consuming and manufacturers are producing the equivalent items in the market so that no one individual consumer or producer can influence the market price. Plans to buy or sell an item are made based on the prices of the items offered in the market. In a competitive market, the left-hand side of the above equation represents the consumer and his or her demand for water and cups given the price relationship holds. The right-hand side is the producers' supply capabilities for the water and cups demanded. The prices in the middle of the economic relationship should reflect the value to the consumer to meet his or her demand for the products and the value to the producer to provide the products, considering both production cost and profit.

On the basis of observation and experience, three principles affect the use of this equation (Samuelson, 1964, pp. 430–431, 518–525; Daly and Farley, 2004, p. 127):

1. Diminishing marginal utility—This principle indicates that after a person has consumed one of the item, such as a cup of water, the person has or receives less satisfaction from having another of the same item to consume again, at least at the time of consumption.
2. Diminishing marginal physical product (MPP)—As a producer adds one more input to the manufacturing process, other inputs unchanged, the additional output resulting from extra input declines. Assuming it takes a crew of two people with a drill rig to install a shallow well in 1 day (this depends, of course, on a range of conditions and may not be reality) and when an additional person is added to the crew, they may install one well and have one-fourth of another one started in 1 day. The MPP of the additional person is 0.25. The limits of the other input factors did not allow the additional person to perform to his potential.
3. Equimarginal principle of maximization—Consumers will cease changing their allotment of income for a range of goods, such as water and cups, when they have reached their highest degree of satisfaction or "maximized their utility" among the array of purchased goods. In that circumstance, the marginal utility of each dollar paid for every good is the same.

Applying these principles to the basic market economics equation above means:

- Prices are central in the equation to balance the consumers' satisfaction (their marginal utilities for products and services, e.g., a cup to hold water and water to satisfy thirst) and the means of allocating resources to produce the cups and water. Therefore,

$$\mathrm{MU}_{\mathrm{w}n}/\mathrm{MU}_{\mathrm{c}n} = \mathrm{MPP}_{ac}/\mathrm{MPP}_{a\mathrm{w}} \tag{8.2}$$

the marginal utility ratio is equal to the marginal productivity ratio. Basically, this indicates that the relative demand for this set of products in relation to each other is equal to the relative supply of each. A dependency exists in this equation. If more cups are produced by adding inputs at the margin, then an inequality will exist and

$$\mathrm{MU}_{\mathrm{w}n}/\mathrm{MU}_{\mathrm{c}n} < \mathrm{MPP}_{ac}/\mathrm{MPP}_{a\mathrm{w}} \tag{8.3}$$

that is, at the margin, more cups will not be demanded, based on the consumer's marginal utility of cups relative to water.

- The price relationship of the products for the consumers reflects their relative value for the products, given their utility for more of either. Thus,

$$\mathrm{MU}_{\mathrm{w}n}/\mathrm{MU}_{\mathrm{c}n} = P_{\mathrm{w}}/P_{\mathrm{c}} \tag{8.4}$$

Stated another way

$$\mathrm{MU}_{\mathrm{w}n}/P_{\mathrm{w}} = \mathrm{MU}_{\mathrm{c}n}/P_{\mathrm{c}} \tag{8.5}$$

which is an expression of value to the consumer. Given person n's utility for water, at the margin of n's use or need for another unit of water, the value of that added unit of water divided by the price per unit of water is equal to an amount of dollars that is also equal to the value for more cups at the margin of n's utility for cups. At a certain price relationship between water and cups for person n's practical desire for them, the equation will balance, and likewise the producers of water and cups will seek to balance their production in the market to meet those relative values reflected in the price relationships for the collective group of individual consumers, each having different utilities for water and cups, or any other good (This relation also applies to any set of goods as long as the equimarginal principle of maximization holds).

- Rearranging the equation further gives

$$\mathrm{MU}_{\mathrm{w}n} \times \mathrm{MPP}_{a\mathrm{w}} = \mathrm{MU}_{\mathrm{c}n} \times \mathrm{MPP}_{ac} \tag{8.6}$$

This says that the marginal utility of an additional unit of water for person n multiplied by its MPP of some amount of additional water produced with some amount of input a (labor and/or capital) equals the marginal utility for that person of another or additional cups multiplied by the production of another or extra cups manufactured with the same amount of input a (from a different group of labor or set of capital). To understand the units in the mathematics, this can be expressed as:

(Utility of water/Unit of water) × (Units of water/Units of input a)

= (Utility of cups/Unit of water) × (Units of water/Units of input a)

Then canceling the units gives the following:

Utility of water/Units of input a = Utility of cups/Units of input a.

Thus, for person n, the marginal utility of additional water produced by input of a just equals the marginal utility of more cups produced for the same amount of input a in competitive labor and capital markets. This represents the possibility of balancing demand with factors of supply.

- Also, since the price of input a in that competitive labor and capital market should be the same for either producing water or manufacturing cups, then

$$P_a = P_{\mathrm{w}}(\mathrm{MPP}_{a\mathrm{w}}) \text{ and } P_a = P_{\mathrm{c}}(\mathrm{MPP}_{a\mathrm{c}}) \tag{8.7}$$

This translates to the price of labor and capital, P_a measured in \$/time unit, is equal to the price of water, P_{w}, multiplied by the marginal product of producing additional units of water over that same timeframe and is also equal to the price of cups, P_{c}, multiplied by the marginal product of producing additional units of cups over that timeframe.

What might be the further significance of this set of equations? If input a represents one person to pump (labor) and a hand pump (capital) in the case of water or one person to mold a cup (labor), one cup mold and a limited amount of clay to fill a mold (capital), will the addition of another person in either circumstance produce more water or cups? If the answer is no, then the MPP of that additional person in either case is zero and the economic decision would be not to add more labor until more capital is used for more pumps, molds, and clay—the equality represented in the equations holds.

The concept of "utility" assumes a certain level of information existing in the market about product or service. To continue with the water and cups example, the consumer may need to know how much water is necessary to drink to maintain an adequate level of health. If the local water is untreated and has high levels of certain metals in solution with the water that could harm the consumer, finding an alternative source of water may be required. This latter circumstance could affect the marginal utility of untreated water and other waters, which, in turn, will affect the value of the different waters and the prices that the consumer is willing to pay for them. Thus, information may affect the individual utility and therefore demand for particular products and services.

INFORMATION EFFECTS ON INDIVIDUAL'S TASTES AND PREFERENCES

An individual's tastes and preferences, which may serve as a basis for utility, are influenced by information. In our current world, a significant component of information to influence purchasing of goods is advertising. One view of advertising is that it has a positive effect on the economy by spurring increased demand and promoting competition for products and services. In turn, consumers benefit from lower prices, which stimulate more sales of larger quantities to the benefit of producers and allowing them to lower the costs through economies of scale. Such processes promoted by advertising may influence cultural values. In the global economy, advertising may affect consumer purchasing worldwide (MSC, 2005).

Worldwide in 2004, the retail industry has calculated that it spent \$246.1 billion on advertising (\$25.1 billion of which was for Internet advertising) (IIM, 2005; NYTC, 2005), while other sources suggest that this expenditure is as large as \$350 billion (MSC, 2005). Whatever the correct figure is, it is a very large sum spent annually to influence people's tastes and preferences on what they spend their money in the marketplace. In relation to the sales of groundwater, the bottled water industry in the United States spent \$42.9 million dollars in 1990 to market water, some of which came from underground sources (NRDC, 1999, citing Business Trends Analysis, Inc., 1992). Thus, the market for some amount of water used directly as a final product is viewed as being able to be influenced by targeting information at people to buy more water. The irrigation industry, promoting the sales of its equipment for the largest use of groundwater, uses advertising for agricultural and other irrigation markets segments (for example, see IndiaMart, 2005; Rain Bird, 2005).

A critical question about information, and specifically information used to influence people's tastes and preferences to affect purchasing goods and services in the market, is "Since advertising messages are from private corporations with their own self-interest at stake, will the messages fully convey the scope of information necessary to adequately inform the consumer about the full range of outcomes and consequences resulting from being influenced to purchase a particular good or the services emanating from it?" This is important particularly when the "good" or the "service of a good" turns out to be "bad," such as a product that involves greater water use that may be a wasteful use when water is scarce or that has polluting potential. Encouraging greater water use in locations with declining water tables and aquifers being depleted may not be "good" if little precipitation is ever expected. In these cases, advertising may be harmful to the long-term well-being of the people who live in those areas. Products could include more complete consumer information on the results of using products or services so that the purchasers have a broader view of the product they are buying, including ecosystem effects of a long-lasting nature.

ECONOMIC UTILITY AGAIN

In practice, a person's utility for groundwater may be a composite of factors that then responds to their tastes and preferences. Hanemann (2005, p. 23) notes that water is not a homogeneous commodity, but has a range of characteristics, including quantity, location, timing, quality, and variability/uncertainty. To a groundwater user, water delivered in a different volume, place, time, and with a different chemical or microbiological composition may have an entirely different usefulness than other groundwater. Untreated groundwater for irrigation on a farm has a different utility than treated groundwater delivered to an urban apartment. Because of treatment and piping, it will also have a different cost. Reliability of supply and consumption can vary with time of the year.

Relying on the Lancaster (1966)–Maler (1974) model of utility, Hanemann defines a utility function that takes into account the range of characteristics of water:

$$u = u(x1, x2, \ldots, x\mathrm{N}, q1, q2, \ldots, q\mathrm{N}, z) \tag{8.8}$$

where

xi, separate (water) commodities, based on their characteristics

qik, the amount or level of the kth characteristic associated with one unit of consumption of commodity i

z, other consumption

In defining the utility function for groundwater in this way, one can consider pricing water relative to the user's demand for volume, place, time, composition, and reliability of supply. The changing characteristics of groundwater indicate different commodities from the user's perspective.

WILLINGNESS TO PAY

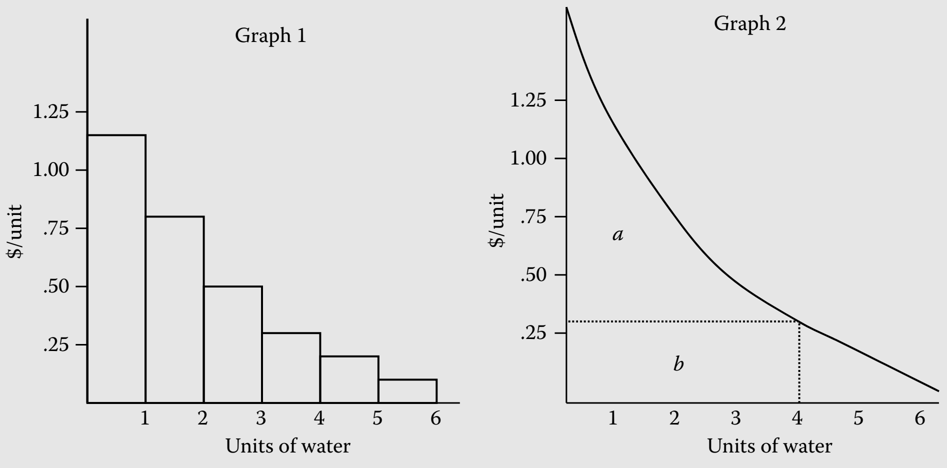
As consumers value different sets or "bundles" of goods and services, as suggested by the groundwater utility function just presented, they manifest their preferences for more or less of them by their "willingness to pay" for those goods and services. Willingness to pay is defined as "the maximum sum of money the individual would be willing to pay rather than do without an increase in some good" (Freeman, 1993, p. 8). A person can go to the market (store, outlet, shopping mall, etc.) where goods are exchanged for money and decide whether they are willing to pay the prices or not. If some items sell for a very low price relative to the consumer's value for that item, the consumer may actually buy more of them. On the other hand, if the price is too high in comparison with what the consumer believed was the value for the good, then the purchase may be less. In the market today, clearly many types of choices exist for purchase (i.e., food, clothing, shelter, entertainment) and the choice does not only concern quantity (how much to buy) but also quality (e.g., synthetic or leather shoes). A person's value for a particular good is measured by the amount of money or other item(s) of worth that will be given for it (Field, 1994, p. 47). The sacrifice in this sense is the giving up of money that would enable a purchase of a good. A land purchaser may be willing to pay more for land that has groundwater close to the ground surface and therefore having lower groundwater access costs than a similar property with groundwater at much greater depth (and greater drilling and well installation cost). Exhibit 8.1 graphs an example of a hypothetical willingness to pay, in this case, for water.

A similar concept to willingness to pay is “willingness to accept.” Willingness to accept is defined as the stated compensation level (price) that an individual must receive to accept a given or prescribed risk or the loss or diminution of an environmental service (NRC, 1997, p. 173; OECD, 2005). A person may be willing to accept payment of sum of money for loss of a right to pump unrestricted amounts of groundwater as long as the person has access to water supply for essential needs.

In the hypothetical case of willingness to pay for water, Exhibit 8.1 allows us to consider both marginal and total amounts that the consumer might be willing to pay for more water. Focusing on the marginal willingness to pay, Graph 1 indicates that for the first unit of water (perhaps a liter or some other appropriate volume), the individual would be willing to pay $1.15, but after that the willingness drops off. For one more unit in addition to the first, the individual would pay $0.80, for the third, $0.50, and for the fourth, only $0.30—this last value is nearly a quarter of the amount paid for the first unit (Considering actual use, health advisories suggest that a person consume approximately two liters of water per day—about half of total water consumption for an adult who also eats normal portions of other meals and snacks (receiving water from “solid” foods) and consuming other beverages [Tufts University, 2004]).

Total willingness to pay measures the complete amount a consumer would pay for a particular number of units of a good instead of fully foregoing them (Field, 1994, p. 47). In the hypothetical case of Exhibit 8.1, this person’s total willingness to pay for four units of water is $2.75, which equals $1.15 for the first unit plus $0.80 for the second unit plus $0.50 for the third unit plus $0.30 for the fourth unit. This amount is equivalent to the area under the curve of Graph 2 up to four units, which is also the same as adding together areas *a* and *b* under that curve. In the market, the consumer pays $0.30 for each unit of water. In Graph 2, 4 units of water with a price of $0.30 per unit has a total exchange value equal to area b.

EXHIBIT 8.1 WILLINGNESS TO PAY FOR A GOOD—A HYPOTHETICAL CASE OF WATER



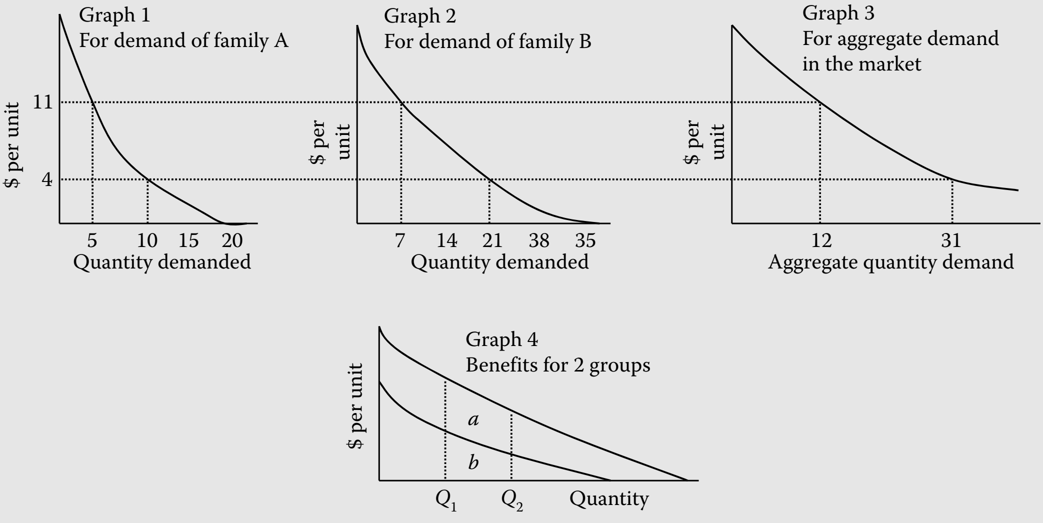
Source: Adapted from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 47.

DEMAND

Willingness to pay for a good or service may also be thought of as a person's demand for that good or service. Typically, in the market, many people have utility for and therefore demand for goods and services. However, their utilities and resulting demands may be different. This circumstance is reflected in Exhibit 8.2. Graphs 1 and 2 portray the marginal willingness-to-pay or demand curves for two families in a village that has a market. The quantities demanded for the same prices are not the same for each family. Their combined total demand, or "aggregate demand," is presented in Graph 3, indicating that at $4 per unit the demand in the market would be 31 units, but at $11 per unit, would be only 12 units.

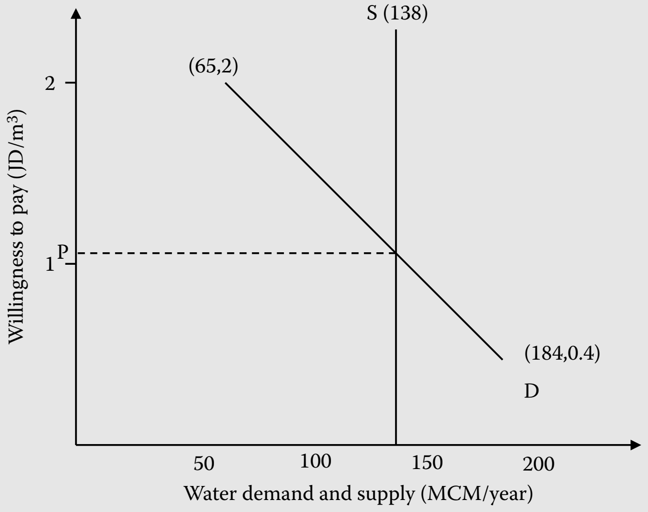
In the field of groundwater, a demand for a number of goods, such as drinking water or irrigated crops, may come to mind, based on the context previously discussed in Chapters 1 through 7. Demand for groundwater to supply a basic need to quench thirst may be the most obvious. Agricultural irrigation is the single largest use of groundwater worldwide. Demand for groundwater to maintain streamflow and wetlands in dry seasons may be acute during a drought. Groundwater discharge to streams, wetlands, and coastal areas exceeds that used in irrigation. Water for irrigation usually has a cost to produce even if the farmer owns the land—the water consumer has to install the well, pump, and distribution system for the water, as well as use energy in some form to pump the water out of the ground and through the system. If they had to pay the same for the groundwater as an urban water consumer, would they still irrigate? Probably not, since their per unit cost for groundwater has to be a small part of the cost of producing the crops to be competitive in the world market. And if they pump such a large volume of water that they reduce the flow of an adjacent stream, will they include the cost of the lost stream water and the affected wildlife as a water use cost? These questions get us into the realm of water production being an intermediate good in the production of other goods. Before we address that subject, we will briefly cover measurement of benefits from goods.

EXHIBIT 8.2 DEMAND AND BENEFITS CURVES



Source: Adapted from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 50–51. With permission.

EXHIBIT 8.3 WATER DEMAND IN AMMAN AREA OF JORDAN



Source: Adapted from Schiffler, M., *The Economics of Groundwater Management in Arid Countries: Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, London, U.K., 1998, 271. With permission.

Exhibit 8.3 shows the essential information used to develop a demand curve for groundwater based on willingness to pay in the Amman, Jordan area (Schiffler, 1998, p. 271). It uses prices and estimated quantities of public and vendor-sold water in association with demographic and economic data to establish a demand curve. At Jordanian dinar (JD) 0.4/m^3, 184 million cubic meters/year are projected to be demanded based on the then current public water charge. At JD 2/m^3, only 65 million cubic meters would be expected to be demanded, derived from purchases from water vendors. An average price of slightly more than JD 1/m^3 is then established for an inelastic supply curve.

BENEFITS

In environmental economics, "benefits are the gain associated with an environmental improvement" (Freeman, 1993, p. 8). From the perspective of the groundwater resource, an environmental improvement might be a good such as inducing more precipitation to infiltrate to recharge an aquifer. If people value having more groundwater, then we may be able to measure the volume and calculate its benefit to them. This result would be a gain and people would be better off. If an aquifer recharge zone is paved and built over, reducing the volume of water being able to reach the aquifer used by the population of a nearby town, then the benefit of the groundwater may be eliminated in whole or part with the townspeople being damaged by this result.

Benefits may be measured by various economic methods (Freeman, 1993). Exhibit 8.2 indicates conceptually how this might be done. Graph 4 has two different demand curves reflecting the willingness to pay for more quantities of some good, such as more groundwater storage in the ground; the community may have had shortages in the past. The initial quantity, q_1, will be increased in aggregate amount to q_2. The lower demand curve may represent apartment dwellers in the community whose demand for groundwater does not fluctuate much. If more water were available, they might wash their cars more often. The upper demand curve might be for suburbanites who have wanted to put in gardens but have had just enough groundwater to meet their typical home maintenance needs. They see a specific benefit from increased groundwater availability. As long as the two groups are willing to pay for their greater water use, they benefit from more water being available. However, the benefits they derive are distinctly different. The benefit for the apartment dwellers from the increased amount is b, but that of the suburbanites is $b + a$. Clearly, this result mirrors the difference in values for and willingness to pay for increased water supply.

SUPPLY

Production Function. Supplying a good to the market may involve employing a range of people and resources locally and beyond the community, depending on the nature of the product or service. A basic production function is $Y = f(L, K)$, which says output (Y) is a function of labor (L) applied and capital (K) used. Furthermore, the quantity produced and supplied should be related to that demanded, as the basic market equation indicates. A supplier can build his capability to produce a good and once done will typically be able to provide many more units of it. Production of groundwater usually requires a number of input factors: installation of a well and pump, construction of a distribution line, energy source to operate the pump, and staff for maintenance of the system. The well, pump, and distribution system might be considered capital stock, but if financed over time may be a fixed cost each year; staff and parts for repair would be fixed costs, and energy use may be a variable cost depending on time of day, week or season of the year. From the incidence of costs for producing and providing groundwater a cost curve can be developed.

A firm's basic decisions about supplying groundwater (or any other product or service) can be modeled in a set of simplifying equations. In practice, the equations may become more complex depending on the requirements of production, such as treatment or specific needs, and depend on assumptions about the ease of specifying relations among inputs to production. Before investing in the capacity to produce groundwater, a firm must have some sense of whether the product it wants to produce will have buyers who have demand for its output over time to warrant investment in equipment and materials for production. The firm would have done some market analysis. At this point, we will simply note that water is essential to all human beings and other living things, so there is a demand. We will also note that many firms produce groundwater, so the fundamental production relationships are known.

A basic production function for water is (adapted from Young, 2005, p. 54):

$$Y = f(X, G, K) \tag{8.9}$$

where

Y is the output of water and a function (f) of the input factors on the right-hand side of the equation
X is the variable inputs, including labor
G is the groundwater from the aquifer
K is the fixed factors of production

The factors of production may be further specified, such as:

X, variable inputs = Labor (L) to operate and maintain a pumping well + Energy (E) to pump water from the aquifer to the ground surface = $X_L + X_E$

G, groundwater of quality 1 during normal pumping + groundwater of quality 2 during peak pumping, if greater pumping at peak demand times pulls groundwater from portions of the aquifer that have a different quality = $G_1 + G_2$

K, Capital, such as a well, pump, machinery, and treatment equipment (W) + Other owned inputs (M) that could include land, management, and entrepreneurship (Young, 2005, pp. 77–79) = $K_W + K_M$

Further specification is possible depending on the complexity of the situation and the need to use a more refined approach. Thus, a more fully specified equation for groundwater production might look like:

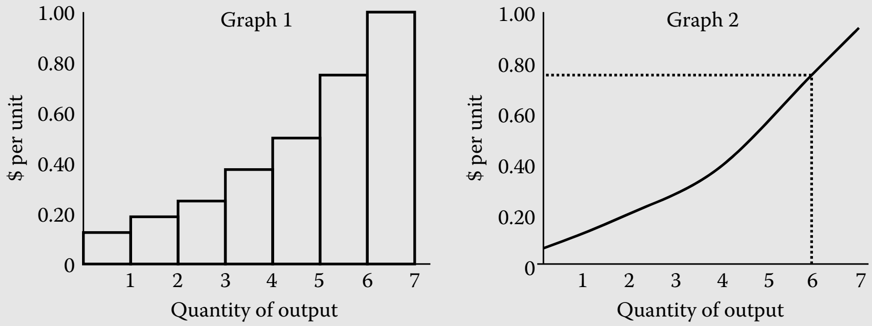
$$Y = f(X_L, X_E, G_1, G_2, K_W, K_M) \tag{8.10}$$

A numeric example is provided later in this section to show how to think about this economic relationship embedded in the production function.

Costs of production. The costs of supplying groundwater to a community can be described on a "per unit" basis, such as per kiloliters or cubic meters. This "per unit" measurement allows both marginal and total costs (TCs) to be derived. Wells of different sizes (such as 5 cm diameter versus 25.4 cm diameter) and depths (30 m compared to 100 m) will have different costs associated with them to install the well and to pump the water (The size of the well should be based on the expected demand for water.). The production of groundwater from different wells will have different cost curves based on their respective production relationships as a result. One hypothetical cost curve is presented in Exhibit 8.4. Graph 1 shows that the first unit will cost about \$0.15 to produce, the second, \$0.20, and the seventh unit, \$1.00. Graph 2 smooths the marginal cost (MC) display out to portray TC as the area under the curve. For some goods, a rising MC curve is typical, for others, MCs may fall and then rise. Such a condition may exist where low-volume demand can be satisfied by local resources, but increased output requires inputs from longer distances that cause costs to rise. In most situations, the cost to produce groundwater often has a declining cost curve because investment costs are spread over more and more units of water when more is demanded and supplied and operation costs are low. Notably, in these cases, no charge for the water itself is made—who will bill nature? However, where groundwater is being mined and depleted and it must be pumped from greater depths, production costs can increase.

Two types of MC curves apply to evaluating the provision of a good: short-run and long-run curves. Short-run MC curves usually fall and rise more steeply, reflecting the circumstance that, over short periods, the relation of inputs to each other are relatively fixed and unchangeable. To produce more water, a well manager may be able to increase the rate of pumping, in which case the pump will be more inefficient for the energy used, so costs will rise, but no more staff can be productively used in this case. In the long-run, another well can be installed with a more efficient pump due to technological advances, allowing the MC of producing more water to be lower for the same increased quantity. Long-run MC curves are typically more gently falling and rising than their

EXHIBIT 8.4 SUPPLY CURVES



Source: Adapted from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 55. With permission.

associated short-run complements. This flatter long-run MC curve results from improvements in production not possible in the short-run.

AN EXAMPLE IN GRAPHICAL FORM

Exhibit 8.5 provides an example of a partial equilibrium analysis of supply and demand relationships for a marketed commodity. In this example, the cost of supply declined (it cost less to produce a unit of a hypothetical commodity in this case), shifting the supply curve from S_1 to S_2, with demand staying at the same level and with more units produced or demanded moving to the right on the quantity axis of the graph. The quantity available increased and the new price is lower in the market, reflecting the efficiency. The supply curves reflect the producers' costs per unit at each quantity made available. Notably, the line segment WZ indicates the decrease in supply cost, which is different than the change in price, $\text{Price}_1 - \text{Price}_2$. The demand curve, *D*, gives the consumers' willingness to pay for one more unit at each increment of quantity. The demand curve portrays the consumers' willingness to pay for each additional unit. The graph indicates that the consumer has a high benefit for the first units (the difference between the demand curve, *D*, for any quantity and the horizontal axis), but less so as more units are supplied. At the intersection of the supply and demand curves, the market is considered to be in equilibrium and sellers are just willing to accept the amount that consumers are just willing to pay. Since the consumers only pay the price in the market and not a different price at each quantity, the area above the price line is considered the "surplus" benefit, in economic terms. This surplus is area a for Price_1 and area $a+b+c$ for Price_2. The difference in the area between the two prices is the change in benefit to consumers from the change in supply costs.

MONOPOLIES AND SUPPLY

The examples and descriptions in the preceding sections, "Demand" and "Supply" assume a competitive market exists for factor inputs that provide the labor and capital to firms and the firms that are the producers and manufacturers of goods that are offered for sale and exchange. This is portrayed in Exhibit 8.6,

EXHIBIT 8.5 PARTIAL EQUILIBRIUM ANALYSIS OF SUPPLY AND DEMAND RELATIONSHIPS FOR A MARKETED COMMODITY

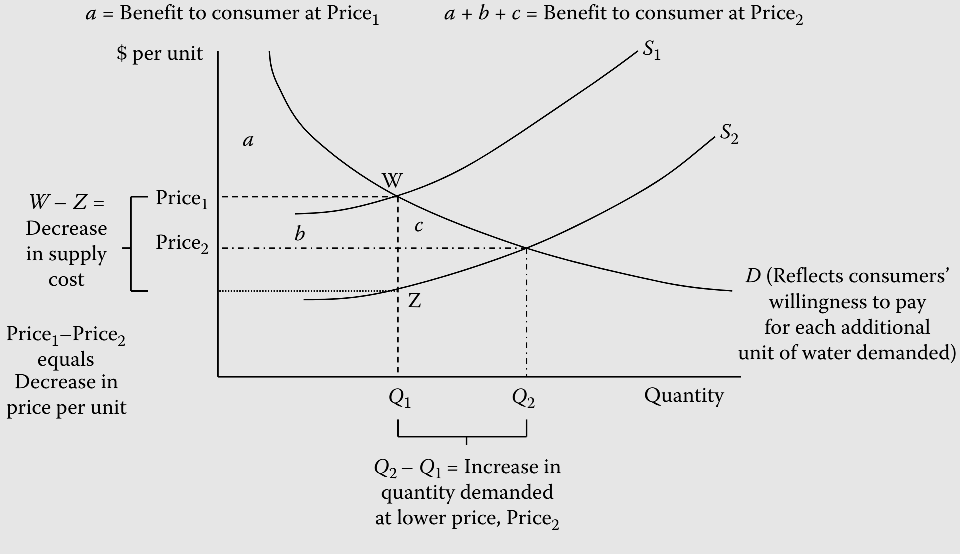
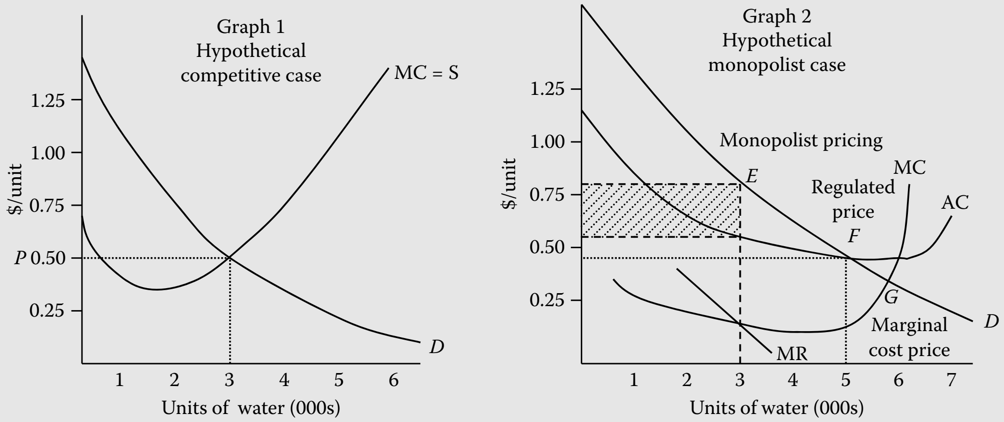


EXHIBIT 8.6 COMPETITIVE AND MONOPOLIST PRICING



Source: Adapted from Samuelson, P.A., *Economics: An Introductory Analysis,* McGraw-Hill Book Company, New York, 1964, 468, 491. With permission.

Graph 1, in which price equals MC, $P = \text{MC}$. However, these conditions do not apply when there is a sole producer of a good, called a "monopolist." In the relevant range of the market, the monopolist finds the MCs falling and to obtain the best profit seeks to maximize revenue while the marginal revenue (MR) is less than the competitive price (Samuelson, 1964, p. 491); in the equations below $\text{MR}_\text{w} < P_\text{w}$. Daly and Farley (2004, p. 134) indicate mathematically the circumstances that affect both consumer and monopolist. In this case, MR substitutes for the price of a good. The MR for water, MR_w, will substitute for P_w in the right-hand side of the basic market equation:

$$\text{MU}_{\text{w}n}/\text{MU}_{\text{c}n} = P_\text{w}/P_\text{c} > \text{MR}_\text{w}/P_\text{c} = \text{MPP}_{a\text{c}}/\text{MPP}_{a\text{w}} \tag{8.11}$$

Rearranging the inequality:

$$\text{MU}_{\text{w}n}/\text{MU}_{\text{c}n} > \text{MPP}_{a\text{c}}/\text{MPP}_{a\text{w}} \tag{8.12}$$

Expressing the inequality in terms products:

$$\text{MU}_{\text{w}n} \times \text{MPP}_{a\text{w}} > \text{MU}_{\text{c}n} \times \text{MPP}_{a\text{c}} \tag{8.13}$$

This last inequality indicates that consumer n has a higher utility for more input a to be applied to satisfy the demand for more water but the action of the monopolist is to constrain further application of input a to produce more water. To do this, the monopolist would not be maximizing profit, so the production is less than desired by the consumer.

Exhibit 8.6 shows the result of the monopolist graphically (adapted from Samuelson, 1964, p. 491). Graph 2 shows the MR below the MC price at *G*. MR intersecting MC gives the amount of production. The monopolist tries to maximize profit at a price along the demand curve *D* relative to the average cost (AC) intersection with the demand curve. This intersection might be the regulated price *F* (the regulatory authority will attempt to bring the price down to as close to the MC price *G* as possible and eliminate as much of the excess profit as it can). The monopolist price at *E* is the average revenue (AR) per unit of production. Subtraction of AR from AC gives the profit for the monopolist, equal to the shaded (cross-hatched) area. If unregulated, the monopolist could capture more excess profit by charging a declining block rate for the earlier units, starting up higher on the demand curve to define the block charges. Many water utilities are monopolies and use a declining block rate structure, which encourages more water use in the large low-rate blocks.

PRICE IN A COMPETITIVE MARKET

Price in a competitive market is obtained where the MC—or supply—curve intersects the demand curve. While water—specifically groundwater—is not offered in the usual sense in a competitive market (one may argue that bottled groundwater and tradable water rights may be examples of exceptions), some of the intermediate components of supply are offered competitively to producers. For example, needs for well installation may be offered for bid to a number of well drillers. For well drillers competing to install wells, their demand for well casing, grout, concrete, or pumps may be such that a number of suppliers offer such products competitively. In Exhibit 8.6, Graph 1 shows a hypothetical case of competitive market pricing. In this case, the MC curve intersects the demand curve and establishes $P = \$0.50$ as the price for three units of production. Thus, $P = \text{MC}$, price equals MC is the "market clearing" position for this exchange.

ECONOMIC EFFICIENCY

From a neoclassical microeconomic standpoint, economic efficiency should be the primary goal of a society (Young, 2005, p. 21), but not the only goal. Another goal may be the distribution of resources in the economy among individuals or groups of people, also referred to as equity. Economic efficiency is the unique allocation of resources such that no other allocation creates the circumstance that someone has a further improved condition at the same time no one else is in a worse state. Otherwise, a "welfare waste" would exist in the original allocation (Bannock et al., 1978, p. 144). This definition is called "Pareto optimality" and is further discussed in Exhibit 8.7. In the neoclassical school, economists use their tools, such as incentives, taxes and subsidies, to enhance the allocation of resources. They compare the "world without" their proposed tool to the projected "world with" the tool in use.

ASSUMPTIONS USED TO DERIVE "COMPETITIVE MARKETS"

Neoclassical economics has established a set of assumptions used in defining competitive markets, which do not apply well to groundwater. The assumptions include (Barlowe, 1972, p. 121):

1. Human beings are rational beings who behave logically and reasonably
2. Human beings act to maximize their self-interests
3. Prices allocate resources

Other assumptions applied to balance markets (supply and demand) are (Barlowe, 1972, p. 121; Schiffler, 1998, pp. 25–39; Daly and Farley, 2004, p. 125):

4. Perfect competition
5. Perfect knowledge among buyers and sellers
6. Perfect mobility of goods and productive factors
7. Perfectly elastic supply of productive factors
8. Spontaneous order and efficiency
9. Substitutability of inputs

Whereas use of these assumptions may be criticized, they allow less significant factors to be "held constant" while focusing greatest attention on the most influential factors affecting economic response. Each of the assumptions will be reviewed relative to its application to the groundwater resource.

EXHIBIT 8.7 PARETO EFFICIENCY CONDITIONS

The concept of economic efficiency in neoclassical economics was developed by Wilfredo Pareto (1848–1923), an Italian economist and political sociologist. Pareto's influential writing, *Manuale d'Economia Politica* (1906), provided the foundation of modern welfare economics. In it, he developed what is referred to as the concept of "Pareto optimum": "the optimum allocation of the resources of a society is not attained so long as it is possible to make at least one individual better off in his own estimation while keeping others as well off as before in their own estimation" (Weiner, 2006). This condition only applies in a "perfectly functioning competitive economy." It is "achieved when the marginal benefits of using a good or service are equal to the MC of supplying the good" (Young, 2005, pp. 17–18).

Several tenets must operate for Pareto optimality to occur (Young, 2005, 28):

1. "Individual preferences count; the economic welfare of society is based on the economic welfare in aggregate of its individual citizens"
2. "The individual is the best judge of his/her own well being"
3. "A change which makes everybody better off with no one becoming worse off constitutes a positive change in total welfare"

Since most changes in policies or decisions result in benefits to one person or group and losses to another, economists have developed a way around the third tenet: referred to as "potential Pareto improvement," "if gainers could in principle compensate losers and still be better off, the change is deemed acceptable, whether or not the compensation actually takes place" (Young, 2005, 28). This latter explanation is central to the basis for calculating benefits of actions or projects affecting water or other resources.

Sources:

1. Weiner, S.D., *Wilfredo Pareto*, 2006, URL: http://sdweiner.home.texas.net/d/archive/theory-method/WILFREDO_PARETO.htm (accessed September 2, 2006).
2. Young, R.A., *Determining the Economic Value of Water: Concepts and Methods,* Resources for the Future Press, Washington, DC, 2005, 357.

BEHAVING LOGICALLY AND REASONABLY

Perhaps from a resource use and environmental perspective, this assumption is of most concern. Historically, when population was small and chemical production and use were minimal, and certainly not broadly applied across the landscape, what individuals did to the land surface and below it, did not cause much problem to themselves or others. In the past, what one did to the land, nature took care of and the effect on well water was not measurable or perceptible, if anything happened at all. Nature could degrade the simple wastes from human activity, then. This was common knowledge and was accepted for a long time. As population density increased, and complex chemicals were formulated for many uses, people acted as though the common knowledge was still operable, and even logical and reasonable. A new perspective has evolved from the fields of hydrology, hydrogeology, and microbiology. This revised understanding indicates that changes in behavior toward the ecosystem we share with all other living organisms are necessary relative to what is logical and reasonable, and even profitable. This revised understanding is briefly reviewed here.

The new perspective that has emerged with respect to logical and reasonable behavior incorporates an improved understanding of the subsurface environment. After the illnesses resulting from past concentrated chemical waste disposal at Love Canal, New York, the discovery of millions of underground storage tanks that continue to have the potential to leak around the

United States, and the densely placed and improperly functioning septic tanks in many locations affecting local water supplies, hydrogeologists discovered that the subsurface environment does not function as common knowledge would have us believe.

Common knowledge no longer leads us to logically and reasonably understand that when someone puts a waste on or in the ground, it is "filtered" or "bound up" so as not to be a problem. Groundwater flows from one property to another, it flows into rivers and lakes, it flows more quickly in certain hydrogeologic settings than in others. Organisms are being discovered in groundwater close to and away from streams. Some biologists believe that an enormous biomass made up of microorganisms and macroinvertebrates are an important link in the food chain and live not only in the subsurface, but also in groundwater (Gibert, 1994), some organisms processing wastes and organic matter (Danielopol et al., 2003, p. 120) and other organisms perhaps being killed by chemical residuals in groundwater (Notenboom and van Gestel, 1992, pp. 311–317). Currently, scientists are still trying to understand the function of these organisms and their role in the ecosystem (as noted in Chapter 2). Because groundwater moves slowly, that part of the biosphere is a very stable environment—fairly constant temperature, no sunlight, and, in the shallow unconfined aquifers, having low oxygen concentrations. Common hydrogeologic understanding of groundwater and the subsurface environment is that it is at least as complex as the surficial landscape environment and must be carefully examined before discarding waste or using the resource profligately.

Some chemicals break down after a time—but their byproducts are not well understood and in fact may be more toxic—while others bind themselves to clay particles, and others are soluble and move easily with groundwater. No two chemicals will necessarily respond similarly in groundwater or the subsurface. Scientific common understanding is that chemicals within the same class may respond similarly, but the numbers and classes of chemicals are growing and becoming more complex.

While these new understandings are changing how people use and influence the subsurface environment, not all people are willing to accept this new set of knowledge, which has grown substantially since the mid-1980s. National laws in the United States do not acknowledge current hydrogeologic understanding. For example, the Clean Water Act does not recognize that groundwater and stream water interact and affect the quality of the other. As noted in Chapter 5, other countries have laws that incorporate this interaction and flow of the larger water resource. But financial interests involved with transferring large properties have accepted this new common scientific knowledge: Banks routinely require a commercial or industrial property assessment for subsurface and groundwater contamination before lending money to a potential buyer. If the groundwater is contaminated and should affect nearby properties' water supplies or the use of the property being transferred, the bank may be holding a liability that has less value than previously. In such a case, the bank may need to spend money to remediate the problem if the mortgagee defaults. The banks are protecting their self-interests: maximizing income from lending money through interest charges and minimizing potential future large costs in financing investments with knowledge of contamination first. A lesson from hazardous waste site cleanup is that groundwater remediation may be expensive and difficult. Long timeframes for cleanup represent more cost, which may not necessarily be balanced with income, depending on the use of the property.

The financial institutions have become logical and reasonable in considering the subsurface resources their investments represent. The information about actual or potential contamination of soil and groundwater has affected their demand for different commercial and industrial properties. Carried to one extreme, this knowledge combined with the current understanding of hydrologic processes have led bottled water companies to purchase or acquire access to relatively pristine areas of the United States for future production of clean, safe groundwater, which they may use as a factor input to future bottled water supply (for example, see Glennon, 2002).

Thus, the assumed expectation of the results of logical and reasonable behavior may not have caught up with reality, with people largely acting as if no change in demand or impact from residuals has occurred in most situations. Logical and reasonable action toward the groundwater resource may not be fully informed.

MAXIMIZING SELF-INTEREST

The "economic person" acts to maximize economic returns. This is most evident in businesses that work to earn the highest profit. Investors attempt to put their money into financial instruments with the greatest return or interest rate. However, each investor balances risk and uncertainty against the greatest returns differently. Maximizing current returns may be balanced with maximizing a stream of expected returns into the future. An investor may accept a lower return now for a stable, continued return in the future. For example, if all the water is pumped out of an aquifer (an extreme case, admittedly) now so that no or limited water is available in the future, total return may be maximized to the individual; the alternative of gradual production over time unfortunately may result in lower return in terms of net present value, since future income would be discounted. Perfect maximization, however, requires perfect foresight to predict what will happen. Since no one is capable of this, application of probability and reason tempered with risk acceptance controls the process of individual maximization of self-interests. Use of groundwater at a point of safe yield may be preferable to the individual than overdrafting—but this requires greater knowledge of precipitation, geology, pumping rates, evapotranspiration, and many other factors in the vicinity affecting the amount of water in the ground at any one place and time. In this latter scenario, individual self-interest, when looking to the future, may give way to community or social interests serving many individuals. At this point, law gives rights to individuals and controls their responses through the legal and economic systems, which may result in pumping groundwater to depletion and saving none for future generations.

The issue that the use of common property resources poses reflects the dichotomy between individual near term maximization of self-interest and the effect of maximizing community interests on the individual user of groundwater. Hardin (1968) highlights the impact that one user of a community resource can have on other users when only considering the benefits and costs to himself, except that every user was that individual user acting to maximize self-interests and the common resource (a common, shared pasture in Hardin's example) was lost unanticipatedly. For groundwater resources, this could be excessive use—for either water production or waste disposal—by isolated individual actions happening through many individuals in an uncoordinated manner, diminishing the use of the resources for everyone. Focusing on self-interest alone may not provide sufficient direction to use groundwater resources wisely for the collective and long-term welfare and benefit. Providing an adequate supply of public goods is generally recognized as a challenge and failure of a totally free, competitive market with no institutions defining rights to these goods. This is particularly true as a growing population using a limited public good causes it to become more scarce and unable to sustain the population (Daly and Farley, 2004, p. 161).

PRICE ALLOCATES RESOURCES

The price of a good or commodity, such as groundwater, is its monetary value to the purchaser as it is being brought into use. The supplier of a commodity can place a price on a given amount of water based on what it cost him to produce it. If the supplier's price is too low relative to the value that a consumer might place on it, the consumer may use (or demand) more units of water than he can efficiently use, thereby engaging in wasteful practices. The converse may hold also. In this way, resources are allocated—the resources for the final product, e.g., drinking water, and also the services used in supplying it.

While prices allocate resources in a free market situation, some circumstances may interfere with the allocation of groundwater through the price mechanism. In times of shortage, such as low seasonal precipitation reducing water availability, the water utility may require rationing to allow some equitable distribution of the resource to meet minimum needs. It has been suggested that water is typically undervalued and we come to understand its value when it is scare to allocate.

Furthermore, price does not take into account the critical needs of the ecosystem of which we have little understanding and need more research and information to recognize needed water allocations essential to this function. Pricing does not take into account harm to neighboring users and to streams with reduced flow because of shortsighted or ill-planned groundwater pumping. Nor does it take into account effects on land subsidence or saltwater intrusion in coastal areas. We have not provided safety margins to manage groundwater pumping or to more fully protect the subsurface from contamination, which will affect supply cost and price of water supplied. One bright spot is wellhead protection which is voluntary in most of the United States and required in the European Union to manage contaminant sources that could affect groundwater capture zones around wells, but often these steps only actively consider a 2 or 3 year time-of-travel protection zone for groundwater (Job, 1997). Thus, price typically only considers the immediate cost of supplying water and normal business profit, allocating the resource in the market with incomplete information in most circumstances relative to the longer-term costs of supply that should be incorporated in the price (Daly and Farley, 2004, pp. 412–414).

PERFECT COMPETITION

Perfect competition occurs when all the producers of a good are in a market, in which none of them individually can affect price and all are producing the good such that their marginal unit production costs are the same, regardless of how many cumulative units they are producing at that cost. Most drinking water suppliers are publicly regulated for health protection and are generally recognized as “natural” monopolies because of the perceived added cost of having more than one water supplier for a community. Irrigators may often be competing with other water producers in the sense of withdrawing large quantities of water from the same aquifer (a common, shared resource), since water is a major raw material in their agricultural production, accounting for 68% of all uses of groundwater in the United States and 74% worldwide. Irrigators do not typically have monopoly power in their use of water or for their agricultural production. Irrigators either have a use right that limits their groundwater production or must be reasonable in their groundwater use, governed by law. Perfect competition does not apply to groundwater production with the exception of bottled water production, where considerable competition exists to sell ground, spring, mountain, and processed water in bottles. These products try to distinguish themselves in the market based on water source and quality.

PERFECT KNOWLEDGE AMONG BUYERS AND SELLERS

Knowledge about water supply to a particular property is typically available, but must be sought. Information about drinking water supply has become more available in the United States with the implementation of consumer confidence reporting under the Safe Drinking Water Act Amendments that require water quality information for public water systems be provided to all consumers. However, as noted previously, the effects of withdrawing groundwater on the ecosystem and other people and other life forms inhabiting it, and of disposal of waste and chemical residuals underground is not fully understood. If one community’s or company’s unlimited use or pollution of groundwater could contribute to the loss of wetlands or a coastal fishery (for example, see Glennon, 2002), is that important knowledge for sellers and buyers of groundwater to have? Should that knowledge affect the cost to supply safe, usable water to the community or company causing the damage? And what is the cost of this damage and can it be reversed? Rarely is information provided through advertisement that a critical resource could be threatened, unless it is almost on the brink of loss, with unknown costs to sellers and buyers of the resource in the future. Perfect knowledge relative to groundwater in the market place does not exist.

PERFECT MOBILITY OF GOODS AND PRODUCTIVE FACTORS

Perfect mobility of goods and productive factors means that capabilities to produce a good and, once produced, the good itself can easily, and without additional cost that could affect price, be moved anywhere necessary. Water is not perfectly mobile; it is considered a high-bulk, low-value commodity in more humid areas, expensive to transport, inexpensive to store (Hanemann, 2005, p. 16), but essential and highly valuable in drier climates or times of the year when it is scarce. While groundwater is not considered highly mobile, its existence in drier zones contributes significantly to their habitability, considering drinking water, domestic, and irrigation uses. Productive factors—labor, drilling equipment, and capital—may be more mobile than the water itself, and in this case, contribute to groundwater being available in drier locations that have an otherwise attractive climate. The costs of moving groundwater may be substantial due to construction needed for conveyance by canal or pipe.

PERFECTLY ELASTIC SUPPLY OF PRODUCTIVE FACTORS

Perfectly elastic supply of productive factors implies that regardless of the quantity of groundwater demanded, the factors to support its production will grow to meet the need. In other words, if there is an infinite demand, an infinite number of drill rigs with people to operate them, casing and pipe, grout and concrete, materials for hand installation of shallow and tube wells, and importantly groundwater will be there to provide the supply. None of the factors is infinite in its supply characteristics, including groundwater. In India and Pakistan, one million new wells are added each year and yet 25% of India's crop harvest may be at risk because of groundwater depletion (IWMI, 1998). Clearly, productive factors for groundwater production and food supply are not perfectly elastic.

SPONTANEOUS ORDER AND EFFICIENCY

Taking into account the considerations highlighted, markets are assumed to make possible "spontaneous order" (Daly and Farley, 2004, p. 125) in equilibrating prices among sellers and buyers and their respective supplies and demands. This is presumed to occur based on communication of exchange values among them and to result in orderly allocation of resources, products and services. However, as indicated above, relative to groundwater—and other resources, most likely—this is based on incomplete information. Even in circumstances where information exists, sellers (producers) and buyers may decide to ignore it or not pursue further inquiry about it because it does not fit their view of the operation of the economy in relation to the ecosystem that provides the resources.

Efficiency through this assumed spontaneous order in the market is characterized in neoclassical economics as the optimal allocation of resources (Pareto optimum, as noted previously). This efficiency is focused on the well-being of individuals acting on their own in the market (Freeman, 1993, p. 19) communicating with buyers and sellers, rather than considering individuals who are not isolated but are interacting and communicating with other individuals in communities (Daly and Farley, 2004, p. 262) and incorporating an understanding of their collective actions on the resources on which they all depend.

SUBSTITUTABILITY OF INPUTS

Neoclassical economics assumes that capital and labor are substitutable in the production function. "Two goods are substitutes if a rise in price of one causes an increase in demand for the other because the goods perform a similar function or serve a similar taste" (Bannock, 1978, p. 428). In reality, the extent to which this assumption applies depends on the application. Some economists, however, have indicated that water may be nonsubstitutable in most uses, but this depends on context and scale (Daly and Farley, 2004, pp. 91–92). Schiffler (1998, pp. 24–25) suggests, while water may be irreplaceable in some uses, it is human use that holds the prospect for at least partial substitution and that a range of substitution is possible for water along a continuum of six levels:

1. Water users can change their behavior while relying on the same inputs.
2. Water users can adopt existing water-conserving practices (this corresponds to the classical approach of a production function).
3. Demand for water-using products can shift to less water-intensive products.
4. Water users can relocate to places in which climate contributes to less water being needed.
5. Production of goods requiring intensive water use can be shifted to regions where climate allows less water use or water is less scarce.
6. New technologies are developed to use less water in production of goods, causing the production function to shift.

While these six levels can be observed, a basic relationship is not addressed by them: hydrologic cycling and natural services that provide public goods. At the most basic level, implied in the six levels of water substitution is that water is still needed and we cannot substitute it to a zero-use condition. Furthermore, groundwater cycling of nutrients and temperature flux is required for many aquatic micro and macroorganisms to exist; their habitat would disappear if groundwater did not perform the functions it does. In a more observable circumstance, groundwater provides geologic structure and support to maintain ground surface levels rather than contributing to land subsidence and hydrogeologic pressure to preclude salt-water intrusion where groundwater levels are maintained. It would be difficult to imagine a substance other than water performing these functions.

Substitution focuses attention on defined human economic processes that create demand for water. We can partially substitute capital or labor for water in some of these processes. Water scarcity may be a significant driver for this substitution.

DECISION MAKERS IN GROUNDWATER PRODUCTION

Most economic examination focuses on the decision-maker's optimization of providing or employing factor inputs to produce outputs, or the market's determination of equilibrium. The market equilibrium is defined by supply–demand analysis (Hirshleifer, 1976, p. 22). The decision maker optimizes inputs and outputs through the evaluation of total, average, and marginal relationships. Actually, many people may participate in the decision to produce groundwater. These participants may be the landowner, the groundwater abstractor and seller, or governmental representative trying to correct any economic issues that may arise. The natural conditions—depth to groundwater, type of geology, access to the well site, price of energy—are significant in affecting the cost of producing groundwater. A partial list of these decision makers include:

1. A land or home owner—A land or home owner deciding to develop a property and needing water must decide on the amount of water he needs over different intervals of time—e.g., per day or per year. Important factors with respect to quantity include, well depth, screened interval, pump size, diameter of casing, and the number of wells.

   If the water table elevation fluctuates significantly, the well may need to be deeper and the screened interval longer to ensure access to groundwater over the entire year and to reduce the need to have additional and deeper wells drilled. Pump size and casing diameter are directly related to the volume required to be pumped at any particular instant. All of these factors affect the cost to develop and supply water. The size of the pump and the depth from which it must push or pull the water up the casing will influence operating costs for electricity.

If the water is "hard" (higher mineral content) or has chemicals that need to be removed for human consumption or other use, groundwater treatment costs must also be included in production decisions. If the location of production is a distance from the location of use, a transmission line will be needed, usually installed below ground to be out of the way of activities on the ground surface and to avoid accidental breakage or tampering. Long distances can add large fixed costs for transmission pipes. Depending on maintenance, these costs may be considerable. Transmission losses through cracks in the line can add costs for additional pumping.

2. Well driller/installer—A well driller/installer is typically familiar with the soils and near-surface geology and the labor and materials costs of drilling and installing wells in a locality. Geological conditions under which groundwater is found and produced vary widely, even for locations just a few tens of meters apart in many situations. The well driller/installer must decide how much to pay his drilling assistants to obtain the quality of work that will guarantee proper well construction. He must also stay abreast of materials costs for well casing, screen, grout, and well protection. Equipment maintenance costs are also a significant factor. The well driller generally operates in a competitive environment and his rates (prices may be quoted on the basis of per unit of well depth and diameter, and type of casing and screen) must be adequate to cover costs but in line with other well drillers and installers. In less developed countries, millions of wells called tube wells have been installed by hand.
3. State or local technical/planning/zoning official or water master—A local planning/zoning official or state geologist can inform a land/homeowner whether his property is an area in which residential/commercial-industrial wells are allowed. Important considerations might include: location with respect to septic or waste disposal systems, limits on production over given timeframes or on pump size/capacity, depth to the top of the well screen, length of screened interval, and well capping and protection requirements. A State or local official may be required to issue a permit to the landowner or driller indicating proper construction of the well before it can be installed or used and limits on the amount of water that can be pumped and withdrawn. The State or municipality may also require a yield or aquifer performance test. In some countries, a water master may define the volume of water that a groundwater user may produce.
4. Water user association—Often defined in law, water user associations with responsibilities for coordinating groundwater use and management over large areas may have technical expertise that specifies the volume of water that can be pumped from an aquifer.
5. State/local public health official—A public health official may work along side a planning/zoning official to identify well location and groundwater treatment needs based on soil type and local water quality. A public health official may require that the groundwater be chemically and biologically tested before use.

   Relative to use of groundwater, state officials may determine that groundwater must be treated before human use because of naturally occurring or human-caused contamination of an aquifer or a portion of an aquifer. Local officials who are trying to promote greater groundwater availability and quality may encourage zoning to allow for storm water retention and recharge ponds to provide for infiltration of precipitation into the ground. Local or state officials may be responsible for determining the number, density, and depth of wells in aquifers to ensure a long-term supply and that adjacent users do not interfere with each other's use. They may also have responsibility through zoning and groundwater and land management regulations to prohibit or restrict certain land and subsurface uses associated with contaminants of concern that may compromise groundwater quality and use.
6. Fire chief—Fire protection is heavily dependent on a reliable supply of water that can be drawn immediately and in large volume rapidly. Fire protection needs must be balanced with regular needs of other domestic and commercial users.

7. A water utility company official—The local water utility, which may be a public or private company, and usually a monopoly organized under state law, may act in many ways like an individual landowner. The company may have or need to obtain the rights to the groundwater. The utility company decision maker, in addition to getting local and state permits, must meet federal and state drinking water quality requirements. Those standards have substantial water testing requirements and associated costs. Utility company managers can also promote conservation within their service area to preserve the supply of groundwater available in the present and future. Importantly, water utility company officials, usually through a board or committee, set water rates or prices for the community their company serves.
8. Groundwater testing/remediation service representatives—In locations affected or potentially affected by contamination, groundwater may not meet water quality standards for the intended use. If groundwater testing/remediation companies are hired to evaluate the extent of groundwater contamination, hydrogeologists, and groundwater engineers will most likely recommend installing monitoring wells, sampling, and chemical or microbiological testing of the groundwater, using reliable techniques to evaluate the presence of contamination. A monitoring well is used to produce water for chemical or microbiological analysis. A piezometer is used to measure water levels. Usually, three or more wells are required for proper sampling and establishing groundwater flow direction. Cleanup of contamination may require the installation of additional wells to produce groundwater in sufficient quantities to provide timely remediation. Large, heavily contaminated sites may have hundreds of monitoring or remedial production wells.
9. Finance company representative/property buyers—Before a property will be accepted for financing, many lending institutions will require buyers or sellers to have an environmental assessment of the property. This assessment entails determining whether any activity previously undertaken on the property may have contaminated the soil, groundwater or structures running through the property. If sufficient information exists to indicate that potentially contaminating activities occurred, then samples are taken and analyzed. Typically, groundwater monitoring wells are installed and samples are analyzed. Soil samples are typically taken while installing the well. The assessment is used to describe the extent of contamination and, if appropriate, the magnitude of the activities needed to remedy it.
10. State utility rate commission—Members of state utility commissions are usually appointed by the governor of the state to set regulated prices on commodities produced and sold by utilities. These utilities are monopolies that are considered as necessarily providing a good or service to the public, which would be provided at greater social cost in a competitive market and not having competition to establish a market price for their good or service. Typically, groundwater is not priced at its MC. Thus, price to the consumer is based on demand and volume to maximize total revenue (TR) to the company (usually a monopoly) and not on the cost of the next available alternative, or on effects of other environmental resources that should be conserved in the long run.

Each of the decision makers, and perhaps others, in some way may be involved in establishing total, average, and MCs for groundwater production and treatment. The first part of this group of decision makers was influencing the availability and production for consumption. The latter portion of the list of decision makers is involved in producing groundwater to test its quality for future use. In some situations, all of these individuals may be involved in deciding the level of resources (factors) to be applied to groundwater production and/or remediation. The rate commission seeks to minimize monopoly profits by the utility company and guide pricing to be more in line with MCs to get the outcome (price charged by a regulated utility) to be as close to a competitive price as possible, still not taking into account ecosystem value of groundwater or ecological effects of producing groundwater.

DECISION MAKERS AFFECTING DEMAND FOR GROUNDWATER

Demand for groundwater is affected by a range of considerations, among which are (modified from Foster, 1999):

- Large quantities of high quality water are required to meet domestic and commercial needs in many cities and towns.
- Seasonally, groundwater may be more dependable in dry weather and during droughts because of the large storage potential of the subsurface environment.
- Different consumers may have different requirements for quality of water and may even have varying quality requirements for different uses. Groundwater quality is usually very steady and dependable, if found unpolluted.
- Groundwater is often viewed as a "safer" source of water because the subsurface is viewed as a screen for contaminants, which is not the case for all contaminants.
- In many locations, groundwater may be less expensive to develop, and if unpolluted, it requires little treatment.
- A major advantage is that groundwater can often be obtained where it is needed, rather than running a long pipeline to a surface water source with limited access.
- Catastrophic events may have less effect on groundwater because of its location.

Potential users of groundwater may not understand the local and even worldwide implications of their decisions to use it as their water source. Demand for groundwater stimulates demand for drilling labor and rigs to provide access. Pipeline companies produce pipe to transport groundwater over longer distances. Demand for these supply factors provides upward pressure on costs. Managers of companies supplying these services and goods must make decisions on capital investment and labor rates to be paid. The key decision makers affecting the demand for groundwater may include:

1. Household consumers—Household consumers drink water and flush wastes away daily, prepare food, launder clothing, water lawns, wash cars, fill swimming pools and in hot, dry locations, such as the southwestern United States, Mexico or the Middle East, evaporate water to cool their homes.
2. Water using appliance makers—Manufacturers of any appliance that washes anything or requires water in its process influences individual consumer's use of water in the design of the appliance. The aggregate volume of water use required by home appliances affects the size of the water production, treatment and distribution infrastructure of a community.
3. Irrigators—Farming that uses water to irrigate the land for food production is the largest water-using activity in the world—68% of groundwater use in the United States and 74% worldwide. The extent that water-conserving irrigation methods are employed affects the amount of water used in irrigation to grow food that would not otherwise be produced.
4. Food processing—Companies that process foods and make beverages use water in cleaning as well as putting it into their consumable products.
5. Business—Cleaning activities in commercial establishments require water regularly.
6. Manufacturing and power production—These activities require water to clean and to cool processes, the latter involving evaporation of water not available for recycling. Many industrial processes have some portion that is affected by water use.
7. Any activity that results in contaminants of concern being applied and allowed to leach, buried or injected into the subsurface may reduce the quality of groundwater to a point that the resource is no longer usable in a particular location. Finding an alternate source of groundwater may require new wells to be installed at greater distance or depth to ensure an adequate water source, increasing the demand for groundwater in those other locations.

These and many other water users create the demand for water that we need every day for personal and business purposes.

AN EXAMPLE

Having examined some of the supporting concepts and activities affecting groundwater supply and demand, focusing on an example of a simple groundwater production process will provide specifics that allow a better understanding of the application of economics to business and management decisions. The example developed is for one well operated by a single firm. The units of production are not important. The real emphasis of the example is on the concepts of marginal analysis. The discipline of economics is largely a study of the process and results of valued exchanges at the margin of human activities. "At the margin" means "adding one more" of whatever is being examined, producing one more liter of water, for example, and evaluating whether the value or the cost of it is greater or less than that of the previous unit. Producing or contaminating one more unit of a limited resource has ecosystem and economic consequences. The analysis may be extended to evaluate who benefits and who pays the cost of the additional production (or if applicable and appropriate, additional pollution), what caused its value to change, and whether the value of alternatives are greater or less than the unit being evaluated and who is affected by changes in the benefits and costs and how. The information derived from this analysis may be used in decisions about production processes or local political decisions about facility operation, or state decisions about resource withdrawal. The economist provides the information to the decision maker.

Exhibit 8.8a through c provide the data and graphs used in this example of a factor input approach to analyzing production. The fixed factor input in this case might be a well or a spring on a parcel of land. The variable factor inputs are labor and electricity, as indicated in the discussion of a production function previously. One could assume for this example that the application of a given amount of electricity to the pump of this well would also require the employment of labor. In this example, each unit increase in electricity requires a similar proportional increase in labor.

Key concepts. A major focus of economic analysis is on the point of diminishing returns and the circumstances affecting and the results of actions taken at the "margin." Taking a factor input-unit approach, the following analytical concepts are important to the operator's production management and will be used in the discussion:

- Fixed inputs are the factors used in the production process that are typically permanent and not easily portable, such as land, structures, and large equipment. This may also be referred to as capital.
- Variable inputs are factors that may change or fluctuate depending on production levels, such as labor, raw materials that are throughput to the production process, and energy. These costs may also be similar to operation and maintenance expenditures.
- Total physical product (TPP) is the total output of the production process. For groundwater, this quantity may be the total liters or cubic meters withdrawn from the aquifer over a specified period of time. An example is given in Exhibit 8.8a Groundwater Production and in Graph 1.
- Average physical product (APP) is the output produced per variable input factor and is calculated by dividing TPP by variable input.
- Marginal Physical Product (MPP) is the additional production from the application of one more unit of variable inputs.
- Total Cost (TC) is the producer's or operator's cost of all input factors to provide a product or service. TC includes the fixed cost of land and structures, such as wells, and the variable cost of labor and operation, including such factors as energy. TC is portrayed in Exhibit 8.8a in Graph 3.
- Average Cost (AC) is the total input cost divided by the total output. In Exhibit 8.8a, to produce 26 units of physical product requires three variable input factors with a variable cost of $6. The average variable cost (AVC) is $6 divided by three variable input factors, equaling $2 per variable input factor.
- Marginal Cost (MC) is the cost of the additional input factors to produce the level of output of interest. In the example, the marginal cost of producing more units decreases then increases.

- Total Revenue (TR) or Total value product (TVP) is the total revenue received from compensation for selling a product or service in the market or the value of production. The revenue or value is constant in the example and the TR line represents this result in Graph 3.
- Average Revenue (AR) or Average value product (AVP) is the revenue or value of a unit produced. AR is calculated by dividing the TR by the total output produced and expected to be sold. In the example, the AR curve is shown in Graph 4 and is a constant amount of $2 per unit.
- Marginal Revenue (MR) or Marginal value product (MVP) is the revenue or value per unit of production for the last (or additional) output unit(s) produced. In the example, the MR curve is the same as the AR curve, since all units of output are expected to have the same revenue from sales.

DISCUSSION

While the example here is obviously simplified, it has important features that are also common to more complex situations. As each combined unit of labor and electricity is applied in Graph 1, the units of total production (TPP) increase up to a point, where, in the example, the increase is zero. The TPP curve shows how physical output increases with successive additions of variable inputs. It is also called the "production function." Point *a* on the TPP curve is the point where production changes from increasing at an increasing rate to a decreasing rate. Point *a* can also be identified by projecting a line from the highest point of the MPP curve to the TPP curve, which intersects at point *a*. The APP curve gives the relationship of the TPP divided by the variable input factor (labor and electricity), as the variable input factors increase. The APP curve is always highest where the MPP curve intersects it. To the right of this intersection, the APP curve gradually declines. Projecting a line through that point to the TPP curve, point *b*, shows where production increases at a decreasing rate. In the groundwater example, more labor and electricity will not produce more water beyond the 63 units. In fact, more power may cause equipment to malfunction, with a loss of production.

Thus, in Graph 2, to the right of the intersection of APP and MPP, average production and marginal production both decrease and TPP in Graph 1 obviously increases at a decreasing rate. This example describes the physical law of diminishing returns.

The economic law of diminishing returns expresses this same relationship from a monetized perspective. Maximization of economic net returns is of interest in focusing on economically efficient decisions, rather than maximization of physical production. To view this maximization of economic net returns, one must place a cost on input factors and value to units produced. The point at which production managers will desire to operate is where, from an input standpoint, the MR equals or is just beyond the MC. "As long as an operator combines his variable input factors around his scarce or limiting factor, he can always expect his highest net return at this point." (Barlowe, 1972, p. 128). While the example is simple and the graph imprecise, inspecting the numbers in Exhibit 8.8(b) indicates that production just slightly more than 58 units with MC = 1.67 and MR = 2 generates the highest net return. However, beyond 58 units, net return diminishes.

The difference between total production costs and TR is the operator's "net return." Depending on which factors are treated as "fixed" and as "variable," this net return may also be referred to as "economic surplus," "rent," or "profit." Net return for this example can be shown graphically: it is the rectangle *hijk* in Graph 4. Notice the point *d* in Graph 3. This is the point at which the TC curve changes from costs increasing at a decreasing rate to costs increasing at an increasing rate. This point is also identified as the dotted line from the low point on the MC curve in Graph 4 projected straight up to the TC curve at *d* (called the "inflection point" of the curve because the rate of change is different above and below that point). In Graph 4, the solid line indicated as "MR & AR" gives the marginal and average revenue, $2 per unit. The dashed line *ij* shows the intersection at *i* of the average cost curve AC with the dotted line coming down from Graph 3. This dotted line intersects the TC curve at *e* and the TR curve at *f* in Graph 3. The dotted line crosses the TC curve at the point of tangency of a (dashed) line parallel with the TR curve. Mathematically (through the application of calculus), it can be shown that the length of the line segment *ef* is the greatest distance between the TR and TC curves, and therefore net revenue (TR minus TC) is maximized at this level of the firm's operation.

A principal observation about production processes is that applying more labor or resources to a fixed factor typically will cause production to increase only to a point where application of additional labor or other resources will not increase the additional physical product. The additional production in this case is called the marginal production. If the law of diminishing returns did not apply to the production of groundwater, a growing community could supply all the water it needed forever from one simple well, as long as an infinite supply of groundwater were available (which is not a practical assumption). The table in Exhibit 8.8a illustrates the law of diminishing returns as it

EXHIBIT 8.8 EXAMPLE OF GROUNDWATER PRODUCTION AND NET RETURN

(a) Groundwater Production

Fixed Input Factors: Land and Well	Variable Input Factors: Labor and Electricity	Units of Total Production (TPP)	Average Production Per Variable Input Factor (APP)	Additional or Marginal Production (MPP)
1	1	4	4	4
1	2	12	6	8
1	3	26	8.67	14
1	4	42	10.5	16
1	5	52	10.4	10
1	6	58	9.67	6
1	7	62	8.86	4
1	8	63	7.86	1
1	9	63	7	0

(b) Net Return

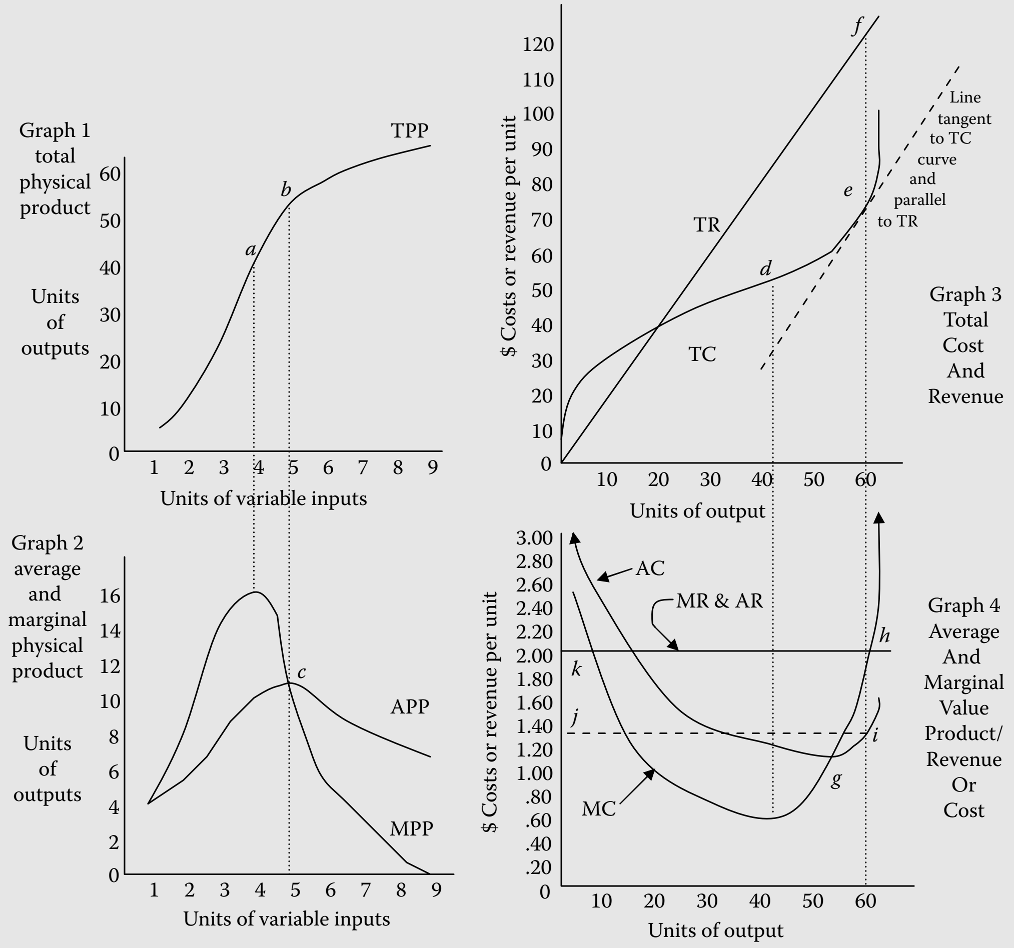
Units of Total Production[a]	Fixed Cost	Variable Cost	Total Cost	Marginal Cost	Average Cost	Price of Output	Total Value of Output	Marginal Revenue	Average Revenue	Net Return
	10	0	10	—		—	—	—	—	−10
4	10	10	20	2.50	5.00	2	8	2	2	−12
12	10	20	30	1.25	2.50	2	24	2	2	−4
26	10	30	40	0.71	1.54	2	52	2	2	17
42	10	40	50	0.63	1.19	2	84	2	2	43
52	10	50	60	1.00	1.15	2	104	2	2	66
58	10	60	70	1.67	1.21	2	116	2	2	67
62	10	70	80	2.5	1.29	2	124	2	2	56
63	10	80	90	10.00	1.43	2	126	2	2	33
63	10	90	100		1.59	2	126	2	2	−2

[a] Units of total production (TPP)

(*continued*)

EXHIBIT 8.8 (continued) EXAMPLE OF GROUNDWATER PRODUCTION AND NET RETURN

(c) Graphs



might apply to groundwater production. Assumed in the data for this table is that a growing community has one water-supply well (a fixed factor). It can increase the supply of water from this well by using a larger pump, more energy and maintenance to operate the water supply facility. Because of physical flow limitations through a given size of pipe (well casing, in this case), the volume of water produced can only increase to a certain point. At this point (not considering safety margins in this case), an additional well would be needed to supply more groundwater.

PRODUCER/OPERATOR DECISIONS

The operator of the water supply well would seek to employ variable inputs and produce output only up to the point where the net return was greatest. Graphically, he would choose the last whole unit of variable input before MC equaled MR that is the level of variable inputs at which the MR was still in excess of MC, providing a net return of approximately $67.00. We can see that this level is about seven variable inputs, already in the zone of diminishing returns, which begin to decrease at around five variable inputs. At approximately seven variable inputs, the operator is producing 58 units of output. The MC of one more unit is $1.67, which is close to but not in excess of the market price of $2.00.

Since the operator desires to maximize his net return, he would produce groundwater up to the point where the greatest vertical difference can be measured (or calculated) between the TR and TC curves. This point can be established as indicated above by two graphical methods of (1) drawing a line parallel to the TR curve that is just tangent to the TC curve in the right-hand side of the TR–TC graph, or (2) by projecting a line from the intersection of MR–AR curve (the Price line) with the MC curve—this conforms with the Price = MC rule of economics—to the horizontal axis in Graph 4, at approximately 58 units of output. Price is the AR received in this example. The TR received is calculated by multiplying the units of output (about 60, in this case) by the price per unit expected to be sold of $2 each. The rectangle *hijk* is the amount of net return the operator receives, equaling AR minus AC, then multiplied by the production units. (Note: Do not rely on the accuracy of the graph in measuring the length and locations of the lines; these are approximate values.).

The operator would not produce beyond the point *h* on the MR and AR and MC curves because any production choice on the rising MC curve past this point means that MC of production is greater than MR.

CAPITAL AND FINANCING ASPECTS OF ECONOMIC PRODUCTION

Capital Financing

To apply capital to a production process, it has to be acquired. Capital in production economics typically refers to either (Bannock et al., 1978): (1) “fixed capital” comprising durable goods such as structures and machines, or (2) “circulating capital” which includes raw materials and “semifinished” goods used to process or incorporate into the output and used up in the process. These are all physical goods. The prospective owner of an enterprise may purchase capital by outright payment of cash or by financing the purchase over time. The payment of cash assumes that the owner has adequate savings and has determined that the use of the money to purchase the capital needed to produce a good is the best use of those funds. This means that it has been determined, given the preference for or avoidance of risk, that the funds will earn their highest rate of return in the new venture in which the capital will be used. In other words, he could invest his money in other ways and do no better than in his new production process. Thus, he has considered his “opportunity cost” for the funds and determined the best course of action for their productive investment. Opportunity cost is the value of the alternative foregone (Bannock et al., 1978) by choosing to use the funds in the new production venture, in this case. The evaluation of alternatives at the margin of a project or program is a significant function of economic analysis.

If the prospective owner decides to finance the purchase of the necessary capital, then he chooses to go the credit market, which can channel others’ savings to his investment in the capital he needs for his new production process. Financial institutions that manage savings for investment establish a price for the use of the money they have for lending, referred to as the interest rate. The market interest rate is the competitive premium paid by the borrower to the lender in excess of the amount initially lent (Bannock et al., 1978). Different types of credit instruments depend on the length and nature of the loan (Gonzalez, 1989, p. 7):

- Short-term—used for short periods of months to buy circulating capital.
- Medium-term—used for periods covering several years to procure capital goods and machinery.
- Long-term—used for periods of 5 or more years to obtain durable goods such as structures.

The financial institution will set interest rates based on the loan term and type of good acquired as well as the credit-worthiness of the borrower. Goods easily or quickly used up may command higher interest rates, whereas buildings that can be sold and reused may have lower rates applied to them since the risk of loss is less. Groundwater wells are typically in place and use for many years, usually exceeding the length of a loan's term (e.g., 30 or more years for a well and 5 to 20 years for a financing term). On the other hand, equipment for on-site treatment for groundwater contamination removal may wear out more quickly and require higher interest rates to finance.

Interest payment for use of the loan funds is expressed as a percentage of the initial loan amount, referred to as the "principal," and is related to the length of the loan (e.g., 3 months or 5 years). Applicable parameters are: M_0, the initial amount of funds lent; M_t, the amount of funds to be repaid including interest; t, the time interval of the loan; r, the interest rate. Several methods of calculating interest are (Gonzalez, 1989, p. 7)

- Simple interest: $M_t = M_0(1 + rt)$
- Compound interest: $M_t = M_0(1 + r)^t$
- Continuous interest: $M_t = M_0\, e^{rt}$, where e is the natural number = 2.71828…

DISCOUNT RATE

A discount rate has similarities to an interest rate, except that the former is applied to funds or monetized equivalents (or worth) to be received or recognized in the future and stated in the value of the present time, reflecting a "time rate of preference" for money today rather than money received in the future. Discounting is applied to prospective monetized values due to uncertainty about the future, inflation expectations and changes in productivity because of technological advances, for example. Described another way, a dollar (or other monetary unit) today is worth less 1 year or 10 years or some period of time in the future. Conversely, a dollar received 10 years from now will be worth less than in the present. This concept has been applied to investments in the future.

The specific rate of discount to be applied to an investment is a significant issue. It has been asserted that for public goods a low "social discount rate" should be used so that the services and benefits of long-lived investments are not undervalued in the present by the current generation. The social discount rate is "a rate of conversion of future value to present value that reflects society's collective ethical judgment, as opposed to an individualistic judgment such as the market rate of interest" (Daly and Farley, 2004, p. 439). A low rate might be 2%–3%, and some have suggested zero and even negative rates for increasingly scarce resources in which investment could be made or value established (Day and Farley, 2004, p. 274). A market rate of interest will be what the competitive forces at work in the financial realm indicate it should be to balance supply and demand for money.

The calculation for discounting future funds in its simplest form is

$$M_0 = M_t/(1+r)^t, \tag{8.14}$$

where

M_0 is the amount of funds in the present time
M_t is the value of future funds in time t
r is the discount rate

Other presentations of the discount rate for measuring environmental and resource values are given in the literature (for example, see Freeman, 1993, pp. 199–218). This calculation is also referred to as "present value" of future payments or values, meaning that discounting presents these future values in terms of their current monetized worth. Exhibit 8.9 shows the results of applying discounting at different rates.

EXHIBIT 8.9 THE EFFECT OF DIFFERENT DISCOUNT RATES ON A FUTURE STREAM OF BENEFITS

Applying the formula $M_0 = M_t/(1 + r)^t$ for computing the current value of a stream of benefits nominally estimated to be $100 each year for 8 years gives the following results. The formula is applied to the $100 of benefits each year and then summed, shown as

$$\begin{aligned} M_0 = \Sigma[M_1/(1 + r)^1] + [M_2/(1 + r)^2] + [M_3/(1 + r)^3] + [M_4/(1 + r)^4] \\ + [M_5/(1 + r)^5] + [M_6/(1 + r)^6] + [M_7/(1 + r)^7] + [M_8/(1 + r)^8]. \end{aligned}$$

Since M_1 through M_8 are each equal to $100, r is the indicated rate, and t is 8 years, the calculations provide the following results:

At Discount Rate of:		**−10%**	**−5%**	**0%**	**2%**	**5%**	**10%**
Present Value of $100	1	111.11	105.26	100.00	98.04	95.24	90.91
in Time Period	2	123.46	110.80	100.00	96.12	90.70	82.64
	3	137.17	116.64	100.00	94.23	86.38	75.13
	4	152.42	122.77	100.00	92.38	82.27	68.30
	5	169.35	129.24	100.00	90.57	78.35	62.09
	6	188.17	136.04	100.00	88.80	74.62	56.45
	7	209.08	143.20	100.00	87.06	71.07	51.32
	8	232.31	150.73	100.00	85.35	67.68	46.65
Summations		$1,323.07	$1,014.68	$800.00	$732.55	$646.31	$533.49

Notably, in the cases considered, a negative (-) 10% discount rate provides the largest present value of the sum of future benefits over 8 years, nearly 2½ times the present value of a positive 10% rate. Significantly, $100 from the 8th year in the future under the −10% rate is worth almost five times that of the 10% rate.

Under what circumstances might this occur? If population is growing and its demand for a resource, such as groundwater, is also growing and the resource stock is getting smaller through being consumed or contaminated, the resource from a societal perspective may be considerably more valuable in the future regardless of its absolute supply cost or its market price.

DEPRECIATION OF CAPITAL

The value of fixed capital decreases because of deterioration over time, being out-of-date due to technological advances, or unneeded use. From these considerations, the concept of "useful life of a capital good" evolved to recognize that these items wear out or become obsolete. "When a firm computes its annual production costs, it makes an annual allowance for the depreciation of each capital good. The purpose of these allowances is to build up a fund which allows the same item to be replaced at the end of its useful life or depreciation period" (Gonzalez, 1989, p. 8), although Bannock et al. (1978, pp. 123–124) indicate that accounting depreciation is to "ensure that the cost of the flow of services provided by capital assets is met in the price of the company's products" and not to provide for a "replacement" fund, since the funds can be used in practice to invest in other capital that will provide the highest return. Depreciation may simply be calculated as (other more complicated formulations are also used):

$$A = [Cr(1+r)^n]/[(1+r)^n - 1] \tag{8.15}$$

where

A, annual allowance in the case of constant depreciation
C, purchase value of the capital good
r, interest rate
n, useful life

(Gonzalez, 1989, p. 8)

Wells are capital investments that are relatively long-lived but can wear out. Depreciation of wells may be warranted in business applications. Exhibit 8.10 gives an example of depreciation allowance for a well.

NATURAL CAPITAL

Natural capital equates to "stocks or funds provided by nature (biotic and abiotic) that yield a valuable flow into the future of either natural resources or natural services" (Daly and Farley, 2004, p. 437). Natural capital available in and taken from the ecosystem is transformed by the economic system. Every raw material for industrial processes is extracted from nature and usually not assigned an economic value to be monetized. The processing of raw materials to transform them into goods results in wastes and all goods themselves ultimately become wastes after they are used up or worn out, returned in both cases to the ecosystem, degrading or damaging its quality as well as its viability to provide a similar level of natural capital in the future. Groundwater is both a final product for the satisfaction of human, animal and plant thirst and bodily requirements, as well as an intermediate good to be used in irrigated agriculture and manufacturing and incorporated into other goods which provide services, such as food, paint, and other objects, and used as a conveyance and sink for wastes. When groundwater is "produced" from the subsurface, it already existed there, placed in those subterranean zones through hydrologic and geologic processes, with no cost to past or current generations for its availability to use. Natural capital, such as groundwater, can be depleted through human economic activity; it then becomes scarce.

Pollution can destroy the quality of natural capital so that it cannot be used, thereby removing it from availability for human use or assimilation by other life forms, except bacteria, which may decompose it over long periods of time to be harmless once again. Pollution can then cause

EXHIBIT 8.10 DEPRECIATION ALLOWANCE FOR A WELL

If a well has a useful life of 30 years, the annual allowance for constant depreciation of this capital may be calculated by

$$A = [Cr(1 + r)n]/[(1 + r)n{-}1],$$

where

A, the annual allowance at constant depreciation (to be calculated)
C, the installed price of the well and pump = \$10,000
r, the interest rate in the market = 5% or 0.05 (for example)
n, 30 years

$$A = [\$10{,}000 \times 0.05\ (1 + 0.05)^{30}]\ [(1 + 0.05)^{30}{-}1] = \$650.51$$

previously clean, safe freshwater to be depleted. In these two cases, this water becomes scarcer. In the circumstance of degradation, groundwater does not typically receive a depreciation allowance to be replaced later by the acquisition of new freshwater.

In the case of depletion, in the United States, depreciation allowances are provided to farmers who irrigate and mine groundwater, but no new water has ever been purchased to replace the water used up. Since these groundwaters have become scarce, the value of the remaining groundwater may be greater than in the past and in the future compared to the current time. If the scarce water value were monetized, its value might be able to be calculated using a negative interest rate for its future worth to the next generations. Otherwise, its value is immeasurable and since it is getting scarcer, approaches to using it must take into account its invaluable nature. Certainly, the value of groundwater is greater than zero and more than the cost to pump it out of the ground.

This aspect of groundwater value has national and international implications well beyond the use by individuals, as each person's or firm's demand for groundwater added up has macro level consequences. The rest of this book will delve into various aspects of the value and inherent state of this essential and ubiquitous resource.

NATIONAL AND INTERNATIONAL IMPLICATIONS OF GROUNDWATER PRODUCTION

While many texts are devoted to the development of national economies and international economics, some basic economic relationships should be highlighted relative to groundwater and macroeconomic and international considerations. National economies are built on the collective actions of individuals with preferences that can be aggregated to demand. Likewise, in response to this demand, firms acting in competitive microeconomic settings collectively provide the mechanism of transforming raw materials of the ecosystem to goods demanded by the populations served in the marketplaces and producing wastes in the process of this production. The goods, once used up or worn out, become wastes for the ecosystem to, in some way, absorb. Neoclassical economic thought assumes that the natural capital of the raw materials of the ecosystem will always be available—and the economy can grow indefinitely. At the international level, the world population was 6.1 billion in 2000 and is projected to grow to 9.4 billion by 2050, a 54% increase (USCB, 2005). During this time, total world water resources will not have grown and the usable groundwater portion, while large, will likely shrink from what it is today to meet demands for food and water, given current technology and urgent needs for water. Just meeting human demand will take more water, not taking into account the needs of the rest of the ecosystem on which humankind rely. Thus, water will become scarcer and more valuable due to population growth and its demands (Schiffler, 1998, p. 10).

Some discussion of "virtual" water on national and international fronts seems on the surface to address the need for water, but this may be a shallow path. Virtual water suggests that one region or country can obtain water for food by importing food from other countries that have the capacity to produce food. In other words, importing countries do not have to use up their scarce water to produce food—but they must have some way to pay for it by producing other goods offered in exchange. Exhibit 8.11 provides some facts about what is referred to as the "water footprint" of some foods and countries. Notably, countries that eat more foods higher on the food chain or that are produced by irrigation require more water.

Thus, countries relying on irrigated agriculture for export revenue are "sending water" out of the country, perhaps depleting aquifers that will not provide water for their future generations, in the form of food. These countries are exporting their natural capital. While the market for food may attract such economic activity, national governments may desire to consider the long-range implications for their own populations as to how increasingly scarce groundwater is being used and implement steps to use it more efficiently.

EXHIBIT 8.11 WATER FOOTPRINT FOR SOME FOODS AND COUNTRIES

- 1 L of milk needs 800 L of water.
- 1 kg of wheat needs 1100 L of water.
- 1 kg of rice needs 2300 L of water.
- 1 kg maize needs 900 L of water.
- The production of one kilogram of beef requires 16,000 L of water.
- To produce one cup of coffee we need 140 L of water.
- The water footprint of China is about 700 cubic meters per year per capita. Only about 7% of the Chinese water footprint falls outside China.
- Japan with a footprint of 1150 cubic meters per year per capita, has about 65% of its total water footprint outside the borders of the country.
- The water footprint of the United States is 2500 cubic meters per year per capita.

Sources: UNESCO, *Water Footprint*, 2004. URL: http://www.waterfootprint.org/ (accessed October 22, 2005); GDRC, *The Concepts of Water Footprint and Virtual Water*, 2005. URL: http://www.gdrc.org/uem/footprints/water-footprint.html (accessed October 22, 2005).

In a balanced review, Higgott (2005) notes that globalization of the world's economies, characterized by trade liberalization, financial deregulation and privatization has increased economic efficiency among trading partners, which are typically trading companies, and profited major international corporations which conduct that trade. Wealth has grown, but it is not clear that the poor of the world have benefited from the ability to move capital and operations to the lowest cost locations. Leaders of countries have expressed skepticism in this regard as well as their concern about the consolidation of capital in large multinational corporations and the need for distribution of wealth more fairly (Reel, 2005). Furthermore, some international arrangements, such as through the World Trade Organization, may not support equivalent environmental protections (Daly and Farley, 2004, p. 329) which lower production costs even more to the detriment of the country losing employment for the sake of reduced prices to consumers. Thus, countries that inadequately internalize social and environmental costs of production have a competitive trade advantage (Daly and Farley, 2004, p. 329). This point strikes at the heart of the basic market equation and thus relates macroeconomic and microeconomic consequences that require national and international attention for countries to develop policies that recognize internal and transboundary policies affecting their economies and social and intergenerational equity and justice at scales they can manage. In both the national and international arenas, an emphasis is needed to understand resource use beyond the individual and firm as products, services and information may move with greater efficiency and speed than policies can incorporate the changes in the sociopolitical fabric that could promote their wise use and stewardship of those resources, including groundwater.

SUMMARY

Human economic utility for goods is driven by tastes, preferences, and needs. The market balances consumers' demand, derived from their utility for goods and services with firms's capacity to produce them, through prices. Prices of each good and service relative to each other affect firms' willingness to produce more or less of a good and consumers' willingness to pay for them. Economic production of groundwater or any other good is guided by business monetary return, which is to be maximized. Economic measurement and equations facilitate calculating the value of factor inputs to and outputs of production processes. The market would indicate that groundwater should be priced at its MC, except in a monopolist's case. However, MC pricing may not reflect the full cost of producing this resource. Information may be useful or not in guiding our use of goods, depending on whether we receive the full details on the implications applying those goods to their intended purposes. Groundwater is a good with both final and intermediate uses. It can be depleted through consumption or pollution. Information about products and services that were produced through consuming or polluting groundwater may not be sufficiently complete to inform consumers about the impact of their purchases. Groundwater is a public good and natural capital provided by the ecosystem. Discounting its monetized value in the future does not recognize its invaluable nature. Nations should develop an understanding of their resource use and ensure that their participation in international economic exchange does not sacrifice economic distribution concerns at the national level. Whether or not allowance is made for this removal of the resource, no one is replacing what has been taken. It is becoming scarce because of these reasons and its value may not be able to be measured, even though it exists nearly everywhere, albeit in decreasing amount.

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9 Cost, Benefit, Price, and Value of Groundwater in Market and Nonmarket Settings

The “value of groundwater” suggests benefits from this resource. Is it groundwater that has value or the services that groundwater provides? This question is fundamental to the understanding how the tools of economics apply to resources, and, in this case, to groundwater. Groundwater existed below the ground of Kansas in the central United States for millions of years. The Native Americans hunted over it thousands of years ago. Did they value its existence? Probably and unknowingly, since they may not have used it directly, except when it kept streams flowing during dry seasons or kept springs flowing. When the first European Americans came to Kansas, did they value it? Probably not, until they had the knowledge and were able to dig wells and use it first to supply their household and then basic farm needs. After the advent of large capacity pumps in the 1920s, groundwater meant increased agricultural yields from irrigation. The service of these large volumes of groundwater had value where no other readily available water source could be drawn on. The ability of tapping large amounts of water even increased the value of the agricultural land at that time in that location. The conditions ultimately showed that this groundwater production was under competition for a free public good, the *only* cost of which was considered to be that of extracting it from the ground. So how can the value of groundwater and its services be estimated? Or, is it a priceless good?

The value of groundwater for human use is typically related to the cost to produce (physically access, distribute and, where necessary, treat) it, and to the price people will pay for it. This value reflects the benefits people receive in using it—their utility, and may be less than its total inherent value as a basic component of sustaining life on earth. The economic value of natural assets (including groundwater) is more than their market prices (Hanemann, 2005, p. 3), as we will explore further in this chapter. While it is typical to consider the value of groundwater in a positive way, for human purposes, such as the value for water supply or irrigation, it may have negative value in certain situations affecting people. For example, when flooding occurs from long extended precipitation, as happened in 1993 in the upper Mississippi River Basin of the central United States, water in the subsurface that was slowly released to streams, had negative effects and costs such as undermining dikes, saturation of agricultural fields, and hydrologically connecting sewage-leaching fields to groundwater pumped by wells for drinking water. In Bangladesh, untreated groundwater had high levels of naturally occurring arsenic and was making large numbers of people ill and even causing death. Thus, the value of groundwater is more than just availability at a price and also involves quality and may be positive or negative. Chapter 1 contains the definitions for the terms of cost, benefit, price, value, and market for continued reference.

A FRAMEWORK FOR CATEGORIZING ECONOMIC RESULTS

To evaluate the outcome of actions affecting groundwater or other natural resources, categorizing the results allows comparison. Categorization of economic results contributes to analyzing costs and benefits, the advantages and disadvantages, and provides information for decision makers. Many ways exist to consider the costs and benefits and are highlighted here. One traditional neoclassical economic approach is to focus on the market to provide information to sellers and buyers to improve the efficiency of the exchange of groundwater. However, the previous categorization of groundwater as largely a public, nonexcludable, rival good (see Chapter 3) about which it is difficult to obtain information for specific uses without considerable expense must also be examined.

At the highest level of categorization of economic results for groundwater in exchange or existence are: (1) market goods and services and (2) nonmarket goods and services. For these goods and services exist: (1) costs, (2) benefits, (3) prices, and (4) values. Within these high-level categories are further subdivisions: (1) quantifiable, (2) nonquantifiable, (3) monetizable, and (4) nonmonetizable. Additional categories of internal, external, private, and public effects are applied relative to the recipients of the benefits and costs. These categorizations are described here briefly .

MARKET GOODS AND SERVICES

Groundwater is a market good in some uses that produces services for consumers. First and foremost, groundwater is a source of water, essential for all life, which is the driver for its demand. Groundwater, as discussed previously, has many uses. For some of the uses or locations, it has close substitutes, such as surface water to which it may often be transformed through streambeds and vice versa. Because groundwater is not readily accessed in nature for many human uses, producers of groundwater extract it from the subsurface, incurring costs to do so. After including an economic return set through competitive market forces (many producers supplying many consumers), producers offer the groundwater good at a price to consumers, typically as bottled water or, in situations where water is scarce or difficult to access, provision by truck with a water tank, and even through privately owned distribution systems [e.g., private irrigation water distribution systems in India have existed for nearly a century (Winpenny, 1994, p. 54)]. In the southwestern United States, the rights to use a specific amount of groundwater can be purchased.

Markets provide economic efficiency by bringing together buyers, whose utility for the product (water) dictates their willingness to pay (WTP) for it, with sellers offering their products at the price the market will bear, which sellers anticipate will be at or above their cost to produce them. A highly limiting set of assumptions governs the circumstances in which markets balance the supply of sellers and the demand of buyers (Daly and Farley, 2004, p. 182). Principally, markets can balance when resources, goods, and services are dually excludable (ownership precludes others' use) and rival (only one person can own something), a condition in which property rights to a resource or good must be clear and observed. Markets only reveal preferences for market goods under the current set of prices and incomes (Daly and Farley, 2004, p. 359).

Groundwater, as indicated earlier, is also a regulated good in many locations, because it is a flow resource and its benefits are generally shared by many users. Its availability and price may be controlled through regulation to ensure that all potential users have access to it at reasonable expense because of its essential nature. Bottled groundwater competes with publicly supplied water when it is sold commercially based on its perceived higher quality and portability. As a commodity, which can be captured by a person or company for apparent exclusive individual or corporate gain, groundwater is a *private good*.

Economic theory indicates that evaluating changes in people's well-being based on their individual utilities provides an understanding of the market relationships between price changes to quantities of goods demanded. The theory further assumes that (1) "people have well-defined preferences among alternative bundles of goods" [including various combinations of market and nonmarket goods] and (2) "people know their preferences, and that these preferences have the property of substitutability among the market and nonmarket goods making up the bundles" (Freeman, 1993, p. 7). This theory would apply to groundwater in the market. Consumers derive service from groundwater in many ways. The first service probably is to "quench their thirst" through consumption of it. The service is a benefit to the consumers, for without water they would not survive. Where publicly supplied water is regulated as a monopoly because of the cost and need for access and treatment to

EXHIBIT 9.1 MARKET AND NONMARKET GOODS AND SERVICES OF GROUNDWATER—A PARTIAL LIST

Examples of market and nonmarket goods and services of groundwater are listed here.

Market Goods

Tap water supplied by a water utility for drinking water and other purposes
Conveyance media to remove wastes
Bottled water used for drinking water or other purposes
Brines (brackish groundwater) used for chemical manufacture
Rights to pump a specified amount of groundwater for drinking water, irrigation, or other purposes

Nonmarket Goods

Support to plant life providing climate control through transpiration and CO_2 processing
Geysers in public parks as amenities of aesthetic significance
Cave formation providing habitat of ecological importance and amenities of aesthetic significance
Land support to avoid land subsidence
Discharge to streams, lakes, and coastal ocean waters to provide habitat for wildlife (flora and fauna) particularly important in dry seasons
Discharge to streams and lakes that support recreation and navigation
Maintenance and support of other ecosystem functions not understood

ensure safe water and no alternative is available, a regulated market for groundwater may exist in that the price per unit to consumers may control the volume of water demanded, exerting the force of the market through the income limits of the consumers in trading off other goods and services with those of groundwater in their bundle of goods. Other services may include bathing and food preparation.

How much benefit the consumers receive is based on their demand. Consumers have found other demands for groundwater, such as to convey wastes away from their point of generation through the subsurface [considered to have zero price and therefore in high demand until exhausted (Frederick, et al, 1996, p. 11)]. People may also use substitutes for groundwater in particular uses, such as having alternative sources or alternative waste disposal means. Typically, though, groundwater, particularly because of its flow characteristic, has aspects of both a rival and a nonrival good, since once captured is not available to others, but it may be available to many people in other circumstances such as free flowing springs.

Are there situations or conditions that suggest groundwater is not a market good, for the most part? Groundwater users may not be able to exclude other users of it, at least not easily (see Chapter 3). When market conditions do not exist to efficiently balance supply and demand for a good or service, then “market failure” may exist and the resource may actually be a “nonmarket good or service.” Exhibit 9.1 presents a partial list of market and nonmarket goods and services of groundwater that may be considered as benefits.

MARKET FAILURE

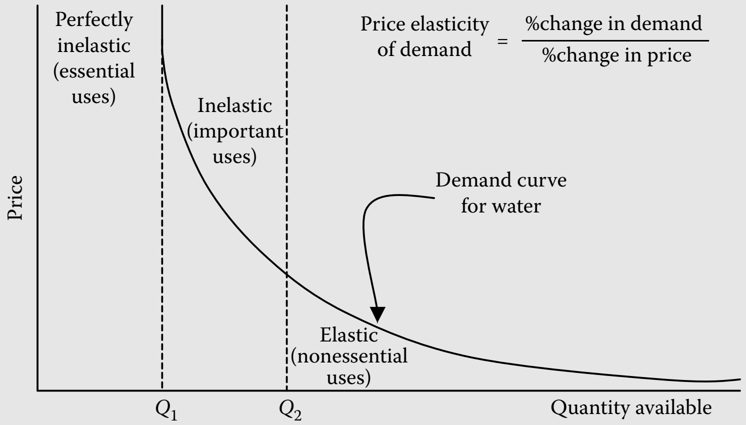
Since conditions for allocating market goods are narrow and well defined, we recognize some goods and services do not meet these criteria and are subject to “market failure.” Nonmarket goods that enhance welfare are not allocated by the market (Daly and Farley, 2004, p. 359). Additionally, it is assumed that transactions among individuals are costless with full information of the benefits and costs of goods involved. Even if we can identify situations where these assumptions actually apply, the markets do not incorporate the interests of the next generations. Market conditions do not apply to transactions involving the supply and demand for most groundwater. Typically, groundwater can be excludable and rival only when it is captured and, even then, this is usually only a temporary condition, as it is used and released as a residual of the process for which it was obtained and allowed to return to the subsurface, a stream or wetland, or the atmosphere by evapotranspiration. When a portion of the resource is captured and not returned, this action may preclude other users from obtaining the benefits of that amount. Likewise, a volume of groundwater may be affected by the release of waste or residuals, thereby affecting the quality of that part of an aquifer and precluding others' use of it, because it does not meet healthful standards for consumption. Residuals release to groundwater is impossible to prevent, making the resource nonexcludable and, therefore, subject to government stewardship. Any market price for it will not be socially optimal (EU, 2003, p. 9). As Glennon (2002) documents with many case studies, groundwater is a public resource available to the private sector in most situations at no cost, resulting in overuse because of no clear market signals or specific public management objectives.

Furthermore, since the larger groundwater resource is mobile in most subsurface environments, moving from under one parcel of land beneath any institutionally recognized boundaries to the subterranean space of another parcel of land—albeit, slowly by modern relation to time and distance, it is inherently physically nonexcludable. That is, use of the resource cannot be precluded to others. Similarly, since the groundwater resource flows due to natural conditions or from pumping, it is nonrival: one person's use of the larger resource does not prevent others' use of it, whether for consumption or waste conveyance. Therefore, typically, groundwater is considered a *common pool resource* (EU, 2003, p. 9). If quality is a concern and groundwater is equated to be a rival good, but is in fact a public good, then the market did not address costs to others' use of the resource. Long timeframes may be required for natural degradation of residuals. Even for human intervention to pump and treat a contaminated resource, long treatment periods and large costs may be a result (EU, 2003, pp. 9–10).

Market failures relevant to groundwater include (Daly and Farley, 2004):

- Institutionally managing groundwater as a rival good that can be allocated through the market raises issues of its essential and nonsubstitutable nature for those who cannot own it, an ethical problem related to water distribution and entitlement for human survival as well as ecosystem sustainability. Water demand is inelastic as price rises or the resource becomes scarce, as Exhibit 9.2 portrays. Water price does not typically account for its scarcity value (Hanemann, 2005, p. 19). "Ignoring scarcity rent leads to underpricing of groundwater, which results in extraction levels above the socially optimal level" (Xepapadeas and Koundouri, 2004).
- As water becomes scarcer from limits to physical supply and greater demands from growing populations, exploitation for thirst quenching, irrigation, or residual conveyance has resulted in transboundary issues for neighbors and nations, creating transaction costs as well as safe consumption problems.
- Because of its ubiquitous and flowing nature, groundwater also has a "common property" aspect to it, meaning that it is potentially available for any one in the community to use at different locations and times, but the community, rather than individuals, may control the property rights, if it has the will to do so. This makes groundwater difficult to protect and manage, creating an "open access problem" (Tsur et al., 2004, p. 18). Thus, many people or corporations may use the resource, which is publicly available but not publicly controlled. Examples exist around the world of this occurrence, such as in Gujarat, India (Winpenny, 1994, p. 55). Because groundwater is often a collective public good (discussion below) rather than being provided through the market, people will exercise their individual self-interests in using it freely (referred to as *free riders*) and understate the value of it for themselves, resulting in groundwater being undersupplied (Hanemann, 2005, p. 13).

EXHIBIT 9.2 ELASTICITY OF DEMAND FOR WATER



Source: Adapted from Daly, H.E. and Farly, J., *Ecological Economics*, Island Press, Washington, DC, 2004. With permission.

Note: To the left of Q_1, any percent change in price of water will not result in an equivalent percentage change in quantity demanded. Between Q_1 and Q_2, quantity demanded is sensitive to the price with some important uses beyond basic drinking water needs being paid for. To the right of Q_2, price changes have little impact on quantity of water demanded.

- In the market place, the most efficient use of a scarce resource or factor is determined by the purpose that has the greatest value. If value is appraised by WTP and the greatest wealth and income is held by a relatively small proportion of the population able to afford an increasingly scarce resource, the poorest people may have limited access to water. This is a distribution problem: the survival of people with the least income should be priority over other uses for which the rich can pay. In most applications, no substitutes exist for water. (This is not to say that technology cannot improve the efficiency of some water uses.)
- The market for water is less than perfect because of the substantial infrastructure required to provide it, usually resulting in a single water supplier for an area's population. If the supplier is a private company, because it has a monopoly on providing water, by definition there is no competition. Water provision for significant populations has economies of scale, with production costs falling as more units are delivered, termed a "natural monopoly." In such a case, demand will not fall equivalently with price increases. Thus, the private monopoly supplier can raise prices in the face of inelastic demand and not have to be concerned about lower costs, thereby maximizing revenue. Relative to this circumstance, Daly and Farley (2004, p. 198) have noted that comprehensive regulatory prescription must apply to such conditions that would otherwise allow a private monopolist water supplier to raise prices and lower quality in the face of no competition operating to control costs. They indicate that under such private water supply, if not regulated, water will probably be provided with lower efficiency and fairness than would occur through public water supply.
- Markets do not apply to matters of scale (Daly and Farley, 2004, p. 359). If volume of production expands vastly, markets simply provide efficient allocation of resources to allow this provision and customers to balance their demand among the bundle of needs at a price. Only when scale of resource production devolves into a limit may the market enhance welfare through efficiency. Otherwise, the market simply operates to find the least costly means of production, regardless of significant negative results of depletion or contamination.

- No market exists for the needs of future generations for resources or the level of risk acceptable to them (Daly and Farley, 2004, p. 359). Water planning primarily focuses on obtaining sources of water for expanding populations. Apparently, water that is safe to drink and adequate for other primary purposes is not scarce enough in much of the world to drive management of the groundwater resource through pricing or encourage other economic incentives or other institutional means to provide for conservation and reuse.
- The need for ecosystem sustainability that provides the raw materials and resources, such as groundwater, on which the survival of people, plants, animals and the economy depend, does not factor into the supply costs or demand prices, except in minor ways when rivers and lakes dry up or a species' habitat is threatened. This characterization reflects a pure public good, which is nonexcludable and nonrival. In these situations, the scale of human economic demand is greater than the capability of the ecosystem to supply the necessary groundwater resources. These are indicators that the ecosystem needs attention and the economic processes for allocating water may be inadequate; in such cases, the market has failed to recognize the value of groundwater and its interrelationship with the larger biosphere that has a limited amount of water available for all purposes on which we rely.

Other market failure considerations important to groundwater include (Daly and Farley, 2004, pp. 157–183):

- If groundwater access is open (excludable, rival) or administered but not effectively monitored and enforced (potentially excludable, rival), it may become a "congestible" resource. Such a resource has too many users extracting from it and reducing the quantity or quality of it. Efficiency can be increased in either situation if the price is based on use, with peak or large volume use being charged higher prices, reflecting real marginal damages and costs to the resource and other users. Furthermore, if many potential users exist who need water, and groundwater is not easily accessible, it may be underprovided and with many potential users, it may be over used with its marginal cost of use difficult to determine (EU, 2003, p. 8).
- Unenforceable regulations concerning use and disposal of products that have been used and have become waste or residuals create a problem for keeping groundwater safe. Regulations put in place by central authorities most often apply to everyone, which make them difficult to monitor and enforce. With groundwater being ubiquitous, almost anyone who can obtain access to it could affect it through use or waste disposal. Regulations exist for use and disposal of products, which have potentially harmful chemicals in them, that can be released if not properly used or disposed. Once pesticides are applied, any residual is difficult to retrieve from the environment. Worn out or used up products, such as waste oils or old computers with components that have toxic chemicals in them, when disposed of improperly may pose health hazards to others using groundwaters affected by poor and illegal waste handling practices. The price of these products did not include provisions for proper disposal to prevent contamination of groundwater, such as economic incentives like a return deposit, for returning used oil, pesticide containers, or computer monitors to be properly handled.
- Institutions do not exist to convey the assets and capabilities held by recipients of ecosystem services to the agricultural sector, which loses the option of not applying large amounts of fertilizer and pesticides and having sufficient water to ensure adequate yields and support itself. From the farmer's perspective, pumping large volumes of groundwater to irrigate his cropland is the "rational choice" even though society may lose a valuable aquifer for the future.
- The ecosystem services that groundwater provides are being diminished because of the public nature of the resource and its nearly free availability—well installation is the cost

of access, which may vary based on groundwater depth and geological conditions, but is typically minimal compared with the services of water. Should the economic system only induce and reward making and allotting market goods, then it will regularly and routinely impair the provision of essential public goods that support the natural capacities maintaining the earth. Furthermore, without research for the production and maintenance of public goods by entities outside the marketplace, scientific progress will neglect providing nonmarket goods. Basically, public goods will be underinvested in by the private sector, since it draws on the resources provided by the ecosystem at no cost other than that spent to extract them. No price signals exist for most groundwater resource users.

- Since perfect information about the effects of human activities on the ecosystem is not possible to acquire, and uncertainty and ignorance are everywhere an impediment to an efficiently functioning market, then it is difficult to estimate the marginal costs and benefits to find their optimal economic intersection, on which traditional neoclassical economics relies. Thus, efficiency by itself measured solely in monetary terms may not be the only driving force to be applied to addressing the public aspects of obtaining the range of useful and essential services of groundwater or any other public good.

The market indicator, measuring efficiency in Pareto terms, cannot be applied to optimal provision of a public good—groundwater—as the sole way to allocate it. See Exhibit 8.7 for definition of Pareto efficiency conditions. The market attempts to simplify exchanges for which currency was typically the unit of measure, inherently failing to capture all—or even major—factors affected in the production of the good or the effects of its ultimate disposal once used. If market failure exists at the microlevel, then it also exists at the macrolevel, as effects accumulate over time and space. That is, we can see effects of aggregated individual actions on aquifers underlying vast regions, as noted previously. Other considerations must be factored into the allocation of groundwater—distribution, scale, sustainability—rather than price as the only indicator of value. Indeed, groundwater has missing markets for intergenerational needs and for other life forms and earth processes in the ecosystem (Daly and Farley, 2004, p. 180). Government or central authority attention to develop policies that address market failure is fundamental to capturing resource value that is not addressed by the economic exchange in markets (Daly and Farley, 2004, p. 360), especially since we do not know the value of the ecosystem services from which we benefit (Daly and Farley, 2004, p. 212). Groundwater's nonmarket goods and services, then, have a substantial bearing on its value.

NONMARKET GOODS AND SERVICES

Groundwater is also, and principally, then, a *nonmarket good* that produces *services* for consumers. The nonmarket good aspects of groundwater have to do with its ubiquitous and flowing nature and its services in the subsurface to support the ecosystem and appearance at the ground surface in the form of springs that are difficult to price. Because groundwater exists under most land areas and anyone with the means to obtain access to it can produce it or dispose of waste in it, groundwater is difficult to define as a discrete item to be easily traded in a market (although it has been done in water short areas and particularly limiting circumstances). In these ways, the larger groundwater resource is a *public good*, which is accessible but cannot be controlled by one person for individual or private gain since it is nonexcludable and rival.

In this case, the aspect of groundwater for which no market exists is its relative free and easy access and its waste conveyance and processing capabilities. Property owners with sewage septic tanks and leach fields rely on microorganisms to breakdown wastes and the movement of groundwater to carry the byproducts away from their wells. Likewise, unsewered storm drains and retention ponds utilize this aspect of groundwater and the subsurface. Certainly, the alternative cost in these situations is that of treating the water before it is returned to the ground. Indeed, underground injection of liquid waste through governmental regulation is the method that handles the largest volume of liquid waste disposal in the United States. This injection must be into deep confined aquifers for commercial and municipal wastes, except for storm waters and septic systems. No market currently exists for this waste disposal and the subsurface is treated as having no or little value in these circumstances.

Additionally, there is no market for groundwater services in maintaining streamflow for drinking water, recreation, navigation, or wildlife. Further, the provision of natural water through ecosystem processes is not considered in pricing water. There is no market for the services of the hydrologic cycle, on which we rely for renewing ground and surface water for all human beings and wildlife down to the bacteria relied on to breakdown wastes and other organic matter in groundwater. This process adds value to water, a fundamental building block of life, but the market economy does not convey information on this value. Nearly anyone can tap into the resource and yet most people have little understanding of its significance in their lives beyond meeting basic bodily needs. However, with the acknowledgment of climate change, water's protection and conservation are recognized as real contributions toward husbanding and stewardship of the resource. This aspect of groundwater has a "sacred" character that is not recognized in its use and in valuing this natural capital (Daly, 1996, p. 70; Llamas and Custodio, 2003, p. 4). In this regard, another nonmarket consideration is the "nonuse value" or "*passive use value*" of groundwater, in which people do not expect to use a resource or natural asset but would experience a sense of loss if it were eliminated or destroyed (Young, 2005, p. 40).

Within this concept of passive use have emerged more specific values. "*Existence value*" incorporates the notion of value of the resource or asset in and of itself and it exists for others to use. Knowing that the resource is clean and ready for future use, even though it is not used now, a person may value clean groundwater to bequest to future generations, known as "*bequest value*." This "bequest value" cannot be considered comparable with groundwater's value as the natural capital of the ecosystem since all the services and functions of groundwater are not well understood and may not, therefore, be defined. Passive uses of groundwater are public goods as they are nonrival and nonexcludable (Young, 2005, p. 40).

Since nonmarket goods are not appropriately valued in the market, how can we attempt to address their value? At the highest level, governments and central authorities could use public forum and legislative processes to discuss the objectives for these natural capital assets. These discussions could establish specific purposes and limits for their use within the ecosystem to serve the community and nation and their values. This subject is the topic of later chapters.

COSTS

In the market efficiency context, costs are the expenditures or resources associated with producing a good, groundwater, or service in response to a demand for it. Cost is, therefore, not a measure of the value of a good or service to a consumer. *Quantifiable costs* are those that can be counted in monetary units or otherwise. For producing groundwater, these include the costs for the purchase or lease of the property and water rights, well materials, labor and energy to install the well and maintain production. Costs of supply can be measured for each additional unit produced: the marginal cost of production. Economies of scale may indicate that larger wells could produce more groundwater at lower cost per unit. These costs would be *monetizable*, because they can be expressed in dollars or other currency. The costs of onsite production or treatment to attain a certain level of water quality are examples of *internal* costs, since they can be isolated to the specific function of producing or treating the groundwater.

Supply costs are reflected in production functions. For groundwater, a simple specification of production was given in Chapter 8 and might be

$$Y = f(X, G, K) \tag{9.1}$$

which says that

Y = the output of water and a function (f) of the input factors on the right-hand side of the equation

X = variable inputs, which could include labor and electricity for pumping groundwater

G = groundwater from the aquifer

K = fixed factors of production, such as the land, well, and pump

Quantifiable but *nonmonetizable* costs might include reduced flow in the adjacent stream that is supplied by groundwater because of increased use of groundwater. Stream flow is capable of being measured. Reduced stream flow is also an example of an *external* cost, since down stream water users may depend on the stream for other uses. If that is the case, then a portion of the external cost may be able to be quantified but not monetized. The external cost can be related to the function of producing groundwater but affects people and the environment beyond the production site or property, or beyond the time of the production, including future generations and environments. If the principal use of groundwater that discharged to a stream was to maintain aquatic habitat, and a specified flow is required to ensure that wildlife relying on the stream have sufficient water, then the reduced flow may only be able to be quantified but not monetized unless the ecosystem maintenance function of groundwater is more fully understood. Further quantification of loss of habitat may be possible through wildlife population counts to determine the density and type of flora and fauna. Importantly, we do not know the value of all externalities (Daly and Farley, 2004, p. 212) to allow them to be factored into precise supply or production equations. These external costs to and experienced by other people or the ecosystem and its other life forms beyond the initial site of use are also referred to as *social costs*. Social costs from uses of groundwater are incurred by the rest of society, and the ecosystem on which society relies, which could be a neighborhood, a region or an entire country, as well as a river basin or other hydrologic unit.

Nonquantifiable costs are those effects, typically but not exclusively for nonmarket goods and services, that may only be able to be described in qualitative terms. For example, production of groundwater may change the cultural character of an area, such as vegetation loss or modification (from a lower water table out of reach of certain plants' roots), or induced urban growth, resulting in people's perception of the area being different from their explanation of it, might be considered a nonquantifiable cost. This cost may be portrayed in words describing the affected people's concerns and then weighted to compare with other costs. Certainly, a survey could be conducted of the residents' attitudes toward these changes in an effort to quantify these effects. These nonquantifiable costs may also be social costs if borne by people beyond the point of use.

Other nonquantifiable costs include natural inherent processes associated with the existence of groundwater. Nature acting through time created vast collection and storage zones for groundwater in porous subterranean rock and unconsolidated sediments and the conditions for slow movement of groundwater to natural points of release that allow use by people and wildlife. The inherent costs of storage have already been incurred in the balance of nature and are typically ignored in development or remediation of groundwater. Often, groundwater is of sufficient quality that does not require treatment for drinking water and other uses. The natural collection and storage of groundwater is typically ignored as a cost, being summarily treated as a free sunk cost of nature. This capacity could be evaluated at the next least-expensive alternative to providing water as a "shadow price" in economic terms, but would only quantify and monetize a portion of the ecosystem value in place.

Note that costs for actions taken relative to the groundwater resource will vary by region of the country or world. That is because the capital cost of installing a well or treatment will be different depending on the depth to the groundwater table or distance from the equipment supplier or the extent of treatment needed for a particular use. Also, the cost of labor and materials to operate the equipment will vary. These factors will affect, in turn, the cost of producing or treating groundwater, which then will influence its delivered price to a consumer.

Generally, reducing costs is a desirable outcome. Lower cost typically means that fewer resources are required to produce an economic product or service. Lower cost translates into a more efficient economic result. In comparing these outcomes to benefits, there is symmetry of evaluation between costs and benefits (Freeman, 1993). Both are complicated and require identifying and examining in detail second and third-order factors for effects. Likewise, there is symmetry between extraction or degradation of groundwater and its reduced ecosystem capacity to support inherent natural functions. All of these other costs can then be specified and may indicate increasing marginal costs and possibly diseconomies of scale as more groundwater is produced at a particular site or in a specific region.

PUBLIC BADS

Previously in this chapter, reference was made to public goods and now we consider *public bads*, uneconomic and harmful use of the ecosystem. Public bads withdraw resources from use principally through waste disposal. Waste absorption as a use of the ecosystem occurs with any production, since whatever is consumed is transformed by use and ultimately ends up as waste. This waste or pollution that is released and disperses broadly is a public bad, which is nonrival (effects on one person do not diminish effects on others in any significant way) and nonexcludable (pollution dispersed is not easily captured and controlled, thereby affecting many others). Furthermore, the scale of waste disposal can create effects over vast areas. Release of waste from a munitions production plant outside a midwestern urban center in the United States, went unchecked for many years and contaminated groundwaters under more than 78 km^2, causing exposure to carcinogens and closure of public and private wells because of unusable and unsafe water. If greater production is encouraged without adequate control of waste, the scale of waste disposal will increase and with it greater public bads, which can be a drag on the ecosystem and the economy. Once usable resources can no longer be used if the capacity of the ecosystem to absorb and breakdown the wastes is exceeded by the scale of the release (Daly and Farley, 2004, pp. 214–218).

BENEFITS

The theoretical foundation for the evaluation of benefits derives from neoclassical welfare economics that postulates that people receive “utility” from consuming goods and services. Following a market approach, benefits are typically conceived of as the service flows from goods demanded by consumers. From this market perspective, benefits can be thought of as the area under the demand curve derived from integrating the expected consumption of goods or services at different offered *prices*. *Quantifiable* benefits that are *monetizable* may be expressed as *prices* of goods. Price is the market clearing compensation in monetary units that a consumer will pay to the producer or provider of the good to receive its benefits in the form of its services. Typically, these are *internal* benefits captured solely by the consumers through the services of groundwater. These services might include satisfying their thirst driven by internal bodily needs and carrying away wastes. The consumers may be residential users or large industries, requiring water for production processes resulting in wastewater at the end of the process. Changes in prices affect the benefits consumers receive. The portion of the area above the price line but below the demand curve is referred to as the “consumer surplus.” Lower prices increase benefits as the consumer surplus grows across more units consumed; higher prices reduce benefits. This reference recognizes that consumers “benefit” from not having to pay for units at those higher prices along the demand curve, but rather pay at the market-clearing price, where supply equals demand and price equals marginal cost in a competitive market.

Not all benefits that can be quantified and monetized have a market to price them—another market failure. These benefits are referred to as “nonuse” or “passive use” values, as indicated above.

A theory has evolved that individuals hold the existence of a pristine or clean resource, or the option for themselves or their posterity to use such a resource, as valuable and they can place a price that they would be "willing to pay" for such existence or option (Freeman, 1993; Bergstrom et al., 1996; NRC, 1997). WTP is "the maximum sum of money the individual would be willing to pay rather than do without an increase in some good such as an environmental amenity" (Freeman, 1993, p. 8). Surveys are administered to obtain this information (see Chapter 13).

A range of benefits can be potentially identified for groundwater services. Depending on the incidence of these benefits, these may be *social benefits* if they accrue to people beyond the point of use. Social benefits range from changes in human health or health risks for provision of drinking water and change in value of crops or production costs for irrigation water to change in the quantity or quality of recreational activities resulting from provision of clean groundwater discharge to streams (Bergstrom et al., 1996; NRC, 1997). A range of techniques to quantify the benefits is provided in Chapter 13.

Note that as price is a neoclassical economic measure of the value of groundwater services, it will vary from region to region in a country because of natural factors affecting access to groundwater and differences in labor and material costs as factors in delivered water prices in the respective markets. Thus, the attempt to use one price for many counties in different parts of a State or for the entire country would misrepresent the community's or society's value of the resource. Even use of an average price would probably need to be developed based on weighting by the volume of water used, or by population using it as a proxy for the quantity of the resource in each local price area to derive a meaningful statistic for a regional or national price for groundwater. However, even approaches to value groundwater through price will undervalue its ecosystem value in an ecological economics context, which with the current state of benefits estimation methods are largely nonquantifiable, or if quantifiable, are not in monetized units.

Nonquantifiable benefits may also occur from actions affecting groundwater. These benefits might include an improved sense of community well-being, an ability to attract industry, reduced risk of disease from regulating potential sources of contaminants, or maintenance of aquatic habitat supporting wild and game species. These and other social benefits may, in some decision processes, be the most important benefits of employing a groundwater service.

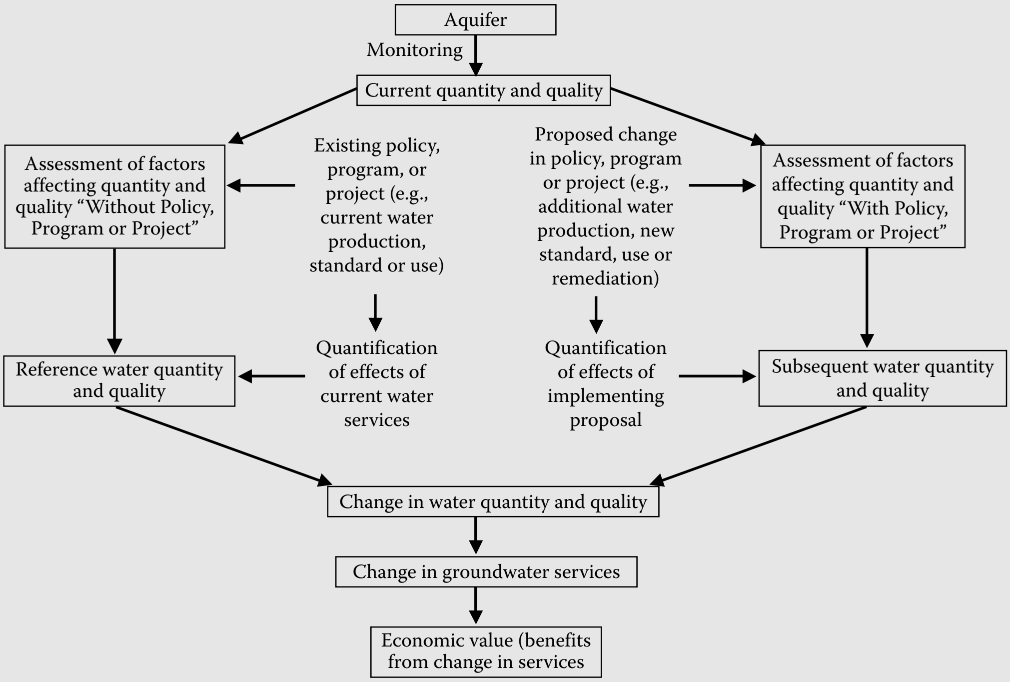
For quantifiable and monetizable benefits, the flowchart in Exhibit 9.3, Process of Estimating Benefits from Changes in Groundwater Quantity or Quality, shows the principal steps in specifying the benefits from changes in groundwater services. These changes may result from decisions to increase water production, change allowable water production limits, modify water quality standards, implement a remedial action to cleanup contaminated groundwater, or conduct some other activity affecting groundwater. The benefit estimation is derived from the change in the service from the groundwater resource, which in turn is the result of a change in the condition of the aquifer, or a portion of it, relative to its quantity or quality, or both.

PRICE

The price of groundwater as it relates to value is affected by a range of components. In a perfectly competitive market, the price (*P*) of groundwater would equal the marginal cost (MC) to supply it (*P* = MC). Factors influencing the price of groundwater include (modified from: Howe, 1979; and NRC, 1997):

- The stock of groundwater available
- Recharge to the stock of groundwater from precipitation, stream effluent, and induced infiltration and injection
- Discharge of groundwater to streams
- Contamination of groundwater

EXHIBIT 9.3 PROCESS OF ESTIMATING BENEFITS FROM CHANGES IN GROUNDWATER QUANTITY OR QUALITY



Source: Adapted from Bergstrom et al, Assessing the Economic Benefits of Ground Water for Environmental Policy Decisions, 1996, 32.

- The cost of access incurred through well installation
- The cost of pumping and distribution
- The cost of labor and materials
- The costs of treatment if needed
- Population demands for water
- Income levels
- Government policies and plans
- Institutional decision-making processes

These factors suggest a complex effort to set prices for groundwater, in most cases, based on the cost to supply it and not on its scarcity value (Hanemann, 2005, p. 19). Exhibit 9.4 gives the average prices for water (groundwater and surface water) in the United States and other countries, indicating the great variability from location to location. [*Note*: It is not clear whether these average prices are weighted or not.] Certainly, the simpler model of Hotelling applied to exploitation of finite resources (Hotelling, 1931, cited in Howe, 1979) that adjusted the price by establishing an optimum rate of change in the stock's rental rate equal to the interest rate might apply but does not include other significant factors identified above. In a competitive market for groundwater in a confined aquifer with no recharge (i.e., a limited or scarce resource), Hotelling's model would imply that the price people would be willing to pay would be the social interest rate (the expected value of the return from alternative investments). However, this model did not account for the rising value of the stock in the ground (unexploited in the current time) and environmental effects of its production (Howe, 1979, p. 94). Considering its increasing scarcity, the pricing of water in developed countries is in no way tantamount to recognizing its quality of being fundamentally essential for sustaining life (Hanemann, 2005, p. 21). People have demands for water that clearly transcend essential use and value it accordingly (Hanemann, 2005, pp. 21–23).

EXHIBIT 9.4 AVERAGE PRICE OF WATER FROM AROUND THE WORLD

The information here shows a range of average prices for water (groundwater *and* surface water supplied) around the world for selected countries. The prices are given per cubic meter. Prices are assumed to be in 2000 $US reported in 2001 and 2005 $US in 2006. It is not clear whether these prices are weighted, so it should be assumed that they are arithmetic means of quoted prices.

		2001	**2006**
		$US per m^3	**$US per m^3**
1.	Germany	$1.52	$2.25
2.	Denmark	$1.46	$2.25
3.	United Kingdom	$1.11	$1.90
4.	The Netherlands	$0.98	$1.49
5.	France	$0.93	$1.58
6.	Belgium	$0.75	$1.72
7.	Italy	$0.62	$1.15
8.	Spain	$0.58	$0.93
9.	Finland	$0.53	$1.03
10.	United States	$0.52	$0.66
11.	Sweden	$0.51	$0.86
12.	Australia	$0.48	$1.01
13.	Canada	$0.37	$0.79
14.	South Africa	$0.34	$0.92

The issue in using average national prices for any particular community in a country is that they are highly variable from places even within the same country and should not be used to make forecasts or projections at or below the national level or on a project-specific level.

For example, water rates in 2002 from specific towns and cities in the United States that use groundwater show that for consumers' initial water use, the following prices were charged:

Nogales, AZ	$0.37 per m^3	Residential (with increasing block rates)
	$0.48 per m^3	Irrigation (for all use, no block rate structure)
Lincoln, NE	$0.31 per m^3	Residential (with increasing block rates)
	$0.26 per m^3	Industrial (for all use, no block rate structure)
Pekin, IL	$0.48 per m^3	All Users (with decreasing block rates)
Dayton, OH	$0.13 per m^3	All Users (with decreasing block rates)

Sources:

1. National Drinking Water Clearinghouse, *On Tap*, Fall, 1 (3), 4, 2001.
2. NUS Consulting Group, 2005–2006 International Water Report & Cost Survey, http://www.nusconsulting.com/downloads/2006WaterSurvey.pdf (accessed October 8, 2008), 2006.

A GENERALIZED PRICING MODEL

Following Howe (1979) and NRC (1997), with modifications, a generalized pricing model accounting for major factors can be developed that attempts to address some limited aspects of market failure. This model will incorporate the factors in the list above, which include:

$S(t)$, the stock of groundwater available in time t, with the initial stock being $S(0)$
$H(t)$, recharge to the stock of groundwater from precipitation, stream effluent, and induced infiltration and injection in time t
$J(t)$, discharge of groundwater to streams in time t
$z(L)$, the cost of access incurred through well installation, considered a one-time cost in this simplified model and also a function of $S(t)$ and the depth of the groundwater table level
$R(t)$, the pumping rate of groundwater in time t
$w[S(t)]$, the cost of pumping and distribution (including the cost of labor and materials), related to the volume of groundwater in stock and thereby the groundwater table level
$A(t)$, a set of human activities and social factors affecting groundwater in time t
$a[A(t)]$, the cost of human and social factors affecting groundwater in time t
$M(t)$, contamination of groundwater in time t
$x[M(t)]$, the costs of treatment if needed in time t
$F(t)$, groundwater units with foregone opportunity of future use because of current pumping ($R(t)$) or contamination ($M(t)$), including the important foregone ecosystem functions
$o[F(t)]$, cost of foregone opportunities to use groundwater used in the present time t and not in a future time
$B(t)$, basic human requirements for water at a given level of water technology application
$O(t)$, other requirements for water at given level of water technology application
$T(t)$, given level of water technology application
$D(t)$, population demand function for water in time t
$E(t)$, effects of investment in conservation devices to reduce water use in time t
$U(t)$, population utility level relative to water in time t
$Y(t)$, income levels in time t
$N(t)$, population size and distribution in time t
$c[B(t)]$, cost to ensure that low-income populations receive required water for basic needs in time t
$G(t)$, government policies and plans in time t, including determination of ecosystem maintenance requirements to the extent that they may be known
$I(t)$, institutional decision-making processes in time t, including transaction costs
$p(t)$, marginal value for water (or price)
$q(t)$, scarcity rent in time t
r, discount rate
δ, random hydrologic events

The model has the following components:

Representing the resource volume available:

$$S(t+1) = S[S(t), H(t), J(t), R(t), M(t), A(t), \delta] \tag{9.2}$$

explained as the stock of groundwater is a function of the previous stock of groundwater, the recharge, the discharge to streams, the contamination of the groundwater stock, human activities, and random hydrologic events. Note that net recharge is equal to $H(t) - J(t)$.

Considering human factors affecting groundwater use:

$$A(t) = A[S(t), D(t), G(t), I(t), c[B(t)], r] \tag{9.3}$$

$$\text{with } D(t) = [N(t), U(t), E(t), B(t), O(t), T(t), Y(t), G(t), R(t), M(t), p(t)] \tag{9.4}$$

explained as human activities influencing groundwater use are a function of the stock of groundwater available, the demand for groundwater, government policies and plans relative to use and protection of the groundwater supply, institutional decision-making processes affecting groundwater use and protection, and the discount rate related to returns of alternate investments. Demand for groundwater responds to the population size, the population's utility for water of varying quantities and qualities, investment effects in water conservation, basic human water requirements, other water requirements, level of water technology applied, income of the population for purchasing water as one commodity in its bundle of demanded goods and services, government policies affecting use of water, the pumping rate of groundwater (volume that can be supplied), contamination of groundwater (influencing purchasing of substitutes), and price.

The price of groundwater (its marginal value) is given by the relation:

$$p(t) = w[S(t)] + x[M(t)] + o[F(t)] + a[A(t)] + q(t) \tag{9.5}$$

explained as the price of water is equal to the marginal cost of pumping and distribution, the marginal cost of treatment, the opportunity cost of current use, and the scarcity rent. In an unregulated market for groundwater with an objective to maximize production of a limited resource, Howe (1979, p. 297) indicates that scarcity rent $q(t)$ has the following features:

$$\text{the rate of change of } q(t) = \dot{q}(t) = \left(r - \frac{\mathrm{d}H}{\mathrm{d}S(t)} \right) q(t) + \frac{\mathrm{d}w(R_0)}{\mathrm{d}S(t)} \tag{9.6}$$

which indicates that the rate of change of the scarcity rent, $\dot{q}(t)$, is affected by the discount rate and the rate of change in recharge (in the formulation above, this would be net recharge, $\mathrm{d}(H) - \mathrm{d}(J)$) relative to the groundwater stock and the rate of change of the cost of producing groundwater relative to the groundwater stock and associated groundwater table depth (which affects pumping cost). Howe notes that both of these rates of change for recharge and production cost are negative. Since the stock $S(t)$ is the same in both terms, but the signs in front of them are different, one being a plus and the other a minus, as recharge increases raising the groundwater table and the production cost decreases, the result is not obvious because of the other factors. However, the anticipated optimized result would show that as $\mathrm{d}H/\mathrm{d}S$ increases, the rate of change in $q(t)$ rises because induced recharge is less. The rate of change of $q(t)$ is also reduced when this happens because of reduced pumping costs ($-\mathrm{d}w$) (Howe, 1979, p. 297).

The NRC (1997) refers to $q(t)$ as the "dynamic cost of [producing] additional [ground] water" and is the "rental value" of that groundwater: the amount of money an individual or company would compensate the groundwater seller for one more unit of water (at the margin). The consequences of producing one more unit and selling it in the market place may be positive or negative for society or the ecosystem. Since the value of producing one more unit at the margin may be greater or less than the previous unit, the implication is that adding the scarcity rent or rental value may approximately double the price if that rent is fully incorporated into the price. If $o[F(t)]$, the opportunity cost of producing that one more unit, can be estimated from the cost of alternative water sources or other means (please see Chapter 13), then the price could be higher yet.

Further implications of this model elaborate on the scarcity of groundwater and associated pricing.

- In the pricing equation, as groundwater production continues and $S(t)$ decreases, implying (1) a falling groundwater table, (2) greater depth to groundwater, and (3) groundwater depletion, then pumping costs $w[S(t)]$ increase.

- If $J(t)$, discharge of groundwater to a stream occurs, then water is likely not scarce and $q(t)$ would equal zero (0). The price of water, its marginal value, would be equal to its marginal cost of production (pumping, distribution, and treatment).
- $M(t)$, contamination of groundwater, may remove a portion of an aquifer from being used, depending on the severity of contamination. The existence of severe contamination could have the same result as a falling water table and increased price $w[S(t)]$, especially if an alternate water source must be found. One alternative is to install a well into a deeper confined water-bearing formation below the contamination. If treatment is a possibility, then the water price is also increased, as the equation indicates.
- $A(t)$, the set of human and social factors affecting groundwater demand, incorporates the need to address a human entitlement to water by poor people.
- $F(t)$, groundwater units with foregone opportunity of future use because of current pumping ($R(t)$) or contamination ($M(t)$), includes the foregone opportunity of ecosystem functions given up when excessive pumping or contamination reduce the natural groundwater resource capital. Significantly, the ability to account for this foregone opportunity hinges on research funded by necessity through the public sector and then by government or a central authority recognizing these functions in policy that is implemented to address these costs through fees or taxes in pricing. Ideally, these fees or taxes would be used to replenish or remediate the groundwater affected.
- An implication of the relationships defined above is that imputing a price of zero for circumstances resulting in depletion or contamination of groundwater is an *in*correct economic or accounting practice (Daly and Farley, 2004, p. 411). Frederick et al. (1996, p. 11) notes that "[a] resource that is provided free to the user will be used until either its marginal value is zero, or the supply is exhausted."

From a practical standpoint, one would utilize as many components of the model as may reasonably apply to a situation and for which data may be available. Circumstances for a particular location may indicate other components that should be added to such a model.

NONMARKET FACTORS

The pricing method just presented attempts to address nonmarket factors. Pricing of groundwater in most applications (residential, municipal, and industrial) does not occur in a perfectly competitive market, even when the property owner owns the rights to the land and its water. Because shallower groundwater migrates and is not an absolute stock resource, it has features of a flow resource and common property resource or a nonmarket public good, as described previously. A key characteristic of such resources is that access and acquisition have minimal cost to the user, which is the case with groundwater in many environmental settings. While cost of access is minimal for most users of shallow aquifers, government usually requires that water delivery to communities is a public monopoly and regulates the price so that all persons can receive it.

Not only is groundwater a public good and essential for life, but it also has a broad array of ecosystem interactions, balances, and support that consumers may not fully understand, but are being recognized from a legal standpoint (USEPA, 2001a). These interactions require research to improve the knowledge of recognizing their essential value to the environment, but the lack of data make pricing these interactions and support difficult. Some knowledge about the ability of the subsurface to breakdown or hold certain contaminants has resulted in contaminant source "setbacks" from groundwater supply wells to reduce disease potential (USEPA, 1997). Additionally, areas prone to land subsidence, where groundwater has provided geologic structure, have limited pumping. These essential inherent capabilities of groundwater, while not fully understood, are not incorporated in pricing. Groundwater is taken as it is and the pricing model shows that pumping costs plus a rent set the price in a finite resource or stock. Price multiplied by the quantity sold gives an exchange value for the commodity sold, but not for the groundwater in storage and providing ecosystem interactions and balances critical for other natural and human purposes.

ASSET VALUE

Asset value can be derived from a stream of contributions to production. If an aquifer is considered an asset and provides an increment to production each year valued at $\$K$ by the producer and the alternate similar investment with perceived comparable risk provides a rate of return of r, the value of the asset is (after NRC, 1997):

$$V = K + \frac{K}{1+r} + \frac{K}{(1+r)^2} + \frac{K}{(1+r)^3} + \cdots = \frac{K}{r} \tag{9.7}$$

This gives the value of a productive asset that is infinitely long-lived, such as groundwater may be in a renewable situation. In this particular case with an infinite asset, the annual rental value is K, the price a producer would be willing to pay for its use annually. The rental value is derived by multiplying the asset value V by the rate of return r. V may not be known for groundwater, while K might be identified by observation in the market. This approach still does not provide a value for nonmarket existence of the resource nor for ecosystem values.

REPLACEMENT SURCHARGE PRICING

Several writers or organizations have stated ecosystem principles to conserve environmental resources that are being depleted. Exhibit 9.5 extracts statements of approach or possible action to address reduction of the resource—even groundwater, specifically, in one instance—for future use. These principles point to the replacement of depleting resources by renewable sources. Such a condition could be addressed by a regulated market-based approach to pricing groundwater. One of the principles indicates that the rate of the resource use should be no greater than the rate at which a renewable resource can be used sustainably, which could be substituted for the depleted unit. Water units from the alternative renewable source would always be priced higher than water units for which it substitutes from the depleting source (assuming a production/delivered cost pricing framework), since, otherwise, the renewable source would have been used in the first place. Another principle suggests that prices should reflect the full social and environmental costs of extraction and use, but does not give guidance on applying these concepts.

EXHIBIT 9.5 ECOSYSTEM PRINCIPLES RELATIVE TO GROUNDWATER DEPLETION AND CONTAMINATION

Several writers and organizations have developed principles for use of resources that have implications for pricing policy under depletion scenarios:

Convention on Biological Diversity

Conservation of ecosystem structure and functioning, to maintain ecosystem services, should be a priority target of the ecosystem approach. "…Noting also that where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimise such a threat…" (CBD, 2002).

(*continued*)

EXHIBIT 9.5 (continued) ECOSYSTEM PRINCIPLES RELATIVE TO GROUNDWATER DEPLETION AND CONTAMINATION

European Union Water Framework Directive

- The presumption in relation to groundwater should broadly be that it should not be polluted at all.
- It is essentially a precautionary one. It comprises a prohibition on direct discharges to groundwater, and (to cover indirect discharges) a requirement to monitor groundwater bodies so as to detect changes in chemical composition, and to reverse any anthropogenically induced upward pollution trend. Taken together, these should ensure the protection of groundwater from all contamination, according to the principle of minimum anthropogenic impact.
- There is only a certain amount of recharge into groundwater each year, and of this recharge, some is needed to support connected ecosystems (whether they be surface water bodies, or terrestrial systems such as wetlands). For good management, only that portion of the overall recharge not needed by the ecology can be abstracted—this is the sustainable resource, and the Directive limits abstraction to that quantity.
- One of the innovations of the Directive is that it provides a framework for integrated management of groundwater and surface water for the first time at the European level.
- Member States will be required to ensure that the price charged to water consumers—such as for the abstraction and distribution of freshwater and the collection and treatment of wastewater—reflects the true costs (EU, 2000b).

Commonwealth of Australia

Pricing environmental values and natural resources: prices for natural resources should be set to recover the full social and environmental costs of their use and extraction. Many environmental values cannot be priced in monetary terms and hence pricing policies will form part of a broader framework of decision-making (COA, 1992).

Rio Conference on the Environment and Development, Rio Declaration Principle 15

"In order to protect the environment, the precautionary approach shall be widely applied by States according to their capability. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" (UNGA, 1992).

Rio Declaration on the Environment and Development, Agenda 21, Chapter 18:

Water should be regarded as a finite resource having an economic value with significant social and economic implications regarding the importance of meeting basic needs (UNCED, 1992b).

European Union Communication from the Commission on the Precautionary Principle

"The precautionary principle is not defined in the Treaty, which prescribes it only once—to protect the environment. But *in practice*, its scope is much wider, and specifically where preliminary objective scientific evaluation indicates that there are reasonable grounds for concern that the potentially dangerous effects on the environment, *human, animal or plant health* may be inconsistent with the high level of protection chosen for the Community. … Where action is deemed necessary, measures based on the precautionary principle should be, *inter alia*:

EXHIBIT 9.5 (continued) ECOSYSTEM PRINCIPLES RELATIVE TO GROUNDWATER DEPLETION AND CONTAMINATION

- *Proportional* to the chosen level of protection
- *Nondiscriminatory* in their application
- *Consistent* with similar measures already taken
- *Based on an examination of the potential benefits and costs* of action or lack of action (including, where appropriate and feasible, an economic cost/benefit analysis)
- *Subject to review*, in the light of new scientific data
- *Capable of assigning responsibility for producing the scientific evidence* necessary for a more comprehensive risk assessment" (EU, 2000a)

Herman E. Daly in *Beyond Growth*

For a renewable resource—soil, water, forest, fish—the sustainable rate of use can be no greater than the rate of regeneration. (For example, fish are harvested sustainably when they are caught at a rate that can be replaced by the remaining fish population.)

For a nonrenewable resource—fossil fuel, high-grade mineral ore, fossil groundwater—the sustainable rate of use can be no greater than the rate at which a renewable resource, used sustainably, can be substituted for it. (For example, an oil deposit would be used sustainably if part of the profits from it were systematically invested in solar collectors or in tree planting, so that when the oil is gone, an equivalent stream of renewable energy is still available.) (Daly, 1990)

Dublin Statement on Water and Sustainable Development:

Principle No. 4: Water has an economic value in all its competing uses and should be recognized as an economic good. Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources (UNCED, 1992a).

Ministerial Declaration of the 2nd World Water Forum (The Hague, 2000):

To manage water in a way that reflects its economic, social, environmental, and cultural values for all its uses, and to move toward pricing water services to reflect the cost of their provision. This approach should take account of the need for equity and the basic needs of the poor and the vulnerable (WWC, 2000).

Ministerial Declaration of the 3rd World Water Forum (WWC, 2003):

Funds should be raised by adopting cost recovery approaches, which suit local climatic, environmental, and social conditions and the "polluter-pays" principle, with due consideration to the poor. All sources of financing, public and private and national and international, must be mobilized and used in the most efficient and effective way (WWC, 2003).

United Nations Committee on Economic, Social, and Cultural Rights adopted the "General Comment" on the right to water (UNCESCR, 2002)

The human right to drinking water is fundamental to life and health. Sufficient and safe drinking water is a precondition for the realization of human rights.

Cochabamba Declaration (2000)

Water belongs to the earth and all species and is sacred to life, therefore, the world's water must be conserved, reclaimed, and protected for all future generations and its natural patterns respected.

What would the price have to be for depleting sources of groundwater? This price would vary from place to place. The ecosystem principles above do not give clear direction on the range of considerations relative to groundwater. Using the considerations of accounting for social and ecosystem costs of depletion of groundwater, one might consider land subsidence as a major factor to be avoided; therefore, "no further depletion" might be a driver for social and ecosystem cost in some locations. The "cost of obtaining water from a renewable source" as long as it is able to sustain itself might be another factor. Also, the alternative cost of producing a replacement volume of sufficiently clean water to recharge a depleting aquifer or to reuse might be a further component in determining a price.

Howe (1979, p. 297) cites an example in La Costa de Hermosilla, Mexico, in which a scarcity rent was calculated for an aquifer experiencing depletion. Using linear programming and base economic parameters, the scarcity rent was calculated each year for 36 years. In year 29, the scarcity rent finally reached \$0.0224/m^3 (1974 \$US), which was close to the cost of replacement water from a more distant source. No institutional barriers to the transfer were cited. However, using such an approach the projection showed that nearly 18 billion cubic meters of groundwater were depleted by agricultural irrigation and threatened by salt water intrusion before the scarcity rent equaled the cost of a replacement source. Policy may suggest that a different approach be used before such a large volume of groundwater is lost irreplaceably, placing social value of more significance than an economic result considering only production cost and scarcity rent.

The approach of considering scarcity rent calculated on an annual basis is an economic way to value groundwater over short periods of time, such as year to year. Another way to consider value is to evaluate replacement cost upfront when estimating the value of water, and use this as the price for conservation of the resource, particularly where there are no known alternative sources. While this circumstance might seem more applicable to the arid U.S. West and similar areas around the world, it increasingly may apply to the humid eastern United States where saltwater intrusion is becoming or is currently a problem. One way to price water is to include total replacement, such as recycling of all water to the subsurface or within the system, only replacing "make up" water (water loss in evaporation or line leakages). While this cost may be considerably higher, such an approach recognizes more completely the full social and ecosystem cost of groundwater. In particular, in areas where the recharge rate is negligible compared with potential or actual production, the nature of the hydrological cycle in the locality is considered in such a pricing approach. While such an approach may result in changing land uses, it may be economically justified in considering the marginal cost of water in the hydrological cycle for the community, and it may represent the potential needs of the future generations and their options for larger populations demanding water.

ESTIMATING $o[F(t)]$, THE COST OF FOREGONE OPPORTUNITIES FOR WATER USE

Under situations of depletion of groundwater (i.e., the groundwater table has declined, is declining or has the potential to decline), or in which a portion of an aquifer is made unusable from contamination, the owner or controller of the resource can make estimates of the cost of replacing some of the services of groundwater. This is the cost of the foregone opportunities to use the groundwater in the future that may have high value, if only considered in the evaluation. Depletion or contamination remove or limit these opportunities for the individuals, communities or corporations affected. These services, for many of which no information may be available, once costed would provide a replacement value, which could then be multiplied by the current discount rate to give an annual rental value. The annual rental value could then be divided by the expected annual production of groundwater. This should be considered a floor for a surcharge, since the many other interactions for which groundwater provides are not known but will be elucidated from research over time (i.e., we are currently ignorant of these services). Theoretically, this approach is supported by using the marginal cost of the next alternative as the way to price the replacement, whether or not the replacement actually occurs. The local jurisdiction may decide that the floor is too low or high and that the total surcharge should be adjusted.

The process of establishing this replacement value might follow these steps:

- Identify all the major services performed by the ecosystem: geologic structure to keep land from subsiding, maintenance of a barrier against saltwater intrusion, treatment to maintain balanced quality in the aquifer, creation of comparable wetlands, the loss of groundwater discharge to a nearby stream and the associated wildlife, installing water collection systems for a comparable volume of water, and other services—these are continuing, long-lived services inherent in groundwater.
- Specify the next least costly method to replace the service.
- Assume indefinite continuing, uninterrupted replacement of the services. Some of the services would require operation and maintenance. The replacements may be large engineering projects for water delivery or treatment and recycling, which would not be constructed but would be designed and costed.
- Establish costs for reconstructing the service(s).
- Multiply the projected replacement cost by the appropriate discount rate reflecting the opportunity cost of investment to obtain the annual rental.
- Add and allocate all ecosystem replacement costs across all projected units produced within an established limit and charge customers the applicable surcharge.
- The volume of water depleted or contaminated would be reported to the State water management agency for macroenvironmental effects tracking and response.

The effect of this would be to increase the price to consumers of groundwater and recognize in an imperfect way the contribution of the ecosystem to the value of water supplied. In situations of continuing mining and depletion of the aquifer or continuing or spreading contamination, these adjustments to price would increase over time. Mathematically, the model for this pricing would start with the previous equations:

$$V = \frac{K}{r} \tag{9.8}$$

and

$$p(t) = w[S(t)] + x[M(t)] + o[F(t)] + q(t) \tag{9.9}$$

As depletion of the aquifer was projected, the water district would obtain prices for water of comparable quality from adjacent regions so as not to impute depletion of their resources, or the cost of total recycling of the community's wastewater along with needed supplements from nearby areas, resulting in:

$\Psi(t)$, the volume of depleted groundwater from or contaminated in the aquifer in time t
$\beta(t)$, the volume of comparable quality water from adjacent areas in time t
$\alpha\beta[(t)]$, cost of comparable quality water from adjacent areas in time t
$\Theta(t)$, the volume of recycled community wastewater in time t
$\in[\Theta(t)]$, the cost of the recycled community wastewater to obtain water of comparable quality in time t, and

$$\beta(t) + \Theta(t) = \Psi(t) \tag{9.10}$$

Since depletion or contamination would continue each year until addressed, the stream of annual increments of water value (V) using a production cost pricing policy would be each year's replacement cost (K) from the next available source:

$$K = \alpha[\beta(t)] + \in [\Theta(t)] \tag{9.11}$$

and

$$V = \{\alpha[\beta(t)] + \in [\Theta(t)]\} + \frac{\alpha[\beta(t+1)] + \in [\Theta(t+1)]}{1+r} + \frac{\alpha[\beta(t+2)] + \in [\Theta(t+2)]}{(1+r)^2} + \cdots \tag{9.12}$$

where r = the discount rate.

With $Vr = K$ and $K = \alpha[\beta[(t)] + \in[\Theta(t)]$, this gives the annual rental for the alternate water supply, which could be applied to the production from the aquifer of concern.

Assuming the costs are equally spread over all the depleted (or contaminated) units of water, the effect on the price of a unit of water to the consumer would be

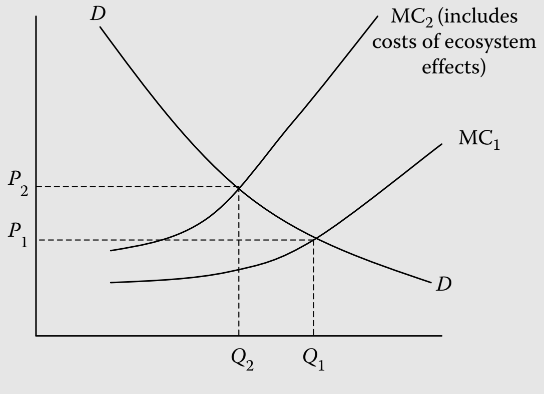
$$\frac{\alpha[\beta(t)] + \in [\Theta(t)]}{[\Psi(t)]} = o[F(t)], \quad \text{and} \tag{9.13}$$

$p(t) = w[S(t)] + x[M(t)] + o[F(t)] + q(t)$, the depletion (or contamination) adjusted the price. Other services could be included in $o[F(t)]$. As the price to consumers rises, the demand would be expected to decline. (See "Price Elasticity of Demand for Water and Income Factors" section in the following text.) This approach would have the same effect as a tax on water use, but could be based on ecosystem services used in the production/consumption of groundwater. Exhibit 9.6 shows the effect graphically. The curve MC_2 includes the marginal cost of ecosystem effects not incorporated in MC_1. Inclusion of the costs of ecosystem effects causes the price of groundwater to rise and the quantity demanded to decrease from Q_1 to Q_2.

In the case where water rights are appropriated and must be used, and depletion has other detrimental effects, prices might higher. For example, if a community acquires extensive agricultural holdings and must pump the groundwater only to be used to recharge the aquifer being depleted, the price equation would include injection costs as a separate factor. This circumstance would also increase the price of water.

While this series of concepts and equations above attempt to point to specific factors that might be addressed in pricing groundwater, particularly in a depletion scenario, and may seem too detailed

EXHIBIT 9.6 MARGINAL COSTS OF ECOSYSTEM EFFECTS ON PRICING



P_1 is the price of groundwater without considering ecosystem costs from depletion of contamination.
P_2 is the price of groundwater that includes some added charge to recognize depletion or contamination of groundwater

to some analysts, the factors indicated suggest possible research paths relative to groundwater economics and pricing and future water management.

Price Elasticity of Demand for Water and Income Factors

Additional factors in evaluating the extent of an increase in groundwater prices are the elasticity of water pricing and available income. Beecher et al. (1994) concludes from more than 100 studies of the price elasticity of demand for water that residential water demand elasticity ranges from −0.20 to −0.40 and for industrial demand the elasticity is from −0.50 to −0.80. Similarly, Young (2005, p. 255) concludes that, while there can be considerable variability in price elasticity of demand for residential water, it is typically in the range of −0.3 to −0.6, inelastic but not unresponsive to price. Young (2005, p. 228) also reviewed price elasticities for industrial water demand and found a range of −0.15 to −1.3, suggesting that effluent fees may be an effective way to reduce water intake and discharge. Thus, a 10% increase in water price reduces demand by 2%–6% for residential users and double that for industrial users. Winpenny (1994, pp. 76–80) reviewed price elasticities for urban water use in seven developed countries and found that elasticities varied by purpose of use and time of year. The price elasticities ranged from −0.06 to −1.07, the latter value suggesting a greater change in use from an equivalent percentage change in price. Generally, however, water has inelastic demand, since the change in price results in a less consequential change in use.

The ability to pay for changes in water price is governed by an individual's or industry's income and has important equity implications. For higher income individuals, changes in price of water may not be as consequential as for those with less income. EPA (2002) used an affordability factor of 2.5% of median household income (MHI) as a target within which to consider the incremental cost of water treatment. In small communities (population of 25–10,000 persons), the MHI ranged from $27,058 to $30,785 (1995 $US) with water bills in 1995 of $181 to $211 per household per year. National MHI in 1995 was $40,816 in this study. For these communities, average water bills were 65%–69% of the MHI affordability factor (0.65 to 0.69 × 0.025). This result suggests that the price of water could rise by several factors for higher income households and not have large negative impacts on household incomes.

Across countries and cultures, water affordability may have significant differences. While 2.5% of household income may be considered a bound on what people in small communities might have to pay in the United States, other circumstances exist elsewhere in the world that result in a significantly higher percentage of household resources expended in providing water. In less developed countries, people and in particular, women and female children spend a significant amount of time supplying their households with water, frequently from distant sources (UNESCO, 2003b, p. 286). Poor people in less developed countries often do not have safe, reliable water and may pay water vendors ten times the cost of water delivered by pipe, which may account for 10%–15% of the family's income (e.g., such as in Namibia) (UNESCO, 2003a).

Most industries, however, have low-cost water sources available to them and may be able to absorb price changes much better than the agricultural sector (Young, 2005, p. 223). Notably, the range of water use by industrial sector varies widely, from meeting basic sanitation needs of workers, to large uses for thermal power plant cooling (Young, 2005, p. 244). Generally, industrial water demand is price-inelastic (Young, 2005, p. 245).

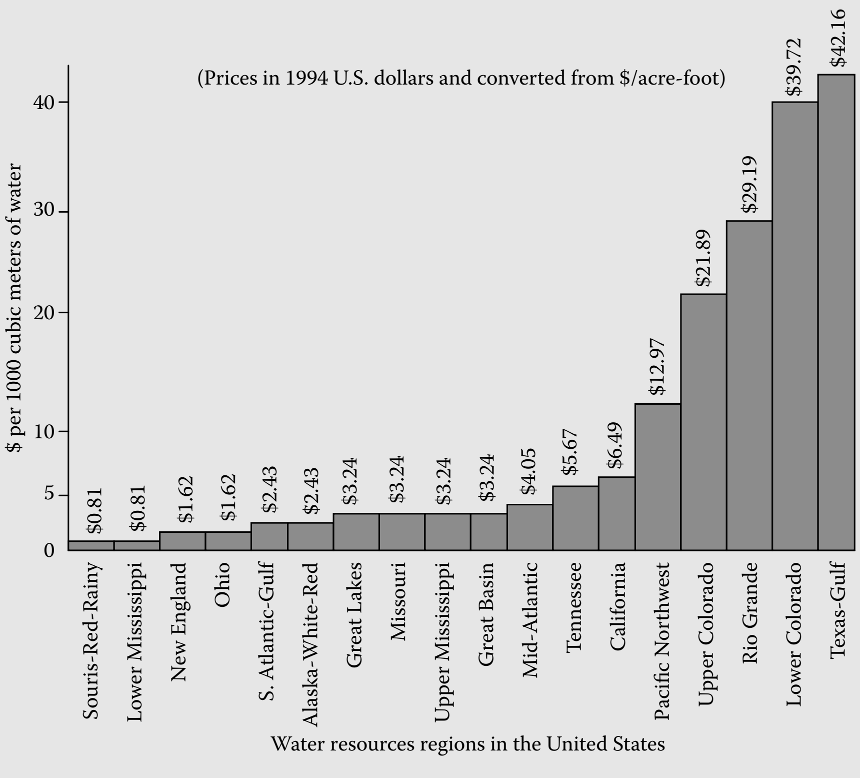
Scarcity and Pricing

As groundwater becomes scarcer in a region or seasonally, economics would indicate that its price should rise. Typically, it is assumed that the cleanest, most easily accessible groundwater is produced first (Daly and Farley, 2004, p, 195); thus, over time, lower quality and less accessible water should cost more to produce, treat, and use. These factors would increase costs and contribute to rising water prices. In other mineral categories, new discoveries and substitutes might offset scarcity (Daly and Farley, 2004, p. 194); however, discovery of "new, less expensive water" is not likely in the typical sense, and there are no substitutes for water in most processes to which it is applied.

Added information may help reduce the scarcity effect, but this is usually temporary (Daly and Farley, 2004, p, 195). One area of "new" water at potentially lower cost is recycling and reusing wastewater. A study of water supply for Beijing, China, in 1987, found that conservation (recycling and reuse) of water was more cost effective for 30% of its industrial needs and for 15% of its domestic requirements than building the next alternative water project (Hufschmidt et al., 1987, cited in Winpenny, 1994, pp. 84–86). For large volume uses, a number of options might be considered: adoption of alternative processes that are less water-dependent; improvement of processes (such as reducing leakage); use of lower quality water, including salt water and wastewater; and embracing new technologies (Tsur et al., 2004, p. 27). The response of farmers relying on irrigation water may be predictable based on conventional economics but the occasion of change in water use is uncertain (Tsur et al., 2004, pp. 27–28). Conservation mitigates scarcity to some extent and maintains prices at a lower level than they otherwise might be and might be considered as creating water supply without additional water (e.g., see Case Study 11, Balancing Ecosystem, Water Use and Pricing).

Exhibit 9.7 shows water values from the water resources regions of the United States. These values were derived from over 500 cases and include both ground and surface water sources (in many

EXHIBIT 9.7 MEDIAN WATER VALUES BY WATER RESOURCE REGION IN THE UNITED STATES



Source: Frederick, K.D. et al., *Economic Values of Freshwater in the United States. Discussion Paper 97-03*, Resources for the Future, Washington, DC, 1996, Table 3.3. With permission.

Note: These median water values were developed considering all major uses and both surface and groundwater sources in water resources regions of the United States. One water source may be an alternative for the other in some locations. Nearly 500 estimates from 41 references were compiled to derive these values. Water uses include: waste disposal, recreation, habitat, navigation, hydropower, irrigation, industrial processing, thermoelectric power, and domestic. The authors indicate that median values may be more appropriate for national comparison.

cases, they may be alternative sources to each other when a transmission line is considered in a resource assessment). These values are across all major uses of water, including waste disposal, recreation, habitat, navigation, hydropower, irrigation, industrial processing, thermoelectric power, and domestic. The range of these values (1994 $US) for the uses was a minimum of $0/m^3 to a maximum of $0.01/m^3 for waste disposal in more arid regions up to a minimum of $0/m^3 in humid regions to a maximum of $2.14/m^3 in more arid regions for recreation and fish and wildlife habitat. The graph (showing median values per 1000 m^3) indicates that generally in more humid areas of the United States where water is more abundant—to the left side of the graph, water values are lower, and where water is more scarce in western locations, water values are higher, as on the right side of the graph.

UNDERPRICING

Water is becoming an increasingly scarce (economic) resource but is not priced to its market value, especially in arid locations. Underpricing is a distortion of the market and creates inefficiencies. In an irrigation economy, water is a limiting factor of production commonly priced under its value in use (Tsur et al., 2004, p. 40). An investigation in two arid countries (Jordan and Israel) with heavy reliance on groundwater indicated lower economic results due to low water pricing (Sexton, 1990, cited in Winpenny, 1994, p. 19):

- "excessive public investment in the sector" and "discourage[ment of] private investment (p. 18)
- "low rates of return"
- "promotion of uncompetitive user sectors"
- "cost to public revenues from continuing subsidies to water use and from disposing of farm surpluses," which can benefit the wealthy and well connected (p. 18)
- "discourage[ment of] technical change in water using sectors" (p. 17).

PRICING METHODS

Tsur et al. offer a review of water pricing methods that are summarized in Exhibit 9.8. No one approach is considered best for applying in every case (Tsur et al., 2004, p. 3). Water pricing is complex and economists do not agree on the best approaches to it, stemming from confusion over fundamental principles and the implication of local physical, cultural, institutional, and political considerations (Tsur et al., 2004, p. 2). The neoclassical approach indicates that the key factor in measuring the performance of a particular method of water pricing is efficiency, including implementation costs, such as administration and monitoring. The performance is demonstrated as benefits to the user/consumer, disregarding the distribution of benefits across users (Tsur et al., 2004, p. 2).

From an economic efficiency perspective, those pricing methods that rely on marginal cost information or competitive situations (water markets with bidding or auctions) provide the conditions for the greatest return to the resource (Tsur et al., 2004, p. 14). However, as indicated previously, these methods as currently applied still do not typically incorporate costs of ecosystem effects. In a marginal cost approach, the price equals the cost of providing the last water unit. This approach assumes that the last unit is of the same quality or value to each user. If not, then the price may be adjusted to reflect these differences (Tsur et al., 2004, p. 15). The challenge with establishing the marginal cost of water is that it may vary over time, with drought conditions potentially creating noticeably higher costs. Furthermore, the costs of measuring use are implicit in marginal cost methods, raising implementation complications (Tsur et al., 2004, pp. 15, 18).

Second-best pricing solutions resulting in pricing water below long-run marginal cost may have other social benefits (Tsur et al., 2004, p. 16). In areas where irrigation or other large industry is the primary water application, other users may also benefit from water development. Regulated monopolistic pricing may address a need for affordable access to water supply that would not otherwise

EXHIBIT 9.8 PRICING METHODS

Pricing Method	Brief Description	Implementation	Potential Efficiency	Time Horizon	Ability to Control Demand	Adapt to Water Quality Conditions
Regulated monopolistic	Long-run average complicated cost	Relatively	Second-best	Short-run	Depends on rate sensitivity	Difficult
Single-rate volumetric	Marginal cost (full cost) pricing	Complicated	First-best	Short-run	Easy	Easy
Output/input	Taxes	Less complicated	Second-best	Short-run	Relatively easy	Difficult
Per area	Fee by location	Easy	None	Not applicable	Through restrictions	Difficult
Tiered	Marginal cost by demand	Relatively complicated	First-best	Short-run	Easy	Relatively easy
Two-part	Marginal cost with admin. costs	Relatively complicated	First-best	Long-run	Relatively easy	Relatively easy
Water markets	Competitive pricing/bidding/auctions	Difficult	First-best	Short-run/long-run	Depends on market type	Easy

Source: Tsur et al, *Pricing Irrigation Water: Principles and Cases from Developing Countries*, Resources for the Future, Washington, DC, 2004, 46. With permission.

be available. These methods would also not consider ecosystem effects in their structure. However, Tsur et al. (2004) conducted an extensive review and analysis of pricing of irrigation water and developed guidelines for such pricing in developing countries. These guidelines, some of which have broad applicability to pricing groundwater in other situations, are abstracted in Exhibit 9.9.

INSTITUTIONS FACILITATING PRICING

Water institutions established under law provide the underpinning for pricing through whatever method is adopted. These institutions administer the body of water law and rights, which serve to distribute, manage, and allocate water (Tsur et al., 2004, p. 28). Water law can create incentives to respond to social and economic interests of property rights, efficiency, distribution, and externalities. These issues are addressed in Chapter 5 on water law. Property rights in water allow for exchange of ownership or use of water, either captured or in the ground. These rights may also ensure that ownership or use is not impaired. Government institutions have been created at many jurisdictional levels in countries to address water issues. Judicial processes provide for legal review of rights to own or use groundwater. Legislative bodies may provide subsidies to encourage certain uses or taxes to discourage other uses of water. Executive regulatory agencies may determine allowable cost recovery in prices set by private and public water suppliers. Water utility commissions exist in many of the United States to set water rates for privately owned water companies which have a monopoly to provide water to the communities they serve and do not consider depletion of

EXHIBIT 9.9 GUIDELINES FOR PRICING OF IRRIGATION WATER, THE WORLD'S LARGEST USE OF GROUNDWATER

Microeconomic Guidelines

1. Marginal-cost pricing achieves efficient water allocation, in that it maximizes the joint surplus of water users, i.e., farmers, and water suppliers (p. 75).
2. Average-cost pricing guarantees a balanced water supply budget but entails a loss in efficiency as it decreases the joint welfare of farmers and water suppliers. Moreover, the farmers carry the burden of the welfare loss (p. 76).
3. Block-rate pricing can be used to transfer wealth between water suppliers and farmers while retaining efficiency (p. 76).
4. The costs of implementing a pricing method are part of the supply cost and should be included in the variable or fixed costs of water supply (p. 78).
5. From an efficiency standpoint, the desirable pricing method to use is the one that yields the highest welfare when implementation costs are accounted for (p. 79).
6. Any charge intended to cover the fixed costs of water supply should be levied in a way that does not affect farmers' water input decisions, e.g., as a fixed payment or a per-hectare payment, but not as a volumetric charge (p. 81).
7. Water prices have limited effect on income distribution within the farming sector and are therefore an inadequate vehicle for addressing income-distribution goals (p. 82).
8. In light of Guideline 6, the question of who pays for the fixed cost of water supply when suppliers' operating profit falls short of the fixed cost can be determined according to income distribution criteria. In developing countries, the urban population is more affluent than the rural population and may carry some of the burden of the fixed costs of the irrigation water supply. They will receive a part of this back in the form of less expensive food products (p. 82).
9. When water derived from sources of different quality, e.g., fresh, saline, or reclaimed water, has different effects on crop yield, each water quality is treated as a separate input and must be priced separately. The demand for each water quality depends on the available supply and demands for the other water types. Given the set of water demands, pricing should be determined simultaneously for all water types (p. 83).
10. When irrigation water is derived from a stock source such as a lake, reservoir, or aquifer in an unsustainable fashion, i.e., the stock shrinks over time or the quality of its water deteriorates, the price of water must also reflect the scarcity, i.e., depletion effect, and stock externality, i.e., effect of stock size on withdrawal cost. These effects show up through the user cost of water, calculated within an intertemporal management framework. The user cost of water should be added to the cost and price of water (pp. 84–85).
11. If demand for water from a number of different sources is the same, e.g., a perimeter or district that uses water from various surface and ground sources, a change in the supply cost of each source implies that the marginal cost of water supply increases when supply shifts from one source to the other. The less expensive sources will be used first, and the water price should reflect the marginal cost of the most expensive source in use (p. 100).

(*continued*)

EXHIBIT 9.9 (continued) GUIDELINES FOR PRICING OF IRRIGATION WATER, THE WORLD'S LARGEST USE OF GROUNDWATER

12. When water is priced volumetrically, efficiency requires that the price of water reflect the marginal cost of water supply, disregarding water allocation between crops; i.e., the water price should not change across crops (p. 108).
13. Under per-area pricing, changing the per-hectare water fee across crops can be used to improve efficiency by influencing farmers' crop choice (p. 108).
14. Because of the prevalence of asymmetric information, water allocation and pricing rules should be designed so as to minimize the administrative limitations on farmers' input–output decisions (p. 127).

Macroeconomic Guidelines

15. Macroeconomic policy reform will have substantially different regional impacts on irrigated agriculture. Even perimeter level changes in water demand have measurable, although different, impacts on the rental rates of other factors of production throughout irrigated agriculture (p. 143).
16. It is important to link macroeconomic analysis of reform to the microlevel analysis of water market reforms at the farm or perimeter level (p. 143).
17. Economic reforms outside of agriculture affect water productivity in irrigated agriculture (p. 148).
18. Reforms outside of agriculture have strong effects on rural agriculture household income (p. 149).
19. Water policies that remain rigid in the presence of reforms outside of agriculture can increase the disparity in water productivity among farmers and crops and potentially lower the overall water productivity (p. 149).
20. Economic reforms outside of agriculture, trade reform in particular, create opportunities for water market reform because farmers hurt by reform can be partially compensated by the creation of a water market (p. 152).
21. Linking macroeconomic reform with the reform of water policies can increase not only the national productivity of water in agriculture but also the welfare of rural households, accomplishing more than macroeconomic reform alone can do (p. 152).
22. The gains from linking macroeconomic and water market reform grow over time as capital is reallocated. However, fully realizing these dynamic gains in agriculture may take up to five years longer than the effect of macroeconomic reforms on the rest of the economy because of the greater difficulty of reallocating capital in agriculture (p. 152).
23. Water market reform in the absence of trade reform can lower the real productivity of water because a greater volume of water may be allocated away from unprotected crops toward protected crops (p. 153).
24. Macroeconomic and water market reform together cause a reallocation of water among crops and farmers, but evidence was not found to suggest that some crops would not be produced or irrigated after reform. Thus, reform appears not to cause a drastic reallocation even though the gains in water productivity are high (p. 153).

Source: Abstracted from Tsur, Y. et al., *Pricing Irrigation Water: Principles and Cases from Developing Countries*, Resources for the Future, Washington, DC, 2004. With permission.

EXHIBIT 9.10 UTILITY COMMISSION GROUNDWATER PRICING DOES NOT CONSIDER DEPLETION

A survey of all 50 U.S. states' public service commissions concerning their policies on pricing groundwater used by regulated public water systems received 32 responses indicating that none of the states reporting used scarcity rent calculations to price water where groundwater was being depleted. Most of these commissions regulate privately owned water systems only. Five states do not regulate water rates set by any of their publicly or privately owned water systems. Nine states specified the number of systems they knew were depleting groundwater. Other major factors cited in establishing rates for groundwater in cases of resource depletion were: cost of alternative supplies and cost of capital and expenses. One state identified water replenishment charges and another, conservation and drought rates.

Source: Job, C.A., Survey of State Public Service Commissions Concerning Water Rates and Ground Water Depletion, 2002.

an aquifer in establishing water rates (see Exhibit 9.10). Water supply organizations can be established to provide water for classes of users or to particular locations. Water user organizations serve to allocate water among users and in doing so, may set prices and determine how water is used. A central water authority may have a range of roles: ensuring water allocation for national or state purpose; setting water prices; providing for market-based exchanges and trading of water; controlling water use and discharge quality permits and trading; establishing international agreements on transboundary water issues; creating water banks for large-volume storage and transfer; setting up spot and options markets to address variability in water availability (Tsur et al., 2004, pp. 28–39). All of these institutional functions affect the price of water.

National and international organizations have identified pricing of water as a critical factor in water allocation. The institutions involved in water pricing and allocation are encouraged to consider the full cost of the water being used. Governments may act to impede appropriate pricing through poorly planned water investments, ignoring water quality and other ecosystem concerns and implementing low water prices, while not recognizing equity needs relative to poor people (Tsur et al., 2004, pp. 31–32). Tsur et al. highlight a number of institutional considerations affecting price and water allocation, principally focused on irrigation water pricing but applicable broadly to other uses of water, summarized in Exhibit 9.11.

AVERAGE VERSUS MARGINAL COST PRICING

In policy development for pricing of water, marginal cost is the measure of interest rather than average cost. Average cost is a crude estimate of value across all units produced: a measure of total cost divided by the number of units supplied. Furthermore, average cost multiplied by the total number of units provides total cost, which is not the value of the resource. The value of the resource is location and time specific relative to particular uses and is determined at the margin based on the cost of the last unit produced. The challenge is to understand how fully that marginal cost was developed and what costs were included or excluded. At the decision-making margin, opportunities to use alternative sources also exist and provide a measure of value beyond production cost. While the volume may be less, the value as measured by delivered cost of adequate quality water supply to urban customers with the capability to be accessed at specific times in a residence may be greater than that of groundwater from the same source delivered to farmers' fields. The cost of urban water typically includes treatment to meet health standards, transmission through an extensive system of pipes and availability at any time of the day. The large volume of the agricultural use will bring down the

EXHIBIT 9.11 INSTITUTIONAL CONSIDERATIONS AFFECTING WATER PRICING

Laws and Property Rights (pp. 29–32, 48)

- Laws and property rights affect economic efficiency, equity, and externalities
- Significant to market allocation of groundwater are well-defined, enforceable, transferable property rights to create certainty for users and recognize needs among water use sectors
- Critical factors affecting results of water law are
  - Integrated treatment of the water source
  - Effectiveness of conflict resolution
  - Degree of integration within water law
  - Legal scope for private participation

Governments of Developed and Developing Countries (pp. 31–32)

- Failures in irrigation projects and activities include:
  - Misallocated project investments
  - Overextended government agencies
  - Inadequate service delivery to poor people
  - Neglect of water quality and environmental effects
  - Underpricing of water resources
- Promotion of efficient irrigation services through
  - Strong policies promoting efficient water allocation
  - Ensuring water fees are applied to operation and maintenance
  - Establishing water fees with fairness
- Characteristics for efficient water allocation through local or regional water user organizations include:
  - Unbiased allocation
  - Provision of water brokerage to lower trade transaction costs
  - Floating water prices
  - Enforcement of 3rd party rights
- Factors for water markets to succeed require governments to:
  - Define and enforce water rights
  - Monitor and regulate externalities and 3rd party effects
- Institutional changes at the international level affecting pricing in the water sector include:
  - Shift from source development to demand management
  - Acceptance of privatization and decentralized control
  - Adaptation of integrated approaches to water management, especially at the river basin level
  - Focus on economic viability and physical sustainability

Water Administration (p. 49)

- Water administration should provide incentives to optimize:
  - Management performance
  - Improvements in system quality and efficiency
  - Savings of government funds through reduced operation and maintenance from transfer of management responsibilities

Source: Tsur, Y. et al., *Pricing Irrigation Water: Principles and Cases from Developing Countries*, Resources for the Future, Washington, DC, 2004. With permission.

average cost while the marginal cost of at-site home use may be greater. Another consideration here in characterizing costs for pricing is that if the site of irrigation use of groundwater is basically "at the source" then transmission costs are low. In urban areas, water may need to be brought longer distances by pipe and may also be delivered "at the site" of use through a distribution system of pipes and be further from the source.

The inclusion of cost elements affects the result of the pricing approach. Average cost pricing includes both fixed and variable costs. Marginal cost pricing considers only variable costs of producing the last unit. Owing to economies of scale and the relationship of average costs to marginal costs, most water providers experience lower marginal costs throughout the relevant range of production. If marginal cost pricing is used, it may ignore the cost of the infrastructure to deliver the water. This infrastructure will most likely need to be replaced in the future and the cost to do so is not recognized under a marginal cost approach.

Full Cost Pricing

Full cost pricing attempts to incorporate all relevant costs into its framework. Full cost pricing has different meanings depending on its application. For public water suppliers, who own and operate the water system, full cost pricing means that all significant business activities relevant to providing water are included. This approach represents a financial basis for pricing. In a societal context, full cost pricing recognizes that all costs to society for providing water are incorporated into the price, including external (third-party effects) and ecosystem costs. This second approach has an economic basis that considers all costs of providing water.

The two approaches are different in these ways. In the first approach, public water suppliers must capture all direct and indirect costs including depreciation and replacement costs for capital items (such as treatment plants and pipes, the latter of which can be long-lived) and the amortization of utility debt, along with a return on equity invested, when considering opportunity cost of capital. This might be considered an extension of marginal cost pricing, when considering all production costs at the margin. The second approach includes the costs of the first approach but also incorporates the "polluter—or depleter—pays" principle through taxes or other charges and fees that are added to the supply cost. This latter approach uses the price mechanism to signal users about the scarcity of water and needs more research, especially as it relates to effects on the ecosystem and their costs—although, it has been used more extensively in Europe—and is widely accepted by economists as the way to use the marketplace and conserve environmental resources (USEPA, 2003, p. 1). Pricing methods to capture a fuller set of costs of the second approach include (e.g., see USEPA, 2005):

- Increasing block rates—water unit charges that increase with use within tiers of consumption, with each tier or "block" of greater use having a higher rate.
- Time of day pricing—peak water use times during the day command higher unit prices.
- Water surcharges—higher unit charges when water use exceeds a specified amount.
- Seasonal rates—water unit charges increase or decrease based on demand during different times of the year.

VALUES

As suggested above in the discussion of benefits, values for groundwater may address the realm of intrinsic processes of nature that sustain life, which when interfered with would disable fundamental provision of water for all manner of needs to support life as the world knows it. Disrupting or damaging services naturally provided by groundwater are typically referred to as "externalities." Per Bergstrom et al. (1996) and NRC (1997), a range of services are provided by groundwater and the natural environment. However, many more services may be provided by groundwater that we cannot recognize because of our limited view of the function of this resource that is "out of sight" from a day-to-day human perspective. Tufte (2006) noted: "The laws of nature are utterly indifferent to what we think about them." Freeman (1993, p. 485) goes further to say that "the economic framework, with its focus on the welfare of humans, is inadequate to the task of valuing such things as biodiversity, the reduction of ecological risks and the protection of basic ecosystem functions. When policies to protect biodiversity or ecosystems are proposed, economists may be able to say something sensible about the costs of the policies; but except where nonuse values are involved and where people use ecosystems…, economists will not able to contribute comparable welfare measures on the benefit side of the equation."

Daly (1996, p. 75) goes steps further to suggest "life enjoyment [*perhaps referring to human well-being*] can be interpreted [by]…recognizing the intrinsic as well as instrumental value of other species." By extension, Daly addresses the importance of natural capital unrecognized in the standard economic framework of circular flows of products and services among human beings in various employments (consumer, labor). Natural capital is being used up locally and globally (addressed under "macroeconomics" below). Howe from 17 years earlier (1979) reached a similar conclusion through the exploration of cost–benefit analysis to natural resources, concluding that the legacy to future generations must include not only human capital, but more so a natural capital of resources and ecosystems, much of which is being irreversibly used and for which demand is growing. He also found that technological change could not supplement natural stocks (Howe, 1979, 316). Howe pointed to conclusions of Smith and Krutilla (1977) that (1) waste disposal technology is leveraged to use the common property waste assimilative capacity of the environment, (2) a considerable amount of the growth in output is ascribed to "technological change, education and other qualitative factors and should have been attributed to increasing use of the environment," (3) prospective expanding use of the environment as an input (e.g., a resource or a pollutant sink used) may not be possible, and (4) "if technological change has in fact been less productive than we have thought, future technological change must be more heavily discounted as a partial solution to our resource problems" (Howe, 1979, p. 329). Thus, a new way of deciding on use of the natural endowment of the earth's ecosystem for its expanding human population is critical.

Fundamental to natural capital is the value of ecosystem relationships not recognized in the standard economic framework (Daly and Farley, 2004). These are natural processes that provide the basics of what human beings have: the hydrologic cycle, sunlight, and natural protection from it, reproductive systems, biochemical interactions, and more—all necessary to sustain life. Groundwater might be captured by an economic process (e.g., domestic water supply or irrigation), but it still exists in the larger realm of the ecosystem, having been extracted from an aquifer and sent to a residence or cropland by pipe for further processing to provide benefits for bodily needs or crop growth and evapotranspiration. Our equations for comparing benefits and costs, while simplistic, must include factors for the replacement of ecosystem functions affected, in effect, taking into account an "intrinsic value." Thus, the total resource (or *ecosystem*) value of groundwater might be written:

$$\mathrm{TRV_{GW}} = \mathrm{TEV_{GW}} + \mathrm{TIV_{GW}} \tag{9.14}$$

where

$\mathrm{TRV_{GW}}$ = total resource value of groundwater
$\mathrm{TEV_{GW}}$ = total economic (extrinsic) value of groundwater
$\mathrm{TIV_{GW}}$ = total intrinsic value of groundwater

$\mathrm{TEV_{GW}}$ is the existing economic values of the goods and services from the stock ($\mathrm{GS_{GW\text{-}S}}$) and flow ($\mathrm{GS_{GW\text{-}F}}$) of groundwater and nonuse values ($\mathrm{NUV_{GW}}$) estimated from studies described in Chapter 13 (e.g., contingent valuation studies). $\mathrm{TIV_{GW}}$ is the existing performance value of the underground portion of the water cycle within the ecosystem (with complex and nonunderstandable [by human beings] but complete relationships with the rest of the ecosystem) for the hydrologic cycling ($\mathrm{HCV_{GW}}$) of freshwater (including quantity and quality) to wetlands, lakes, streams and oceans, maintenance of microorganisms for processing (MPV_{GW}) human, domestic, and industrial wastes and naturally occurring substances entering the subsurface (as documented in Gibert et al., 1994), support of vegetation (SVV_{GW}) for cycling nutrients and photosynthesis, maintenance of climatic balance through evapotranspiration (CBV_{GW}), and other processes (OPV_{GW}) yet to be defined. Mathematically, the relationships are

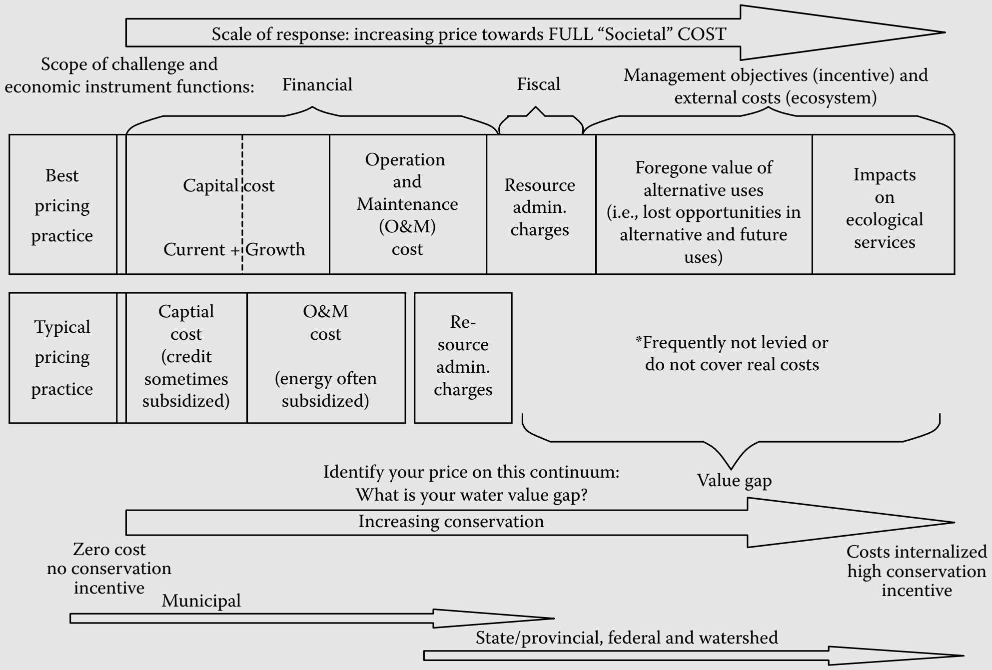
$$TEV_{GW} = GS_{GW\text{-}S} + GS_{GW\text{-}F} + NUV_{GW} \tag{9.15}$$

and

$$TIV_{GW} = HCV_{GW} + MPV_{GW} + SVV_{GW} + CBV_{GW} + OPV_{GW} \tag{9.16}$$

Some of these values may currently be nonmonetizable, but clearly there is a market for the products and services of groundwater that people take only for the cost of putting groundwater in a place (through wells and distribution systems), container (bottles or glasses), or relationship (to process wastes in water and liquids that enter the subsurface through septic systems and injection wells, and otherwise infiltrate the subsurface) that they can use. As we improve our understanding of these processes, we may be able to estimate in a gross and inaccurate way in the near-term and in a more refined way in the long term the economic benefits that these processes provide. Exhibit 9.12 depicts this challenge graphically.

EXHIBIT 9.12 THE SOCIAL VALUE OF WATER AND THE WATER VALUE GAP



Source: Adapted from Sawyer, D. et al., *Analysis of Economic Instruments for Water*, Canadian Council of Ministers of the Environment and Marbek Resource Consultants, Ltd., Winnipeg, MB, Canada, 2005. With permission.

Exhibit 9.12 shows that "best pricing practices" would ideally capture values of the resource, of lost opportunities and future uses, and even of impacts on ecological services that are lost today. Typical pricing practice falls far short of the full social value of water, only sometimes recovering the resource administration costs. In 2007, municipal jurisdictions still subsidize water costs so that consumers do not see the full cost of its production for their use. Implied by the bottom arrow labeled "State/provincial, federal and watershed" is that other jurisdictions that can serve as stewards and administer over the larger resource and its flows through the ecosystem are positioned to address the "water value gap" through intrinsic and ecological services pricing—not that those jurisdictions have perfect understanding of what the value is, but can recognize at a higher level of political–economic hierarchy that these values are significant enough, albeit, essential enough, to be incorporated in the prices water users should pay for the services of water. Policies and actions using economic instruments affecting the price of water and in response to those foregone values and damages to ecological services would be recognition of the social value of water.

OTHER CATEGORIES OF EFFECTS

RISK REDUCTION BENEFITS

In the United States, the Safe Drinking Water Act (SDWA) (as amended in 1996) formally identified a category of benefits called "*risk reduction*." Risk is typically portrayed as a probability of an occurrence of some event or a number of incidents of the event, which, in this case, would be some negative outcome from individuals consuming contaminated water, such as illness (morbidity) or death (mortality). In the context of drinking water, reducing the risk of death from naturally occurring arsenic (e.g.) in groundwater used for water supply by 12–30 persons per year of the 13,000,000 people affected by changing the health standard for the acceptable concentration in drinking water from 50 to 10 parts per billion (ppb) was perceived as a significant health risk reduction benefit warranting the change in the standard. Other acute and chronic health effects avoided were also considered (an additional 19–31 cases of bladder cancer per year and 19–25 cases of lung cancer per year) (USEPA, 2001b). Employing the standard to implement treatment technology for the reduction from the naturally occurring levels may be viewed as increasing the value of the groundwater for human consumption.

EQUITY EFFECTS

WTP for the benefit of a particular outcome is affected by factors including people's income and generation. Typically, economists aggregate from all persons' WTP to a national total benefit. Economic efficiency considerations for social policy development incorporate the potential that those who benefit from a change in policy could compensate those negatively affected. However, this approach does not consider distributional equity among the groups affected, specifically, distribution of benefit or cost effects among persons or groups of people with less income to absorb negative effects and disadvantaged persons or groups who may for some reason, such as physical condition, be affected disproportionately, thereby incurring greater negative effects than other persons. This is important relative to groundwater use for water supply since 97% of public water systems in the United States and a significant proportion of water systems elsewhere in the world serving communities or resident populations are small systems typically using groundwater. Most of these systems serve less than 100 people each.

Distributional equity considerations relative to groundwater use include effects on:

1. Low-income groups
2. Minority groups
3. Sensitive populations (infants, children, pregnant women, elderly, individuals with history of serious illness, other populations with significant risks)

It is possible that the effects of actions on groundwater may have more severe impacts on these groups than others.

Additionally, intergenerational equity should be considered because actions that affect groundwater, such as overpumping or contamination, require a long period of time to reverse, if that is even possible. For example, one negative effect, land subsidence, from overpumping and groundwater table decline is not reversible. In some areas experiencing land subsidence, large open cracks are left in the ground making the use of the area for other purposes problematic. Furthermore, groundwater from aquifers that are depleted from groundwater mining and may have very long times (up to centuries) for recharge, are a continuing loss to future generations (Daly and Farley, 2004, p. 209).

SUMMARY

Groundwater use has elements of both market and nonmarket goods and services. Economic theory indicates that people have preferences for certain bundles of goods and services and can rearrange the combination of goods and services as market forces affect prices. Groundwater has features, such as open access, that make it less conducive to market exchange at its marginal cost of supply. Market goods and services are typically quantifiable and monetizable, as well as being excludable and rival. Nonmarket goods and services are nonexcludable, rival, often unquantifiable, and affect persons outside those receiving the specific benefits. Quantifying or monetizing groundwater services should consider natural intrinsic values that result in groundwater being in existence and not just consider it a free good. Market failure results from inadequate signals from open exchanges of groundwater that affect the welfare of those not as directly involved in the exchanges, often in a detrimental way. A number of pricing methods exist, but all have inadequacies. Pricing may be adjusted to account for market failure to the extent that sufficient information is available. Increasing water scarcity is not considered in most pricing methods. Some intrinsic values that are known and can be quantified by considering the cost of the next alternative source of the service may support pricing adjustment. Equity factors relative to the distribution of effects (costs and benefits) include disadvantaged persons and future generations. Water institutions (laws, rights, governments, user organizations) have a significant influence on water pricing, depending on the specific laws and functions adopted. A significant point is that if we measure groundwater value solely by its production cost to satisfy near-term needs, the resources of the ecosystem, including groundwater, will always look cheap until we get near to depletion or unexpected degradation, for which we did not protect the resource. The value of groundwater may attract more research as we grow in our understanding of its role in the ecosystem that supports us.

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10 Macroeconomics

Since groundwater is believed to be ubiquitous under continents, it is a resource that is a factor in the macroeconomies of nations and the world. The field of macroeconomics focuses on the function and output of the overall economy and principally on national income, money supply and interest rates, saving and investment, general price level, and balance of payments (Bannock et al., 1978, p. 288). Given the dependency of the societies around the world on the existence and use of groundwater, it contributes to the function of nations' economies through its ecosystem services to communities and industries. Groundwater is a fundamental component of the world's "natural capital," affecting income, investment, prices, and balance of payments. Natural capital represents the innate stocks and flows available from the ecosystem that provide a useful and precious stream of resources and services henceforth (see Exhibit 10.1) (Daly and Farley, 2004, p. 437). Nations' macroeconomic policies in these areas will then affect and be affected by groundwater availability and use.

MACROECONOMIC POLICY ACTIVITY

Macroeconomics is more than the sum of microeconomic activity and is mainly concerned with the effect of policy actions with consequences on a nation's product, income, money supply, and interest rates. Other texts cover macroeconomic concepts in detail and, therefore, the reader is referred to them for that background, which will not be covered here except at a higher level (e.g., Samuelson, 1964; Branson and Litvack, 1976; Daly and Farley, 2004). Most nations' governments focus on macroeconomic policies influencing economic growth, ideally unconstrained. This policy perspective suggests that economies should grow without bound. Since unlimited growth in a world with finite resources is not possible, such a policy approach has severe constraints. Because the raw materials on which economies depend are extracted from the ecosystem and many of these materials are public goods or have characteristics of public goods, such as groundwater, they will become scarcer, if they are not already. Reliance on the market will undersupply public goods. While public goods are nonmarket goods by definition, traditional economic approaches may be inadequate to allocate them, necessitating policy interventions to ensure their supply (Daly and Farley, 2004, p. 224; Common and Stagl, 2005, pp. 308–355). In this context, Daly and Farley (2004, p. 297) indicate that:

> Theoretically, federal [policy and] money in a democratic society will be directed toward the goods and services that provide the greatest marginal utility for society as a whole.… [A]n important role of government expenditure is to provide nonmarket goods.

In this chapter, we will consider the macroeconomic policy considerations related to groundwater at the national or state level. Previous chapters have focused on decisions and projects at the level of the individual or firm. This and the next chapters focus on economy-wide policy goals and their aggregate effects as a way to point toward policies and goals we might desire in a resource limited world. In this resource limited world, ecosystem-balancing feedback has already signaled (through climate change) that the global economies have used up excessive capacity in the atmosphere for waste emissions, and are now looking into disposing of a portion of these emissions underground. This chapter attempts to answer the question "In a macroeconomic context, what is the nature of policies and their consequent projects that may address human needs for groundwater, in this case within currently unknown ecosystem limits?" First, we will cover some key macroeconomic concepts and then reexamine some of the macrophysical aspects of groundwater that affect or could be affected by these policies.

EXHIBIT 10.1 NATURAL CAPITAL AND ECOSYSTEM INPUTS

Natural capital

The three categories of natural capital are: natural resource stocks, land, and ecosystems. Together they are fundamental to the "functions" of the economy, which also support the sustainability of the biophysical realm on which humankind relies:

Resource functions are the extractions of materials for the economic production of goods and services used to improve the welfare of people. These materials include minerals, harvested plants, and animals, and groundwater as well as other natural endowments.

Sink functions receive the discarded residuals of production and consumption; wastes are disposed in air, water, or in or under the ground.

Service functions support the living space and processes for human beings and all other life including essential elements of air to breathe and water to drink—necessary to survive. If the service of survival elements are reduced or degraded, biodiversity is threatened.

Ecosystem support

Ecosystem inputs and ecosystem services are different.

Ecosystem services provide assimilative capacity of natural processes and support biodiversity.

Ecosystem inputs are substances produced by and consumed for natural processes such as oxygen, carbon dioxide, water, and nutrients.

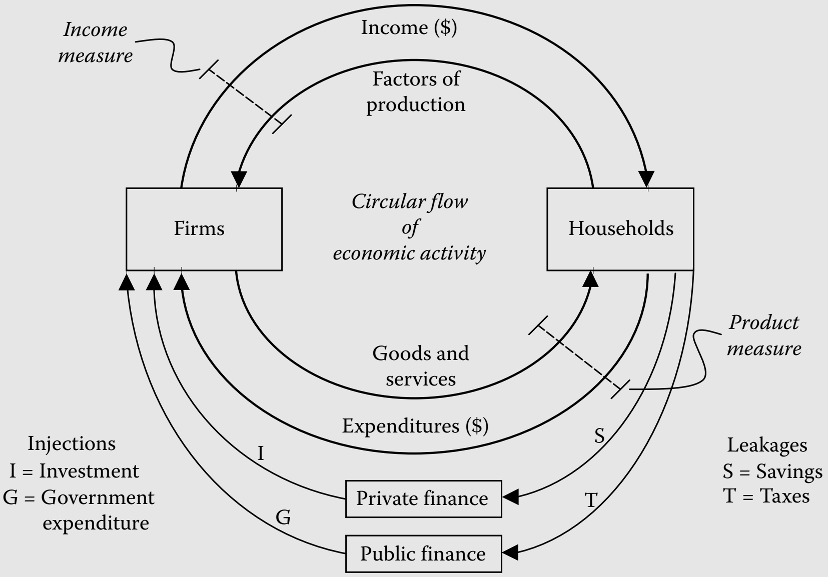
Source: United Nations (UN), 2003. *Handbook of National Accounting: Integrated Environmental and Economic Accounting*. Publications Board and Exhibits Committee, New York, P. 5, 73.

MACROECONOMICS IN OVERVIEW

The activity and output of the larger economy of nations is measured in monetary units as the value of all final goods and services. In the circular flow of the economy, households supply labor to firms which, with other factors of production (usually resources extracted from the ecosystem), are transformed into products (and wastes) demanded by households. Exhibit 10.2 depicts this flow of economic activity. Households provide factors of production and receive income; firms produce goods and services and receive expenditures. "Leakages" from household expenditures are savings (for future expenditure) and taxes (to support government). Corresponding "injections" are investment and government expenditure, working through private and public financial institutions, respectively. In this classical economic flow, waste does not exist. However, once products are consumed or used and worn out, they become wastes. Not only wastes but also the value of the resources extracted from the ecosystem is not typically accounted for in circular flow of the economy. The neoclassical economic production is a function of labor and capital: $Y = f(L, K)$, where Y = output, L = labor, and K = capital, as previously noted in Chapter 8 and in the circular flow of Exhibit 10.2.

The aggregate national product is referred to as gross national product or GNP, the value at market prices of all economic activity in a country (Bannock et al., 1978, p. 207). This is shown in Exhibit 10.2 as the "Product measure" of all final goods and services provided in the economy. But the value of natural resources, including groundwater as a life supporting service, is taken as zero in this accounting framework (Daly and Farley, 2004, p. 228), as groundwater has no market where it could be appropriately valued (Common and Stagl, 2005, p. 156). Though GNP is considered a measure of economic activity, it is not a welfare measurement. If wastes were included in the production function, then they would be noneconomic welfare. Losses from pollution and contamination of resources result in illness

EXHIBIT 10.2 CIRCULAR FLOW OF ECONOMIC ACTIVITY WITH LEAKAGES AND INJECTIONS



Sources:

1. Branson, W.H. and Litvack, J.M., *Macroeconomics*, Harper & Row Publishers, New York, 1976, 17.
2. Daly, H.E. and Farley, J., *Ecological Economics: Principles and Applications*, Island Press, Washington, DC, 2004, 27.

and unusable natural stocks and flows. Defensive expenditures that protect us from the consequences of pollution and contamination are likewise not increases in welfare, even though they are economic activity, and should not be counted in welfare measurement—they are "antibads" (Daly and Farley, 2004, p. 230; Common and Stagl, 2005, p. 148). Exhibit 10.3 elaborates on national product accounting from the perspective that manmade capital and natural capital are complements rather than substitutes in our economic activity measurement.

National Macroeconomic Functions

The roles of national governments are to use monetary and fiscal (expenditure) policies to affect the direction of the larger economy (as distinct from local economies), in turn influencing the use of the natural resources drawn from the ecosystem. As noted above, the principal functions focus on the tools of interest rates, money supply, spending, and taxation. Significantly, some of these tools—spending and taxation—can also be used to stimulate technological change to improve manmade capital, potentially to make it more efficient and less waste producing.

Because these policies are used to influence the economy as a whole—being more "blunt" economic instruments—they are limited in accomplishing specific ecosystem results, but significantly determine the "scale" and extent of ecosystem effects, which drive the economic activities. Expansionary monetary policy (increasing consumer spending in the economy) typically focuses on results that stimulate production and consumption of market goods, thereby increasing the scale of ecosystem resource use. Monetary policy does not address either resource protection and replacement where it is in jeopardy or equity and distribution effects, including access to affordable resources meeting

EXHIBIT 10.3 DEPLETION OF NATURAL CAPITAL IN NATIONAL ECONOMIC ACCOUNTING

Daly and Farley (2004, p. 232) note further on depletion of natural resources compared with manmade resources relative to national production that:

> The depletion of natural capital is a more clear-cut category [of national economic accounting]. GNP is gross national product. It is gross of depreciation of capital. If we deduct depreciation of manmade capital, we get net national product (NNP), which is a closer approximation to what we can consume without eventual impoverishment. But even in calculating NNP, there is no deduction for the depreciation and depletion of natural capital. Even NNP is gross of natural capital consumption (as well as of defensive expenditures). Significantly, manmade capital is not a perfect substitute for natural capital for the simple reason that the former cannot exist without the latter. The two are complements. Putting a dollar value on the depreciation of both manmade capital and natural capital implicitly assumes that both types of capital are perfect substitutes, and that we can accept the loss of natural capital as long as manmade capital grows by a compensating amount. In reality, less natural capital makes our manmade capital less valuable as well.

From this perspective, if no groundwater can be produced or if it is contaminated, then what value is the well, the land or the irrigation equipment?

basic needs. Fiscal (central government spending and financing) policy is more flexible in its ability to decrease scale impacts by protecting and restoring the nonmarket services of ecosystems or to ensure that some level of optimal scale is not exceeded (Daly and Farley, 2004, pp. 296–299). Related fiscal policies applied across the nation may include acquisition of sensitive areas as well as importantly ensuring that compliance with ecosystem requirements is monitored and enforced. For groundwater, these policies may mean protecting wetlands and sensitive habitats, funding recharge area monitoring and protection, facilitating the deployment of efficient water use technologies, checking the use of land applied chemicals and controlling underground disposal of wastes of all kinds. Preservation of ecosystem services through such efforts makes them available for future generations as well. Likewise, fiscal policies can be used to target income distribution effects to provide for the basic needs of the economically disadvantaged, including safe water supply.

Role of the Central Bank: In macroeconomic policy in the United States, monetary system policy is governed by the Federal Reserve System (FRS or the "Fed") of district central banks that have three policy tools, with other countries having similar monetary authorities, such as the Bank of England (Branson and Litvack, 1976, pp. 273–275; Bannock et al., 1978, pp. 40, 331; Daly and Farley, 2004, pp. 253–255):

1. Changing the interest rate that the central bank(s) charge(s) commercial banks for lending them funds when needed—this affects the interest earnings of banks made from loans to customers, with low interest rates attracting customers to borrow and thereby expand the supply of money and high lending rates shrinking money supply.
2. Buying or selling securities (bonds) of commercial banks by making deposits or withdrawals from those banks' accounts with the central bank, known as "open-market" operations, which will increase the money supply (and lower interest rates) or decrease the money supply (and raise interest rates), respectively.
3. Setting requirements of how much money banks must hold in reserve—changing the percent reserve requirements can increase or decrease the money supply with significant effect.

The significance of these activities is that they can stimulate the growth of the money supply in a national economy. The implementation of these policies influences people's decisions about the amount of money to save or to hold in checking accounts for current purchases. As the population grows, the demand for money grows. But an expanding money supply has little value without an equivalent addition in real wealth (Daly and Farley, 2004, p. 257). If the economy expands to produce more goods and services, it will need more money for the transactions. The circumstance of an expanding production of goods and services, while facilitated by increasing the money supply, has a real limit in the raw materials available to respond to this coincidence indefinitely. Thus, the growth of real money (i.e., the money supply divided by the price level) has a bound. We must ultimately look for other ways to measure and contribute to welfare and satisfaction, rather than solely in the creation of more products and money.

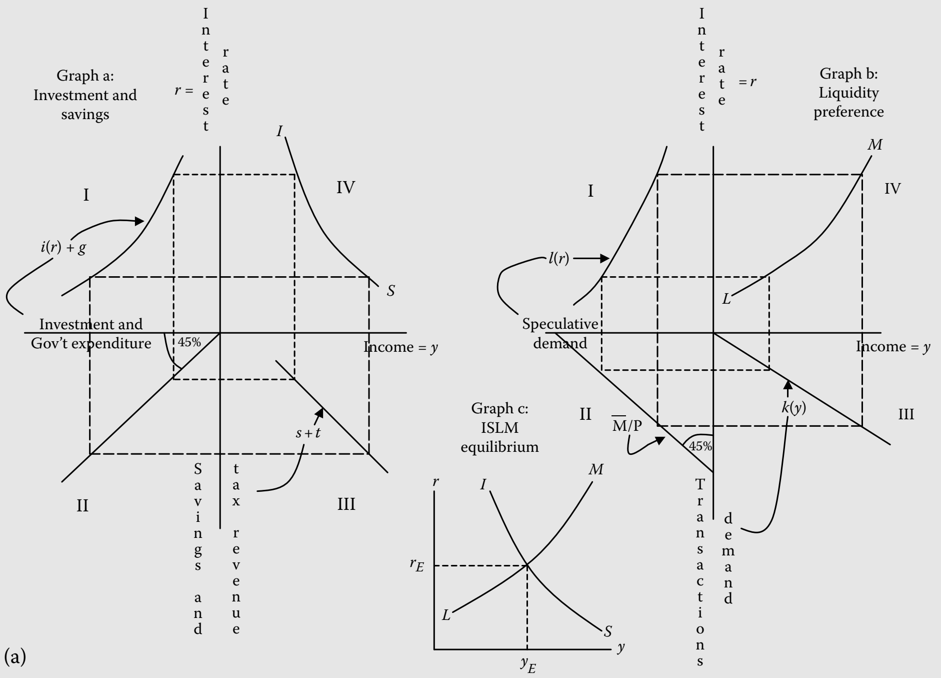
Role of the Central Government: The central government's role in managing a national economy is through fiscal policy in three areas: taxation, expenditures, and the printing of money.

1. Taxation is the principal way for most governments to obtain revenue to carry out the legislated functions it must perform. Governments can also tax items and activities that are determined as less wanted by the society, such as pollution or excessive resource use. To the producer, a tax on pollution raises that product's supply cost that will be passed along to the consumer in the form of a higher price. Relative to taxing pollution, this approach is referred to as the "polluter pays," causing the producer and the consumer to internalize the cost of products manufactured with unwanted pollution. Conversely, tax revenues and credits can be used to encourage activities that society wants more of, such as water or energy saving equipment, by providing subsidies for those products and services. Subsidies lower the prices of items or activities to which the subsidies are directed.
2. Government expenditures can influence the economy by being directed toward particular activities, services or production. As a major purchaser of goods and services, the central government can promote more efficient water use or recycling technology. It can also provide grants and funding to other levels of government to do likewise. Additionally, central governments may fund research for water efficient and pollution reduction technologies, which may have the effect of lowering the price of the technologies for widespread use, promoting efficiency throughout the economy. In these and other policy approaches (such as the granting or controlling of rights to use the resources), central government expenditures can be used to address the allocation of public goods, such as groundwater. To finance these expenditures, the government can borrow money by selling bonds that push bond prices down, increasing the interest rate.
3. Printing money is done to facilitate economic exchange. Governments exercise caution in this area, as it may contribute to inflation and other monetary problems, contributing to misallocation of resources.

MACROECONOMIC POLICY DEVELOPMENT

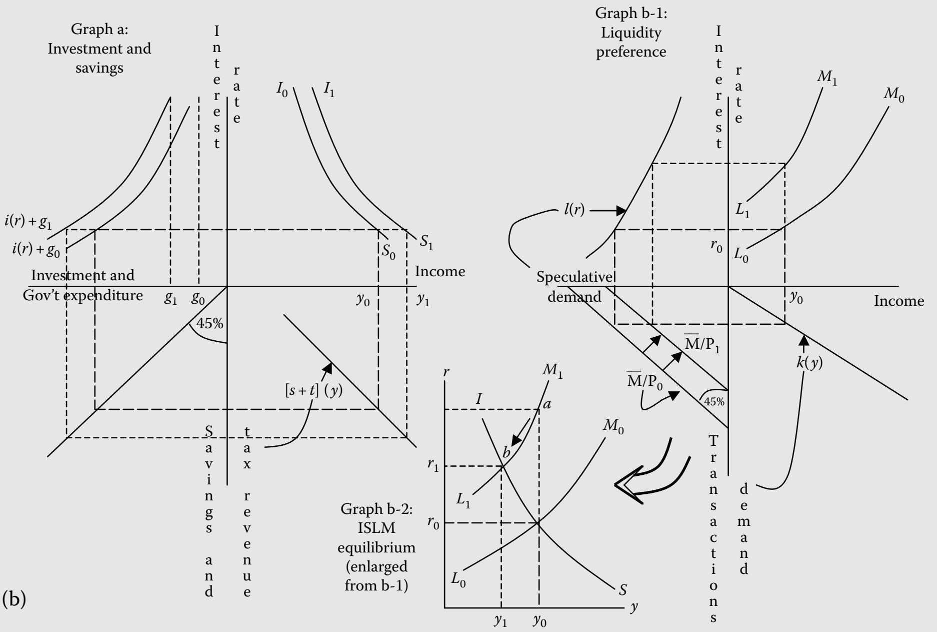
Macroeconomic policy development typically focuses on the use of economics tools to understand the impact of particular policies. One significant tool of modern economics is the use of the investment-savings-liquidity-money (ISLM) model. This model is described in more detail in other texts dealing with macroeconomics, but will be briefly covered here. The ISLM model relates income and interest rates to: (a) savings, tax revenue, investment, and government expenditure, and (b) demand for money for transactions and for speculative interest-earning opportunities. Exhibit 10.4 portrays an idealization of the operation of macroeconomic factors to derive equilibrium for supply of and demand for money. The key point here is that macroeconomic policy can affect use and protection of ecosystem resources and groundwater, but these considerations are not part of the model.

EXHIBIT 10.4a THE ISLM MODEL IN GRAPHICAL FORM



Source: Adapted from Branson, W.H. and Litvack, J.M., *Macroeconomics*, Harper & Row Publishers, New York, 1976, 63. With permission.

EXHIBIT 10.4b EXAMPLES OF SHIFTS IN IS & LM CURVES



Source: Adapted from Branson, W.H. and Litvack, J.M., *Macroeconomics*, Harper & Row Publishers, New York, 1976, 70, 73. With permission.

In Graph a (Investment & Savings) of Exhibit 10.4a

- Quadrant III shows the relation that as income increases, the savings and tax revenue increase.
- Quadrant II indicates that savings and tax revenue equals investment and government expenditure.
- Quadrant I shows the negative relation between interest rates (for borrowing) and investment.
- Quadrant IV indicates that at low interest rates with high investment, income is high.

Note, as shown in Exhibit 10.4b, Graph a, that with low stable interest rates, an increase in government expenditure, $g_1 - g_0$, shifts the i(r) + g_0 curve to the left to i(r) + g_1, increasing income from y_0 to y_1 and shifting the IS_0 curve to the right to IS_1.

For Graph b (Liquidity preference):

- Quadrant III shows that for an amount of income, a certain transactions demand for money exists to provide cash flow for purchases.
- Quadrant II indicates the complementary relation between transactions demand and speculative demand for money at static monetary (*M*) and price (*P*) levels shown as M/P.
- Quadrant I shows the speculative demand for money: When interest rates are low, people will hold more money than when rates are high (encouraging them to invest in interest-earning opportunities).
- Quadrant IV indicates the levels of *r* and *y* in equilibrium in the money market, for a given money supply and price level.

Note that if the price level rises, the 45° *M*/*P* line shifts inward, raising interest rates and shifting the *LM* curve up. In Exhibit 10.4b, Graph b-2 shows the reestablishment of the equilibrium for interest rates and income after a shift up in the *LM* curve, with the movement down the LM_1 curve from point *a* to point *b*, the intersection of *IS* and LM_1. The result is a new equilibrium y_1, r_1.

In Graph c of Exhibit 10.4a,

- The equilibrium position for the investment-savings demand to be balanced with the liquidity preference is at interest rate r_E and income y_E, the intersection of the *IS* and *LM* curves.

Several points evolve from this brief but pointed overview of macroeconomic factors:

- Decisions for monetary expansion drive interest rates.
- Interest rates are a driving force and can affect the extent of saving, investment, and liquidity preference (decisions about how much money to hold or invest).
- Interest rates in turn drive decisions about project and program implementation in the government and private sectors.
- Investment decisions are affected by interest rates, in turn affecting financing at local, corporate, and individual levels of project and program management.

EFFECTS OF MACROECONOMIC POLICIES

Exhibit 10.5 highlights the effects of macroeconomic policies on the economy and ecosystem resources, including groundwater. Expansionary monetary policies may have the effect of increasing demand for ecosystem resources that may include groundwater. Lower interest rates encourage investment and production activities that rely on borrowed money, such as farming and construction, which are sensitive to interest rate changes. Low interest rates will not stimulate the production of nonmarket goods. Rather, they will likely induce expansion of construction, which may be into sensitive ecological areas

EXHIBIT 10.5 ANTICIPATED EFFECTS OF MACROECONOMIC POLICIES

Policy	Interest Rate Effects	Income Effects	Effects on Ecosystem Resources and Groundwater
Monetary expansion accomplished through: • Reduced reserve requirements • “Open market” bond sales • Lowered discount rate	When economy is weak (high unemployment, low investment), monetary policy may have little or no impact on interest rates.	When economy is weak, no impact on income (known as the liquidity trap).	When economy is not weak, monetary policy may sustain and increase demand to consume ecosystem products and services. Lower interest rates encourage investment and make longer-term projects attractive.
Tax increase through • Income taxation • User or product charges	Taxes (especially progressive income taxes) help stabilize the economy.	Taxes collect more money when income grows and less when it shrinks.	Targeted user and product charges across economy reduce demand for targeted items, such as polluting activities or excessive resource use.
Tax decrease through • Reduced income tax rates • Income deductions to taxes • Targeted tax credits	May keep pressure off interest rates. Targeted deductions and credits may have little effect on interest rate levels.	More money for private consumption and less for providing public goods. Targeted decrease may have minimal effect on economy.	Targeted tax decreases shift demand toward targeted desired products and services.
Increased government expenditure	Can be spent on market or nonmarket goods.	Increases income (See discussion and exhibits of ISLM graphs).	Targeted expenditure increases demand for targeted items. Can be used for providing more nonmarket goods, such as ecosystem goods, including groundwater. May be useful in stimulating targeted technology research.
• Financed by deficit spending	Impact on interest rates may be small when economy is weak, large when economy is operating at full capacity.	Income will increase when economy is weak, but may not increase when it is already operating at full capacity (latter condition is known as “crowding out”).	When economy is weak, may increase demand for ecosystem resources and groundwater.
• Financed by taxes	Increase in interest rates is less than when occurring with deficit spending.	Growth rate is less than when occurring with deficit spending.	Depending on what is done with tax funds may reduce demand for ecosystem goods.
• Financed by seignorage (printing money)		Likely to cause inflation under crowding out conditions, with no real growth in income.	

Source: Adapted from Daly, H.E. and Farley, J., *Ecological Economics*, Island Press, Washington, DC, 2004, 292. With permission.

or zones needing significant resource protection, such as wetlands or recharge zones (Daly and Farley, 2004, p. 297). High interest rates impact debt holders, who may often be poor and economically disadvantaged people, reducing their ability to pay for basic needs.

Targeted macroeconomic policies may improve or degrade groundwater and ecosystem resources depending on the activities and products addressed. Targeted taxes can have the effect of reducing consumption of the targeted items, leaving the choice of more consumption of the item or more income for other items to the consumers across the economy. Targeted taxed items may include products and activities associated with generating pollution or excessive use, such as wasting water, across the economy. Targeted tax decreases can encourage greater demand for and offering of targeted items, such as equipment and activities that pollute less or conserve water. Tax credits may also be a vehicle to transfer payments to the poor to ensure that they have their basic needs provided.

Some examples will illustrate the implications of macroeconomic policies on groundwater.

Example 10.1—Energy Production

In 2007, we are seeing that with oil prices driving economies dependent on petroleum, relatively low interest rates in the United States at this time are supporting investments in alternative energy sources not reliant on petroleum, including biomass, nuclear, wind, solar, and geothermal. Groundwater implications of these decisions vary depending on the location and source, with biomass production, nuclear and geothermal having the greatest possibilities for potential water quantity or quality effects on the subsurface environment. Losses of groundwater from mining for biomass irrigation or contamination from agricultural chemicals or releases of other chemicals or radiological constituents may be irreversible in the foreseeable future or at least costly to change, both on a project level and in aggregate across the economy, if their potential for occurrence is not anticipated and properly managed and addressed. Relative to the widespread groundwater mining of Ogallala (High Plains) Aquifer in the United States used for irrigated farming, groundwater depletion allowances reduce agricultural costs and farmers' income taxes under federal law to spur food production and promote groundwater mining to produce energy crops for biofuel production which could potentially consume water needed for other important requirements in the economy and for future generations. The scale of this impact—including aquifer depletion and agricultural chemicals percolating into the subsurface—would likely be observed across the ecosystem and the national economy it supports. This circumstance assumes zero price being imputed to groundwater with the cost being that of groundwater pumping. Energy conservation across the economy could minimize the impact of further groundwater mining, rather than producing more fuels. A comprehensive macrolevel approach might identify a different selection of macroeconomic policies to facilitate the long-term use of the resource rather than short-term response and gain.

Example 10.2—Water System Financing

In the United States, as elsewhere in the world, the level of municipal bond interest rates are in part affected by interest rates in the larger economy established by the central bank and influenced by government borrowing. The United States has established a water system financing program primarily aimed at small water systems that have difficulty obtaining credit to build necessary infrastructure for safe drinking water supply. The program provides federal funds to states annually to capitalize state revolving loan funds that enable water systems to apply for financing at interest rates below market rates, giving them a subsidy. As of 2007, the program has grown to a $13 billion dollar financing activity, providing assistance mainly to small water systems, two-thirds of the nearly 6000 loan recipients. While this is a small part of the overall water infrastructure financing in the United States, the level of the rates and subsidy is targeted at a national scale and affects the ability of small water systems across the nation, often in rural and economically disadvantaged areas, to receive the benefits of implementing national health standards for water supply. Most of these small water systems rely on groundwater as their source. Interest rate levels affect the cost to finance their projects.

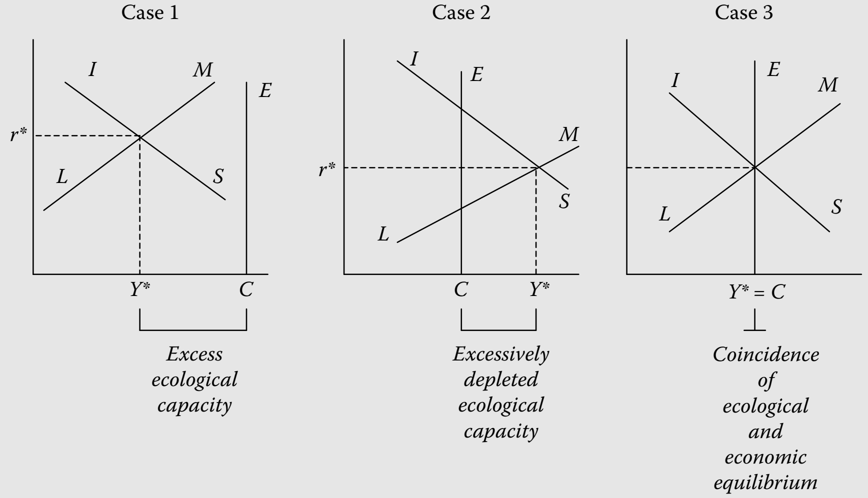
ECOLOGICAL CAPACITY IN THE MACROECONOMY

Daly and Farley challenge macroeconomic analysis with considering the "ecological capacity" (EC) of the economy (2004, pp. 302–304). They define EC as the "maximum ecologically sustainable throughput [of natural capital], convert[ed]… into the equivalent Y [throughput intensity per dollar] and impose[d]… as an exogenous constraint on the [ISLM] model. … It reflects a biophysical equilibrium, not an economic equilibrium." Such a constraint is not recognized by macroeconomists. Exhibit 10.6 displays three graphs that provide perspective to this approach.

In case 1, the EC constraint (expressed in equivalent Y) far exceeds the economic equilibrium Y^*. In this nation-state, many ecosystem resources exist so that the constraint is not affecting the economy. Case 2 shows a nation-state in which the economy has overshot its EC, i.e., many resources are scarce or depleted, or becoming scarce. The economy keeps running but demands on resources from the ecosystem are so high that prices increase for the available nondepleted natural capital. Daly and Farley note that most ecological economists believe that we currently reside in case 2, whereas conventional economists are not concerned with "natural capital drawdown." Case 3 portrays the coincidence of ecological and economic equilibria. The *ISLM* model does not provide for this happening—ecosystem constraints are not part of or contribute to any underlying assumptions in the model. No current economic or resource planning or institutions are addressing this on a nation-state basis (Daly and Farley, 2004, p. 303). Implied here is a second model focused on sustaining ecosystem resources for greater long-term existence of human society within the resource capabilities of planet Earth. This second macroeconomic model will be explored in the next section.

Reinforcing the point made by case 2, Common and Stagl (2005, p. 410, citing Wackernagel and Res, 1996) examine ecological footprints—the aggregate land and water area claimed by an economy that provides all the resources consumed and absorbs all the wastes generated by its people on a continuing basis with existing technology. They indicate that the ratio of footprint size to land area for the global economy increased from 0.7 in 1961 to 1.2 in 1999—basically, we need 1.2 earth equivalents to provide what we collectively used in that year. Ecological footprints vary by national

EXHIBIT 10.6 ECOLOGICAL CAPACITY IN THE MACROECONOMY



Source: Adapted from Daly, H.E. and Farley, J., *Ecological Economics: Principles and Applications*, Island Press, Washington, DC, 2004, 303. With permission.

economy, with the average global footprint being 2 hectares per person while in the United States it is 9.7 hectares. Many earths would be required to have everyone on the planet live in the U.S. manner. Clearly, strategic economists, ecologists, and planners need to explore realignment of economic and ecological factors for a sustainable future.

MACROECONOMIC MODELS OF THE ECONOMY

Two basic macroeconomic models have emerged to address large scale, interindustry, intercommunity, national, and international considerations in resource allocation and use. The "production growth" model, the current dominant model, has as its vision "growth in production throughput to keep an expanding number of persons employed and relying on unlimited resource inputs and assimilative waste capacity." The second model, "sustainable development," is emerging and focuses on "maintenance of the resource base and improved quality of life for a stable population within a finite natural system." Whether the production growth model is durable enough to guide a world now with a population of 6 billion and on its way to 10 billion in 40–50 years through the resource allocation issues, including waste handling, is still a question. Whether the sustainable development model can replace the current model may be determined by its ability to reflect the realities of any limits of the natural resource base in time to avoid major ecosystem disruptions affecting major national economies, should it be incrementally employed by changes in policies in industrialized countries.

What are the implications of the different macroeconomic models used for policy and decision making for groundwater? Certainly, the current production growth model encouraging increased natural resource throughput and waste assimilation has evolved to produce the thinning ozone layer, uncontrolled commercial fisheries, and fully allocated streams for predominantly human use in the United States, and depletion of groundwater in the United States, the European Union states, the countries of the Arabian Peninsula, China, India, Mexico, the former Soviet Union, and elsewhere (UN, 2001, p. 60). These and other circumstances have occurred by focusing on individual, single firm, single project, or single program activities as the appropriate economic scale of evaluation and policy making from an efficiency or cost-benefit standpoint. At the individual, single firm or project level, the only constraint is on the input which is scarcest, either labor or capital, but not natural capital, which is typically taken as free with no cost to consume it (Daly and Farley, 2004, pp. 228, 233).

The untested "sustainable development" model focuses on maintaining the natural resource base, minimizing production for capital maintenance and promoting quality development at the individual level with a stable population sharing wealth rather than concentrating it. While it is not clear what outcomes this model would hold for specific groundwater use, it matches well with the hydrogeologic concept of safe yield, the groundwater management construct that would balance the use of aquifers with their natural recharge while sharing water among users, as might be recognized in national, state, or local law. From a strictly macroeconomic perspective, diminution of national groundwater resources through aquifer depletion is a loss of national assets and savings (Auty, 2004, p. 37). Certainly, more efficient use of water could be one component, such as drip irrigation in arid locations. This approach could require major investments in manmade capital for such irrigation systems, which, in turn, would require more natural capital throughput to maintain. It is not clear that such managed irrigated agriculture would necessarily stop declines in aquifers to a point of safe yield. Thus, agriculture irrigated by groundwater could be defined as exceeding the carrying capacity of the ecosystem in arid areas, and, with rising populations, push agricultural production pressure back to lands of greater natural precipitation. However, the location of these humid areas may be questioned in the longer term because of climate change.

As Exhibit 10.7 suggests, the scale of evaluation and policy making is at the ecosystem level under the sustainable development model. This model incorporates the "preanalytic vision" (Daly, 1996, p. 6, citing Schumpeter, 1954) that the economy is a subsystem of the ecosystem and is therefore

EXHIBIT 10.7 KEY FEATURES OF MAJOR MACROECONOMIC MODELS

The "production growth" model is characterized by many features, particularly:

1. The circular flow of factors of production from households to firms and goods and services flowing to households (See Exhibit 10.2) in open unconstrained economic system.
2. Assumption of unlimited natural resource base for raw material supply would allow continuing increase of throughput of raw materials.
3. Assumption of technological change perpetually addressing labor-capital substitution.
4. Raw materials occurring in nature are costless.
5. Use of raw materials from the natural resource base is costless to ecosystem balance.
6. Discharge of wastes, other than impacts to humans, is costless to ecosystem balance.
7. Manmade capital is substitutable for natural capital.
8. Human action in self-interest will manifest the greatest benefit.
9. The market will establish prices to balance supply and demand.
10. This model counts all products and services as the same result, not distinguishing between manmade capital and labor and activities to protect the natural resource base on which production relies.

The "sustainable development" model has different features:

1. The circular flow of factors of production from households to firms and goods and services flowing to households occurs within the ecosystem and the resources and waste assimilation capacity available from it.
2. Assumption that the natural resource base for raw materials has limits.
3. Technological change may address substitution of capital and labor and conserve resources within limits.
4. Raw materials exist in nature at a cost (and this cost is more than to abstract them from air, land, or water).
5. Use of raw materials from the natural resource base has a cost to ecosystem balance.
6. Discharge of wastes has a cost to ecosystem balance.
7. Natural resource capital is complementary to manmade capital.
8. Societal interests will manifest the greatest benefit through qualitative development of the natural resource base, such as greater efficiency of use or phase out of use recognizing resource limits.
9. The market will establish prices to balance supply and demand.
10. This model suggests that protective services for the natural resource base be separately accounted for in national product accounts.

The "production growth" model relies on capital and labor substitution and technological change to solve all scarcity and waste assimilation problems without limits to expanded production for larger populations who will benefit from economic growth resulting from greater resource input. The "sustainable development" incorporates currently unspecified natural capital limits, affecting resource input and waste assimilation that must be maintained at a sustainable level to allow a large but limited population to improve its quality of life for a larger percentage of human beings.

Sources:

1. Daly, H., *Beyond Growth*, Beacon Press, Boston, MA, 1996.
2. Daly, H.E. and Farley, J., *Ecological Economics: Principles and Applications*, Island Press, Washington, DC, 2004.
3. Common, M. and Stagl, S., *Ecological Economics: An Introduction*, Cambridge University Press, Cambridge, U.K., 2005.

natural capital limited. Furthermore, natural capital cannot be substituted by labor or manmade capital. However, manmade capital going into water conservation devices that are planned at the outset to have a long life could help humankind meet goals of less water use and safe yield for aquifers so as to maintain streamflows and vegetation relying on shallower water tables. The extent to which this could be achieved under either model depends on how society incorporates the value of other species along with the value of water to humans in its policies.

Another way to think about these models is to recognize that the economic value of a good is price multiplied by quantity. Under the first model of production growth, producing more water for human demands multiplied by a lower price may give a quantifiable economic value of X, not considering the loss of habitat or species that is not accounted for in the growth model. Under the sustainable development model, a smaller (conservation) volume of groundwater at a safe yield that maintains habitat or species (or other environmental resources) multiplied by a higher price accounting for the supply cost of manmade conservation devices in delivering the water or just reduced use with a higher unit supply cost may result in an economic value of X as well. However, the sustainable development model may also have a higher ecosystem value of X plus V, the value of the environmental resources maintained for support of the ecosystem, including future water supply for human beings. Thus, a more comprehensive view of resource use and its implications at an economy level may demonstrate higher values with a sustainable ecosystem approach, rather than a production growth model.

At the ecosystem level, the relationships may be difficult to define and therefore the value may even be more troublesome to determine. One group has estimated the cost of providing seventeen ecosystem goods and services and developed a macrolevel estimated annual value for them of US$16–$54 trillion, with an average of US$33 trillion per year. The uncertainties in this estimate suggest that this is a minimum value. Global GNP total around US$18 trillion per year (Costanza et al., 1997). If these values can be derived at the macroeconomic level, then they can be used to establish policy in the circumstance where the economy is large relative to the ecosystem and show more clearly tradeoffs between growth strategies and sustainable development.

What are the cost and benefit implications of the two models? The production growth model weighs the costs and benefits at the individual or project level and determines whether benefits outweigh costs over the time horizon during which the streams of benefits and costs would accrue and be discounted. If the incremental benefits are greater than the costs, then the project is conducted. But the accounting perspective is important. A (hypothetical) project may only focus on one land development with one groundwater wellfield and maximum pumping capabilities for a deep well to avoid replacement of a shallower well if groundwater declines are too great over the accounting period. The accounting may not include costs for further declines in water tables increasing energy costs of pumping not just for that development but also adjacent established developments if its accounting area is too small. An adjacent stream may dry up during certain times of the year with greater pumping and less precipitation, affecting vegetation along the stream and displacing wildlife, even if lands along the stream are not developed. Additionally, groundwater pumped from the subsurface may be sent to a central wastewater treatment plant and then discharged downstream, transferring water from groundwater users to distant riparian users. Thus, within the boundaries of the development, the benefits may far exceed the costs, especially if the price of water may be slightly higher to reflect the higher pumping costs.

The sustainable development model may evolve into accounting over large natural resource zones and to the extent possible, reflect state, national and, where appropriate, global balances. Sustainable development would require maintenance of the natural resource capital available for service to human beings and other creatures. Groundwater withdrawal for national or regional programs would have to equal natural recharge. To accomplish this, water-conserving devices would be required for most, if not all, water uses. Additionally, treated water may be pumped back into the subsurface, allowing the natural subsurface organisms to further degrade any residual wastes, rather than pumping the discharge water downstream, and allowing natural groundwater discharge to maintain stream flow, riparian vegetation, and wildlife. Furthermore, the size of the development may need to be limited by the groundwater carrying capacity (sustainable production) and the ability of subsurface organisms to degrade residual wastes. Groundwater production would be evaluated on a regional level to ensure that pumping did not influence water table levels and flow that would in turn affect streams or quality of water available to other users. If sufficient benefit could be derived after considering costs of conserving measures, of impacts to regional users, vegetation and wildlife, and of waste assimilation, then the program might proceed.

GROUNDWATER OCCURRENCE AND USE (AGAIN)

Groundwater is typically associated with a particular property or area, corresponding to a local resource. As a result, economic analyses addressing groundwater focus on the microeconomic level and effects and on individuals or firms. However, groundwater underlies most continental land masses and should also be evaluated in a macroeconomic context. For example, groundwater flow paths may range from 966 km in the central United States to 1800 km in the Great Artesian Basin of Australia (Reilly, 2005), traveling under many political and property boundaries. Groundwater, then, by its nature has inherent macrophysical presence in the ecosystem—not just local existence bounded by law and borders.

Because many countries are heavily dependent on groundwater for their economies—one-third of the world's population rely on groundwater (UN, 2001, p. 60)—and because groundwater discharge is a significant component of transboundary, interstate, and international streamflow, macroeconomic considerations are important relative to irrigation and water supply effects, as well as power and navigation. The single largest use of groundwater globally is for agriculture: an average of 74% of the groundwater withdrawals in 44 countries is for agricultural use—68% of groundwater use nationally in the United States is for irrigated agriculture.

Other demands on groundwater are growing. Half of the population of the United States—more than half of the population in 30 states—relies on groundwater for their drinking water supply. The use of groundwater for public water supply to meet incremental additional demand from 1980 to 1990 grew more than two times that of surface water sources. This latter point also relates to the condition that most major streams in the United States that are used for drinking water supply must maintain flows for other instream uses, including endangered species and other aquatic and wildlife support. These circumstances indicate that groundwater is a resource of macroeconomic and ecosystem significance, rather than just a local stock. Population density in the United States increased from 1.7 persons per square kilometer in 1790 to 9.7 persons per square kilometer in 1890 and to 27 persons per square kilometer in 1990. We are literally filling up the landscape with consequent demand on finite resources, such as groundwater.

In Europe, groundwater use varies by country and within countries. Europe relies on groundwater for 70% of its public water supplies (Haakh, 1998). In association with the long flow conditions noted above that may exist, this information suggests that groundwater is potentially a transboundary concern at the international level with resultant macroeconomic effects, particularly if groundwater flow or quality is altered.

Rising population densities in finite areas also contribute to demands on the subsurface for waste disposal and assimilation, which may include migration of contaminants to groundwater, degrading water quality and in some instances making it unusable. Population concentrations also support more intensive agricultural production, including most recently chicken and hog farms, with their associated wastes. These wastes can leach through the soil and pollute groundwater, with the subsurface and ultimately groundwater serving as a "sink" collecting the contaminants. Once groundwater is polluted, it is difficult to treat and restore the resource, necessitating treatment at points of production (wellheads using air strippers for volatile chemicals, for example) or use (activated carbon filters in homes). Poor groundwater quality may even cause a community to seek an alternative water supply, making added demands on a limited resource.

Exhibit 10.8 highlights the macrolevel cumulative effect that many individual groundwater users can have on the resource.

EXHIBIT 10.8 ARE MACROLEVEL CONCERNS RELEVANT TO GROUNDWATER PRODUCTION? THE CASE OF THE CHICAGO, IL, AREA

In the Chicago, IL, area, two aquifers supply most groundwater—a deep sandstone aquifer, the Cambrian–Ordivician aquifer, in which groundwater occurs under confined conditions, and a shallow dolomite aquifer in which conditions trend from unconfined to semiconfined with increasing depth. Water from both aquifers is used mainly for municipal supplies.

From 1864 to 1980 (Figure 10.1), the six-county area of metropolitan Chicago of 5312 mi^2 (13,758 km^2) (1990 population: 7,261,000) had experienced water-level declines of more than 850 ft in the sandstone aquifer (Sasman et al. 1981). Groundwater levels in a well at Elmhurst, IL are characteristic of water-level trends in the deep sandstone aquifer. From 1953 to 1980, the water level declined about 370 ft in response to an increase in the annual withdrawal; for example, from 1959 to 1980, withdrawals increased from 40,504 m^3/day to 77,979 m^3/day.

Groundwater levels in a well at Itasca, IL, are representative of water-level trends in the shallow dolomite aquifer. Water levels declined about 50 ft from 1958 to 1978. The dolomite aquifer, like the deep sandstone aquifer, has been intensively used for municipal water supply. From 1960 to 1979, the withdrawals increased from 1500 to 20000 m^3/day. The water-level decline in the shallow aquifer, although much smaller than the decline in the deeper aquifer, has reduced the saturated thickness of the dolomite aquifer by 57% at Itasca, and the percentage may be much greater in more heavily pumped areas.

The amount of water-level decline in the semiconfined dolomite aquifer is much smaller per unit volume of water pumped than in the confined sandstone aquifer. For example, a 18600 m^3/day increase in withdrawals from the dolomite aquifer between 1959 and 1980 resulted in about 15 m of decline; however, an increase of nearly 38000 m^3/day from the sandstone aquifer between 1959 and 1980 resulted in about 75 m of decline. Although the withdrawal from the sandstone aquifer was double that from the dolomite aquifer, the water-level decline was five times greater in the sandstone aquifer. The difference in the response of the two aquifers to a unit withdrawal of water reflects differences in storage properties, in water-transmitting properties, and in the influence of hydrologic boundaries (Sasman et al. 1981).

The USGS National Water Summary also documents mining or depletion of groundwater in four other case studies: San Joaquin Valley, California (irrigation use); Baton Rouge, Louisiana (industrial use); Franklin, Virginia, area (municipal and industrial use); Dakota Aquifer of South Dakota (irrigation use).

Note that the pumping in the Chicago, IL, metropolitan area, created a regional cone of depression extending into Wisconsin and intersecting with the cone of depression from the Milwaukee, Wisconsin, area (USGS, 1985). Chicago is relatively humid with more than 86 cm as its annual average precipitation. Thus, macrolevel considerations for groundwater use by these metropolitan populations were significant. The City of Chicago Department of Water Management now supplies the city and 124 neighboring suburbs with water from Lake Michigan (City of Chicago, 2003). The sum of past and current individual groundwater pumping decisions is demonstrated in these and other cases.

Source: Abstracted from USGS, National Water Summary, Water Supply Paper 2275, 1984, 108–109.

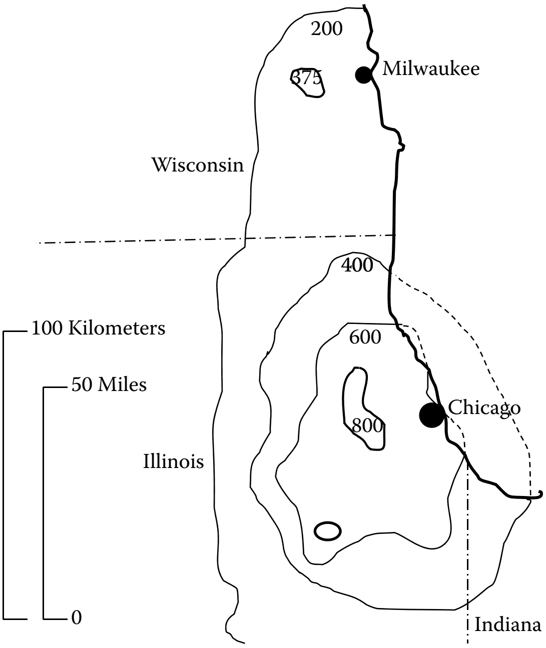


FIGURE 10.1 Groundwater level decline in the sandstone aquifer of the Chicago and Milwaukee areas, 1864–1980 (map units in feet; one foot = 0.3048 meter). (From USGS, National Water Summary, Water Supply Paper 2275, 1984.)

BASIC RAW MATERIAL FOR MANY INDUSTRIES

As noted above, groundwater is a basic raw material for irrigated agriculture and livestock watering. This resource is also important to other industries such as mining in most western United States and in the east central United States and Florida. Thus, the use of groundwater cuts across regions and industrial sectors. In irrigated agriculture for example, groundwater is a basic resource in many locations, which, along with sunlight, seed reproduction, biological photosynthesis, and soil, provide the underpinning of the economy in many areas and food-supplied energy and minerals to the United States population and other countries. Without groundwater, this production would not be possible, or not be possible at these levels under normal precipitation. In these situations, groundwater is natural capital being used to produce food for the sustenance of human beings around the world.

Having considered the macrophysical aspects of groundwater use, we will examine the resource as "natural capital."

NATURAL CAPITAL

The concept of natural capital is long standing, with contributions by Boulding (1945, 1949), Hicks (1946), Marshall (1961), Soddy (1920) and Georgescu-Roetgen (1971) and Daly (1996). Daly (1996) defines "natural capital" as "the stock that yields the flow of natural resources" and further indicates "(t)he natural income yielded by natural capital consists of natural services as well as natural resources. Natural capital is divided into two kinds:… renewable… and nonrenewable…" Daly also suggests that a "more functional definition of capital is "a stock that yields a flow of useful goods or services into the future," and "natural capital fits this concept very well, as do durable consumer goods." The reference to consumer goods, which are manmade capital that provide services in the future, is made here to point out that human beings value manmade capital, but do not value in a monetary way natural capital. For many years, economists have indicated that user costs for capital depletion should be applied as the opportunity cost of programs or projects. User costs could be derived from contingent valuation surveys or establishing the next least-cost alternative (Daly, 1996).

Importantly, though, the concept of "value-added" by nature without cost to human beings is not incorporated in the economy to allocate resources or even in most programs at the microeconomic level. Mankind would have spent untold amounts of money to build huge collection devices (like ponds and lakes and reservoirs), researched meteorology to know precisely when to cloud seed, develop precision cloud seeding methods, then cloud seed at the right time over large enough areas that would not be able to be used for other purposes (opportunities) and over countless years to store and make available the amounts of groundwater that nature has stored in the subsurface. The subsurface also acts as a sink for wastes, breaking down those wastes over longer periods of time, sometimes taking hundreds of years—and not instantaneously, even though the waste seemingly disappears in the subsurface. The waste disposal facilities needed to replicate this capacity would be enormous. The preexistence of this natural capital is like a subsidy. Subsidies distort resource allocation by making the resource appear cheaper than it is. This is the case of groundwater and the subsurface. We do not pay for nature's production and storage of groundwater, but only for its pumping, treatment, and distribution.

The value that human beings have associated with groundwater is the cost of production and delivery. From a manmade capital standpoint, production is the "rearrangement of matter" to give it new utilities (Daly, 1996, p. 62). Because of the first two laws of thermodynamics, matter/energy can neither be created nor destroyed and matter/energy move from low entropy to high entropy states,* humankind rearranges natural capital (iron, wood, water) to be more useful in providing service. For example, water in the ground in a low entropy state is pumped in thousands of places to the ground surface and then to treatment plants and finally to homes and businesses as drinking water, with a human value added to meet the local tastes and preferences of the many communities for drinking water of specified qualities. Treatment produces wastes and water used for cleaning, cooking, and bathing then becomes wastewater, returned to the environment in a high entropy state. The water has been dissipated, just as the energy applied to it for different processes has been dissipated. Wastewater, based on current tastes and preferences, has a lower value than drinking water, even though considerable expense may have gone into treating it before and after use.

At the national level, the nation recognizes the value added by manmade capital (wells, treatment plants, distribution systems, etc.) and adds it to GNP. However, the GNP does not place a higher value on more easily accessible groundwater (naturally closer to the ground surface or, better yet, artesian) or less polluted groundwater (water of naturally higher quality, for example) to recognize the product of nature, which would have cost much more to make it more accessible or of higher quality. Historically, the more accessible and higher quality groundwater was used first. In locations where the safe (sustainable) yield of the aquifer has been exceeded and water tables are lower, deeper wells must be installed to reach groundwater and more energy must be used to pump it to the ground surface. For example, in the humid eastern area of metropolitan Philadelphia,

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* This is an "analogous" simplified restatement (Daly, 1996, page 29) of the second law of thermodynamics which as formally stated only applies to energy, not matter. Energy in use is transformed from a low entropy condition—concentrated, high quality—to high entropy—dissipated, rearranged.

pumping of groundwater has lowered the aquifer which used to discharge to the Delaware River to a level below the river raising concerns that New Jersey groundwater producers supplying growing population centers may ultimately get water that has seeped through waste disposal sites on the Pennsylvania side of the river (McCabe et al., 1997) and have to treat it. In such cases, what was once a renewable resource has now become a depleted resource of lower quality. This portion of the Delaware River basin's natural capital may be unusable or eliminated without maintenance or treatment.

The Hicksian income definition includes the "concept of sustainability" (Daly, 1996, p. 75): "the maximum amount that a community can consume over some time period and still be as well off at the end of the period as at the beginning" (citing Hicks, 1946). Being "as well off" at the beginning and end of the period translates into maintaining the capital and thus a basic capability to provide the income stream each year. Capital here includes natural capital as well as manmade capital. Traditionally, microeconomics has treated manmade and natural capital as interchangeable, one can substitute for the other. Both Herfindahl (1969, p. 6) and Daly (1996, p. 76) note the complementarity of natural and manmade capital. As noted above, groundwater cannot be replaced by tractors to produce corn in an irrigated field. Thus, tractors and water in irrigated agriculture are complements; the use of either for corn production being limited by the scarcest one. In this case, wells are also manmade capital for irrigation that are complementary to this production and are one "agent of transformation of the resource flow from raw material inputs into product outputs" (Daly, 1996, p. 76). From another perspective, wells are the additional capital outlay necessary to "release" the productive services of the natural resource (in this case, groundwater), which might be thought of as a "partly finished capital good" (Herfindahl, 1969, p. 6). For the production to occur each year providing the income, both the manmade capital (wells and tractors) and the natural capital (groundwater) need to be maintained. If either becomes scarce—wells cracked and leaking and tractors worn out, or groundwater depleted—the product providing income will be diminished.

Kenneth Boulding (1949, cited in Daly, 1996) observed that human beings obtain "satisfactions" from the services of capital stocks, not from production or consumption. Production and consumption should be minimized; that is, production directed at maintaining the capital stock is a cost to be avoided to the extent possible and consumption of the capital stock reduces the level of future services. Therefore, the natural capital stock must be maintained.

Importantly, to achieve the level of production today, groundwater is a necessary and complementary "natural capital," existing freely in the environment only subject to control on maximum production in some States so as not to unduly interfere with other uses of the resource. No other capital (or labor) could substitute for groundwater in such a situation, or even in other types of production (e.g., mining in arid areas). More people (labor or human capital) cultivating the land could not substitute for groundwater used in irrigation. More tractors or fertilizer (capital) could not substitute for groundwater. Not even planting more seeds (another component of natural capital) would substitute for groundwater. The only thing that could substitute for groundwater is another water source, such as more natural precipitation or an easily diverted surface water source. Not even conservation or recycling substitutes for groundwater, which is consumed or degraded to some extent in any application, but those actions do reduce the demand for it. These other sources would have been relied on if they had been available at an acceptable price that was less than the cost of producing groundwater (with a zero price). The complementarity of groundwater use is significant here because classical economics indicates that capital and labor are "substitutes" with one being able to replace the other in short supply. In the case of groundwater, not even manmade capital (more tractors) could provide the service that groundwater provides. Thus, maintenance of the natural capital of groundwater should be the goal, rather than maximizing current production and associated income.

NATURAL CAPITAL AND DEPLETION

The concept of freely existing "natural capital" has far reaching implications in terms of future use of environmentally supplied resources. As pointed out earlier, groundwater is a resource drawn from the ecosystem. The ecosystem of Earth is finite and therefore its natural capital is limited (Herfindahl, 1969, p. 7; Daly, 1996, p. 91) with the volume of water of various qualities being fairly stable in its different states and spaces: atmosphere, oceans, underground, streams, lakes, glaciers, and icecaps. Global climate change may redistribute among the locations where the finite amount of water resides in the future, but the volume is more or less fixed. Obviously, some of these states (or forms) of water (underground, streams and lakes) are more useful to human beings for individual life support than others (glaciers and icecaps), which also support the ecosystem, although less obviously since most people do not live near those water forms to observe them or use them. Manmade capital in the form of wells and water and sewer lines can also redistribute groundwater. For example, historic groundwater levels in the 1900s maintained the flow of the Santa Cruz River, which is now a dry streambed in Tucson, Arizona, and the vicinity because of pumping for water supply, livestock, and irrigation by many individuals and firms. The aquifer supplying the Tucson valley has dropped many tens of meters, even causing land subsidence. Land subsidence creates a subsurface environment that cannot hold the same volume of water as it did previously, potentially reducing the future stock of water available if groundwater levels were to rise in the future. In the case of the Tucson valley, a permanent "depletion" of the natural capital occurred, perhaps in perpetuity. The groundwater was used beyond a sustainable level.

The examples above point to what Daly (1996, p. 49) refers to as the problem of the "empty" and "full" worlds that the global economy exists in, and is analogous to problems of common property resource use. When the economy was small relative to the ecosystem, the demands on natural capital for water, metals, wood, etc. and for waste assimilation resulting from their production and transformation to drinking water, wagon wheels and cabins was minimal, often dispersed and not concentrated, so as not to create much demand on the ecosystem services that allowed it to restore water and trees and degrade simple wastes. Today, the economy, in particular in North America and Western Europe, is large relative to the ecosystem. Population densities are high, creating enormous demands on a finite ecosystem for water, metals and minerals, and wood and other renewable and nonrenewable resources. Human economic activities are resulting in fishing limits in the oceans, modification of local and global meteorology and atmosphere, extinction of many nonhuman species, and groundwater tables are dropping in many locations, among other outcomes. In a full world with a finite resource base of natural capital, as population grows and resources become scarce, with possibilities for substitutes of manmade capital for natural capital limited, natural resources must be assigned a value to allow their allocation. This is the fundamental focus of microeconomics to allocate scarce resources where marginal costs equal marginal benefits, considering social costs and benefits. In the full world, maintenance of capital stocks means recognizing them as natural capital which is the limiting factor and not manmade capital (or labor). Depleting natural capital, including groundwater, devalues the manmade capital, such as wells, which have no use if they do not reach the water table. Both are essential and must be maintained for the benefit of humankind.

MACROECONOMIC BALANCING AND POLICIES

The basic problem amplified by Daly (1996) is that while microeconomics operates at individual and firm levels to balance costs and prices—supply and demand—to clear the market, the obstacle of scarcity faced by individuals and firms must be able to be cumulated and confronted at the macroeconomic level. At that level, community, state, and national policies must be able to realign rights to use natural capital as sources of raw materials and sinks for wastes once human beings have received value from and organized processes to maintain that natural capital. A problem at the national macroeconomic level is that GNP adds together the value added to process iron to make steel for cars with the costs of disposal of the pickling liquors from steel production injected into deep geologic strata as one result counted as dollars or other monetary units. Furthermore, GNP gives no value to water produced to process the steel except the cost to make it available. Also, counted in GNP is the "value added" by treatment plants that remove contaminants from ground or surface waters before use as drinking water, a cost imposed on the water suppliers by consumers' chemical uses. The chemical producers' product values are added to the cost of the contaminant removal in GNP accounting. In the United States, and probably in other countries, there is no good compass on applying value to water, from whatever source nor on the relevant scale (local, state, national, international) that the compass should be used, because microeconomics gives one approach and macroeconomics another as they are currently practiced.

Several writers have proposed a new system of national accounts that attempts to separate benefits from costs and establish a capital account. One definition of what these accounts might be (Daly, 1996, p. 113):

1. "A benefit account, which would seek to measure the value of the services yielded by all accumulations (capital) (not just those rented during the accounting period, and not just those used by consumers, but also those used in production that is enjoyable and self-fulfilling)."
2. "A cost account which would seek to measure the value of depletion, pollution, and disutility of those kinds of labor that are irksome (and of "waiting" in Alfred Marshall's sense). With separate accounts for costs and benefits we could occasionally ask if the extra benefits of further accumulation (capital produced) were worth the extra costs."
3. "A capital account, an inventory of the accumulation of stocks and funds and their ownership distribution. Included in the capital account would be not only produced stocks and funds, but also natural capital such as mines, wells, and ecosystem infrastructure."

Such an accounting scheme would enable marginal costs and benefits to be evaluated at the national level to establish a direction for all types of activities. Microeconomic costs and benefits could be added nationally to determine the appropriate scale at the macrolevel for setting policy and maintaining natural resources.

Natural capital historically was treated as and even consciously managed now as ever available and plentiful—free for the taking—and therefore was priced at zero. As population has simultaneously increased, has become more dense and spread out to fill up relatively "empty" areas, which previously had low populations, the "commons" has expanded. More people share the same finite public goods, such as resources like groundwater, that have been managed as private goods (such as under U.S. western water law) and are recognized as having a public good component—they flow (slowly) from one place to another, affecting many users drawing on the same water. To that end, to ensure the availability and quality of a resource in greater demand, the government can adopt policies to protect it at a macrolevel, whether the government be local, state, or federal.

MACROECONOMIC POLICY GOALS AND PRINCIPLES

GOALS

Moving to the macroeconomic level with policies to allocate resources is controversial but may be necessary to preserve spaceship earth for future generations, not to mention the groundwater resources in limited availability. In particular, where monetization of macrolevel strategies and their effects are not currently possible, setting goals that are quantifiable in other metrics may be necessary to determine achievement or success relative to ecosystem and social requirements. Specific goals may include (Daly and Farley, 2004, pp. 360–365):

1. Sustainable scale—a level of use, replenishment, and recycling of a resource that through stewardship allows observable ecosystem maintenance with no harm to future use,
2. Just distribution—equitable sharing of resources that ensures that all fellow human beings and species have basic needs addressed, and
3. Efficient allocation—an apportionment of resources that would make at least one person better off without anyone else being worse off.

The order of these goals is important given the limited resources of the planet and the fact that products and services of groundwater and the subsurface are finite and largely complementary to human capital. While in neoclassical economics, efficient allocation is paramount, in a resource-constrained world, sustainable scale should take precedence over the other goals (Daly and Farley, 2004, p. 363). If efficient allocation took precedence, then scarce resources would go to the highest bidder, likely making those resources unaffordable to most of the population (note that in 1998 in the United States, 20% of the population held more than 80% of the wealth [Daly and Farley, 2004, p. 263]). Relative to groundwater—a public good becoming increasingly scarce for which markets do not function well, scarce resources may not be available to most people, presenting a "just distribution" issue for a good essential to human survival. Thus, at the macroeconomic level, sustainable scale must be considered first, followed by just distribution, and then efficient allocation once those positions have been established.

PRINCIPLES

To address these goals, principles to guide developing implementable steps will aid in making them effective as long as they are workable and acceptable. Daly and Farley (2004, pp. 359–372) describe what these principles might be:

1. Each policy goal should have an independent policy instrument—for example, we cannot use the price instrument (tax or fee on water) to both increase efficiency and increase income of poor farmers. We would need another economic instrument to address poverty issues.
2. Policies should focus on achieving essential macrocontrol with the least loss of microlevel freedom and variability—with climate change potentially reducing precipitation to recharge aquifers, water objectives may still be met but through conservation techniques to reduce resource demand, with both use and technique guided by the circumstances of the situation.
3. Policies should incorporate a margin of error relative to services of the ecosystem—we must make estimates of groundwater availability conservatively, since making an error may be costly and have detrimental and severe effects on people's lives—not just health but survival.
4. Policies should incorporate conditions that include historical factors—many groundwater use institutions are in place ranging from existing residential plumbing systems and features to irrigation systems with depreciation tax laws that may need to be replaced incrementally over time with water conserving methods. Replacement will not happen immediately.
5. Policies must be flexible to accommodate change—as we have learned that groundwater and surface water interact, laws, and ordinances should change to recognize this new scientific understanding of the "single resource" nature of water in many environments to achieve effective and efficient solutions.

6. The policy-making organization's area of control should coincide with the region or zone of the problem—a single state should not attempt to set policy for an aquifer, which underlies other adjacent states and expect to be successful in managing the aquifer, unless the states are all focused on the same aquifer management goals.

MACROECONOMIC INSTRUMENTS

A range of instruments may be considered for application to maintain ecosystem resources and groundwater for current and future use:

1. Taxes on use and taxes on waste disposal. Taxes raise the final product price to consumers.
2. Limits on production, use, and disposal, with criteria set by states to recognize local circumstances. Limits may present artificial constraints on the resource and keep prices higher than they otherwise would be. These policies are tools that may be used to reflect local, state, or national values.
3. Subsidies to promote maintenance of natural capital. Science can provide guidance as to what resources should be a priority for protecting and maintaining.
4. Targeted interest rate adjustments based on resource condition. Currently, in financial markets, rates can be based on the asset to be financed and its condition. For example, used car loans are typically at higher interest rates than new car loans. Since 1987, the United States federal government has maintained a revolving fund loan program for wastewater systems and in 1996 drinking water systems that provide below-market interest rates as a subsidy to encourage investment in meeting water quality standard and acquisition of wellhead protection areas. Similarly, other investment could be encouraged in protecting ecosystem resources. High rates for investments in or adjacent to known sensitive areas could discourage such encroachment, rather than prohibiting them altogether, which might also be an alternative to the macroeconomic approach.

Other macroeconomic policy instruments may evolve as the value of ecosystem services becomes researched and widely understood. The effects of such macroeconomic policies will be manifest in the microeconomic activities of individuals and firms, in terms of changes in demand and supply costs. These relationships will be examined in the next chapters.

DISTRIBUTION EFFECTS

Distribution effects of a particular policy must be considered at a macroeconomic level. Distributional policies that attempt to bring about a sharing of resources with the poorest groups in society to ensure that they have sufficient resources are a global priority (WCED, 1987, Chapter 2). Whatever policy course is charted, in a world with a growing population and, for all intents and purposes, a reasonably finite amount of groundwater, or most of any other freshwater, water will become more valuable, reflected in a higher price. More than 1 billion people lack access to safe drinking water worldwide (UN, 2001, p. 60). In 1960, two cities had population of 10 million or more inhabitants. In 1999, this number had grown to 17 cities, and by 2015, it is projected to be 26 cities. In 1999, the world population stood at 6 billion and is projected to grow to 10 billion by 2050 (Time, 1999). Intensely inhabited areas will need to ensure that even though water and other essential resources may be highly valued, the poorest segment of society has access to water. In countries with large percentages of society living in poverty conditions, access to a sufficient volume of water, ground or surface water, may be a challenge to be met with just consideration for the needs of the poor and then taking steps to ensure that those needs are actually met into the future. With increasingly scarce water, one approach which invests in resource replacement to account for maintaining natural capital is the development of large wastewater recycling projects, which may also generate huge volumes of wastes to be disposed, posing further problems for adequate water quality.

Two components of equity exist: (1) intratemporal and (2) intertemporal (Common and Stagl, 2005, pp. 333–337). Intratemporal equity considers the distribution of income and wealth among a population within a generation. Intertemporal equity addresses distribution across generations. In either case, a just allocation, which may not be efficient, but can be efficiently delivered once determined, is critical to the well-being of those most in need. Within Pareto optimality, there is room for equity when some people are made better off while others are no worse off and so equity considerations can align with classical economics perspectives. "Redistribution can be efficient in the sense of increasing total social utility" (Daly and Farley, 2004, p. 261). From the societal view that these human needs should be addressed and the evidence that unequal distribution of income affects death and disease (Daly and Farley, 2004, p. 267, citing Wilkinson, 2001), nation-states concerned with the welfare of all its citizens—since we all have a stake in the use of ecosystem resources and the resulting economy—must focus attention on equity in the conduct of the society. However these challenges may be addressed, fair distribution of essential ecosystem goods and services must be addressed by central governments in their macroeconomic policies.

CONVERGENCE OF ECONOMIC MODELS

The question of whether the models of economic growth with ever expanding resource consumption and of economic maintenance of a sustainable natural capital resource base are mutually exclusive is significant. Over time, we see that the economic growth model is being constrained by the recognition that we cannot use carbon energy sources profligately and release carbon dioxide into the atmosphere without significant effects for climate change, economic and ecological systems, and carbon dioxide processing through the photosynthesis of the oceans' phytoplankton and the continents' forests and ranges. Indeed, as climate change manifests more potentially severe effects of greater drought and less groundwater recharge in arid regions and more precipitation in already humid areas, setting clear objectives for natural capital, and specifically for groundwater, in this case, from which nations derive a portion of income will require input of the most current hydrologic science and the understanding of the effects on communities and their supporting watersheds and ecosystem to the sociopolitical processes of open dialogue and public priority setting. While groundwater availability may decrease in certain regions, clear price signals that it is scarce will be important in guiding its use, but sustainable use in these areas may be possible as demonstrated by communities that are limited by water rights or ecological requirements. Such communities have set specific legal and ecosystem objectives for their natural capital in groundwater that must be met recognizing that ecosystem scale effects are important relative to the aquifers that support them, as in Westminster, Colorado, through a subsidized loan for water reclamation, and in San Antonio, Texas, through locally required water conservation efforts with a considerable amount funded by the public water system. In those communities and others in similar situations, the citizens respect the need to address allocation of scarce natural capital through public processes and requirements that limit the scale of their use of groundwater while facilitating community development, addressing common, shared social objectives for the resource. Whether these approaches will be adequate for long-term sustainability of the resource to meet communities' water resource needs will be the subject of future evaluation. Significantly though, the response of the local governments in these cases ensured that groundwater was and will continue to be used wisely, addressing in these ways potential failure of the market to otherwise make water available to important community purposes and to ecologically sensitive habitats and downstream users while maintaining the local economy. Further evidence of integration of some aspects of the models, although not specific to a particular resource, is the incorporation of the Leadership for Energy and Environmental Design (LEED) green building rating system into development projects across the economy, promoting, among other factors, water efficiency, use reduction (by 20%–30%), and innovation in wastewater technology (USGBC, 2008). In the absence of clear price signals, this construction rating system takes a stewardship approach to the use of resources and waste generation by setting social objectives to minimize material throughput with anticipated cumulative ecosystem effects that have become requirements in construction contracts. Additionally, the development and application of "ecological footprints" describing the land, water and energy consumption of particular activities links local projects to demands on the ecosystem's natural capital (covered further in Chapter 13). Thus, the economic models reflect very different approaches to socioecological accounting which must come into balance for the current and future welfare of society and the sustainability of the natural capital on which we rely. As climate change has demonstrated, ecosystem sustainability needs greater emphasis in this balancing process of policies affecting the macroeconomy supported by the limited resources of earth, including its limited groundwater.

SUMMARY

Macroeconomic policies focus on national income, money supply, interest rates, saving, investment, and the general price level all of which have a significant effect on the scale and extent of economic activities demands on ecosystem resources, including groundwater. Expansionary monetary policy may cause significant important resources to be withdrawn from the ecosystem without consideration for larger resource issues. Fiscal (spending) policy of the central government is more flexible in being able to target potential nonmarket goods—which are generally undersupplied, such as groundwater recharge zones or wetlands, for protection because of the services they provide in water supply and wildlife habitat. The classical economic circular flow of activity, associated with the macroeconomic production growth model, does not take into account waste generation or any constraints to resource availability. The sustainable development model embraces maintenance of the ecosystem's natural capital to minimize diminution of its capabilities to supply humankind—"scale matters"—and protection of access and availability of essential resources for economically disadvantaged people, affecting how resources would be shared. This model is untested at this time, but its important feature is that it overtly recognizes that filling up the ecosystem presents peril to survival with reasonable quality of life for future generations. Therefore, maintenance of natural capital must be a paramount focus of macroeconomic—national or statewide—policies. Current macroeconomic instruments have some ability to address ecosystem constraints through taxes, subsidies, and interest rates used to encourage desirable resource outcomes and discourage unwanted results.

Taxing outcomes of which society wants less has not been a focus of U.S. environmental policy. Typically, in the United States, the approach has been to set national standards that raise the cost of activities that impact natural and environmental resources. The implications of this situation are that, unless the United States would close its borders to foreign products that are not produced under the same environmental standards to protect natural capital (such as groundwater by limiting its use or contamination) and then to recognize groundwater value, the federal, state, or local governments must adopt other approaches. Most attention in international agreements that address environmental outcomes has been to focus on standards affecting environmental quality, such as waste minimization and disposal and their associated costs affecting the supply costs of products. Little attention has been given to quantity control, such as limiting groundwater use in production to maintain long-term supplies at the macrolevel. Unlimited use has detrimental effects on future availability and quality. Policies at the macrolevel that have a vision of needing to protect essential resources on a sustainable level may then be necessary, depending on societal preferences on the quality of life in the future. Setting objectives that demonstrate stewardship for the ecosystem that provide the resources for the economy and from which nations derive income will be significant in balancing a sustainable approach for the macroeconomy. This is the subject of Chapter 14.

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Part IV

Political Economy of Groundwater Management

Part IV addresses the policies and economics of groundwater management. Chapter 11 presents a range of potential policies for managing groundwater as a source of water supply and as a waste sink along with criteria that may be applied to evaluate them. Chapter 12 provides an evaluation of the policy types through the lens of the criteria in Chapter 11, with an emphasis on examining ecosystem scale, equity, and economic instruments, among other criteria. Chapter 13 explores the use of cost–benefit analysis in evaluating the change in services posed by changes in groundwater policies, projects, and activities, noting that cost–benefit information is just one input to the decision-maker's processes.

11 Groundwater Policy

Comprehensive treatment of groundwater policy deals with the resource as both a source of water and a sink for contaminants. A principal reason for governments to develop and implement policy for water resources is the failure of the market to capture the value of nonmarket goods and services of water (see Chapter 9). Historically, the division of source and sink has separated the disciplines of resource economics and environmental economics, respectively. In the U.S. federal government and most states, Congress and the legislatures have preserved this separation institutionally in laws and in corresponding executive departments and agencies and the regulations they establish to interpret and implement the laws. As noted in Chapter 5, however, other countries, such as Canada, the states of the European Union, and Mexico, are taking an integrated approach to groundwater and surface water and addressing water quantity and quality in a single unified law, and applying it on a watershed or river basin basis. Policies are then a country's, state's, or municipality's laws or codes and their interpretive regulations or rules that form the principles or course of action for dealing with situations or issues, such as proper well installation or reducing contamination of groundwater. The activities that use groundwater most invariably affect both aspects of this subsurface liquid medium. Only under this fuller consideration can one realize the more complete economic implications of its use. First, we will consider policies related to water source and then those related to contaminant sink. Chapter 12 will provide an economic analytical perspective on these policies.

The economic use of groundwater should be perceived in the context of both its private value and social value. For example, the geysers and hot springs of Yellowstone National Park in Wyoming (United States) are natural phenomena attributable to the interaction of groundwater and the deep geothermal heat source within the earth's crust. They could be used in two ways. An entrepreneur could have obtained the rights to the area around the geysers and hot springs from the government and developed health spas and resorts around them. Very likely, only those people who could afford to stay in the resort would have received the benefits of this development, which could have been very lucrative to the owner. The area might have even been modified in ways to make the attractions appear differently than in their natural state. The entrepreneur would have captured the private value in a very efficient way with the associated economic rewards. Alternatively, the government could hold the natural wonders in trust as a recreational area for all citizens, regardless of economic status, to behold and be captivated by their grandeur. This action would allow capture of the fuller social value of the resource. Regardless of the use, this same dichotomy must be addressed in the development and implementation of local, state, national, and transboundary policies concerning groundwater.

GROUNDWATER POLICY TYPES

The types of specific policies that could be used by governmental jurisdictions (modified from Turner, 1993; Field, 1994; Schiffler, 1998) and applied to groundwater include the following:

1. Conferring legal status through (a) liability laws and (b) property rights
2. Providing community information
3. Managing risk
4. Establishing standards through (a) quantity limits, (b) ambient standards, (c) emission and content standards, and (d) technology standards

5. Setting performance standards (PSs)
6. Adopting economic instruments as (a) user charges, (b) emissions charges and taxes, (c) subsidies, (d) product charges, and (e) transferable discharge permits or water rights

Definitions of these types of policies appear in Exhibit 11.1. No single approach can or should be applied in all cases and often a combined approach to policy is taken to draw on features of a variety of elements as they best fit the circumstance (Schiffler, 1998, pp. 340–342; Tsur et al., 2004, p. 3).

This overview will cover types of policies and criteria by which they may be evaluated. The next chapter will address the economic relationships specific to each policy type.

EXHIBIT 11.1 DEFINITIONS OF POLICY TYPES APPLICABLE TO GROUNDWATER

Local Relational Policy—Local relational policies that establish or utilize the interaction of persons or corporations with other persons or corporations as the basis for an outcome recognized by those parties.

(a) **Property rights**—The status conveyed by government to a person to have tangible (or sometimes, intangible) objects, such as land or water, that allows the individual the exclusive use of it.
(b) **Liability law**—Typically, this refers to a state common law related to the determination of responsibility and the extent of compensation for loss or damage resulting from one's actions to or on another. Liability may be based on nuisance (an act harming or inconveniencing others) or negligence (not exercising reasonable care resulting in injury to others), as well as other legal considerations.
(c) **Community information**—Knowledge and facts are made available broadly to the public for its use in decision-making processes.

Risk management—Actions taken by individuals, corporations, communities, states, or national governments to minimize the loss, harm, or threat to human health or the resource for near- and long-term use by a person or groups of people corporately or individually.

Economic instruments—Pricing actions to stimulate or encourage individuals, organizations, or corporations by managing value or monetary factors affecting the use or services of resources or objects, such as groundwater.

(a) **User charges**—Fees required to be paid for utilizing a property or service. The fees could be based on frequency, time, and area or volume of use.
(b) **Emissions charges and taxes**—Payments for releasing contaminants or residuals (such as heat) to the ecosystem, including underground release.
(c) **Subsidies**—Compensation received or savings incurred for taking or not taking a particular action.
(d) **Product charges**—Fees required to be paid for manufacturing or purchasing a commodity or good.
(e) **Transferable use or discharge permits or water rights**—A government-granted privilege to use water or release contaminants to water that can be exchanged with another person, organization, or corporation for some mutually agreed on compensation initially to the government and then subsequently to sellers of permits or rights.

EXHIBIT 11.1 (continued) DEFINITIONS OF POLICY TYPES APPLICABLE TO GROUNDWATER

Environmental performance standard—Maximum or minimum level of performance to be allowed in or with the resource, typically applied to the amount of water use, concentration of contaminants, technology, and best practices as a policy targeted to reduce a specific risk.

(a) **Quantity limit**—The level of use not to be exceeded, applied to the utilization of groundwater, in this context.
(b) **Ambient standard**—The amount of contaminant not to be exceeded in the existing conditions of the monitored media (such as groundwater or soil).
(c) **Release standard**—The limit or maximum amount of a contaminant that is permissible to be released, usually based on public health or wildlife receptor requirements.
(d) **Content standard**—The limit or maximum amount of a contaminant that is allowable to be present in a product provided for sale or consumption, usually based on public health requirements.
(e) **Technology standard**—The type of equipment or practice (e.g., best management techniques) mandated for use to treat (remove, neutralize, etc.) a contaminant(s) or its required performance (e.g., removal of 95% of the contaminant by volume or weight [or other appropriate unit of measure]).
(f) **Best practice standard**—Specific steps or gradations of accomplishment directed toward statutorily or regulatorily defined and required objectives for implementing a program, such as completing the delineation of a wellhead protection area.

Sources:

1. Tsur, Y. et al., *Pricing Irrigation Water*, Resources for the Future, Washington, DC, 2004.
2. Schiffler, M., *The Economics of Groundwater Management in Arid Countries; Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, London, U.K., 1998.

WATER SOURCE POLICY

POLICIES IN HIGH-LEVEL OVERVIEW

As Chapter 3 indicated, groundwater has many uses in the economy, most of which have some economic or regulatory control, as noted in Chapter 5. Fundamentally, all these uses rely on groundwater as a water source in some way. The manner in which groundwater is used is the focus of policy because of its implications when used by others. Chapter 8 highlighted the range of possible factors that may influence microeconomic decisions related to groundwater use. This chapter will focus on higher-level decision making. Water source policy addresses the access to and quantity of groundwater use.

Local Level

Local jurisdictions or communities may be organized in various ways to provide groundwater and determine its use, focusing on aquifer recharge, well installation, drinking water and industrial water supply, irrigation, reuse and recycling, and community information. The state may set policies for some of these activities, depending on whether the state's constitution assigns authority to the state or allows the authority to be exercised by or delegated to local jurisdictions. In some cases, policies affecting these water uses may be determined entirely by an individual or a company. Local organizations may be active in providing information to their communities (Groundwater Foundation, 2002). Exhibit 11.2 provides examples of the policies that jurisdictions might use to affect groundwater use.

EXHIBIT 11.2 EXAMPLE TYPES OF JURISDICTIONAL POLICIES AFFECTING GROUNDWATER USE CONTROL

After each decision or policy, an indication of whether the action or activity is a local relational policy (LR), risk management policy (RM), economic incentive (EI) or an environmental performance standard (PS), or in response to (IRT) one of those policies, is given. Some actions or activities may have aspects of more than one approach and this may depend on the context in which it is implemented. For example, recycling wastewater back to the aquifer after treatment may be in response to an EI (least overall operating cost or taxation on residuals), a PS (to reduce discharges) or RM (to ensure near-term supply from the aquifer). This list is not intended to be exhaustive or all inclusive, but is provided as representative of the range of these policies.

Decisions/Policies

Corporate or Local Property Owner/Operator

- Do or do not install and operate water well on property for self-supply(IRT: PS)
- Determine the needed quantity and produce permitted amount of groundwater (IRT: PS)
- Recycle wastewater (IRT: EI, PS, RM)
- Treat and reuse wastewater (IRT: EI, PS, RM)
- Implement water-conserving practices that reduce water use (IRT: EI, PS, RM)

Local Government

- Set standards to minimize impervious surfaces (e.g., material used, area covered) and maximize aquifer recharge in developing areas (PS, RM)
- Establish requirements for groundwater recharge zones and devices (PS, RM)
- Permit well installation (PS, RM)
- Set standards for well installation (PS)
- Determine and finance community water supply system capacity (IRT: PS)
- Regulate amount or timing of use (e.g., during drought or water emergencies, or for specific uses) (PS; IRT: RM)
- Require water-conserving devices (PS)
- Determine water rates (if not regulated by state) (EI)
- Treat and reuse wastewater (IRT: EI, PS, RM)
- Allow groundwater production near wetlands or not (PS)
- Provide information on water use to the community (LR)
- Rely on judicial process to address groundwater misuse and damages to adjacent or nearby individuals or properties (LR)
- Require permeable road, driveway, and sidewalk surfaces (RM, PS)

State/Provincial Government

- Define individual and state trust water rights and due process for damages resulting from misuse of groundwater (LR)
- Determine and implement long-term sustainable or safe yield for future use (PS)
- Establish requirements for groundwater recharge zones and devices (PS, RM)
- Permit well installation (PS, RM)
- Set standards for well installation (PS)

EXHIBIT 11.2 (continued) EXAMPLE TYPES OF JURISDICTIONAL POLICIES AFFECTING GROUNDWATER USE CONTROL

- Regulate the amount of use by certain users (e.g., irrigators) or times (drought) (PS, RM)
- Require use of an alternative water source (PS, RM)
- Determine and, where appropriate, finance water supply system capacity (IRT: PS, EI)
- Determine water rates (typically for privately owned community water systems) (EI)
- Determine and implement water rights for waters of the state (e.g., to protect endangered species) (PS, RM)
- Necessitate treatment of wastewater before discharge to streams (PS)
- Allow groundwater production near wetlands or not (PS)
- Provide information on water use to the public (LR)
- Rely on judicial process to address groundwater misuse and damages to adjacent or affected individuals or properties (LR)

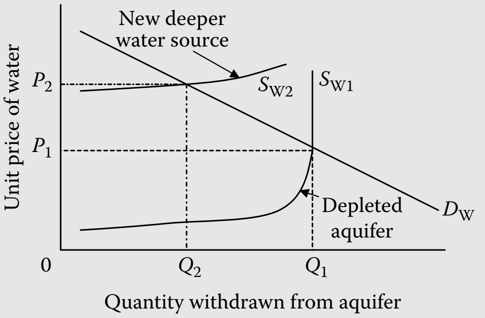
National/Federal Government

- Determine and implement water rights for instream uses (e.g., to protect endangered species) (LR)
- Determine and control groundwater use on federal lands and in federally regulated activities (e.g., coal mining) (PS)
- Require treatment of wastewater before discharge to sewers and streams (PS)
- Do or do not allow groundwater production on federal lands near wetlands (LR, PS)
- Demonstrate aquifer recharge of reclaimed water (LR)
- Provide information on water use to the public (LR)
- Set requirements for recognizing water-saving appliances (LR)
- Rely on judicial process to address damages to adjacent or affected individuals or properties (LR)
- Provide business cost depletion deduction for irreplaceable groundwater units used (EI)
- Make available below-market rate loans and crop supports for agricultural activities to influence water conservation (EI)

State Government

As just noted, states may have policies for similar activities determined at the local level. Most states in the United States also must take a broad view of the state's groundwater resources and ensure that adjacent uses do not compromise long-term yield. States may order that another water source be obtained and used. Exhibit 11.3 shows the result of a population depleting an aquifer and establishing a new deeper groundwater source, but at a higher price because of the increased pumping costs. Juxtaposed to this outcome, states may evaluate groundwater and surface water interactions to determine the level of groundwater use to maintain water rights in streams and wetlands, called "conjunctive use." In doing so, these states may be operating under state laws established to be consistent with similar federal law giving environmental claim on groundwater flow to streams' flora and fauna. The life forms of the aquifer itself may have been given an ecosystem claim on groundwater for its survival. Exhibit 11.4 describes one aquifer control authority that regulates groundwater use for both human and other species sustenance. The state may also provide the public information on water use. Since states typically have jurisdiction over groundwater matters, they have adopted laws that define rights in water and whether an individual can hold those rights or they are held in trust by the state for all users.

EXHIBIT 11.3 AQUIFER DEPLETION AND HIGH COST NEW SOURCE



The aquifer being depleted is no longer a reliable water source and has become very expensive. A new deeper well is installed at a higher cost to pump groundwater from a deeper aquifer. Because of higher price at P_2, demand for water has fallen from Q_1 to Q_2.

EXHIBIT 11.4 GROUNDWATER MANAGEMENT IN THE EDWARDS AQUIFER (TEXAS, UNITED STATES) FOR HUMAN AND ENDANGERED SPECIES SUSTENANCE

The Edwards Aquifer Authority (EAA) manages, enhances, and protects the Edwards Aquifer, a major groundwater system in Texas serving approximately 1.7 million people (EAA, 2006). This carbonate aquifer underlies an area approximately 257 km long and from 8 to 64 km in width, traversing three river basins (UMCP, 1996). The Edwards Aquifer is the primary source of water to the region of south central Texas serving the cities of Austin and San Antonio and other towns and rural areas, and received a federal government designation of "sole-source aquifer" in 1975, providing special review of federal financially assisted projects affecting it (USEPA, 2006). The aquifer also supports a unique ecosystem of aquatic life, including 14 threatened and endangered species (EAA, 2006; EARDC, 2006). The aquifer is used for a range of household, agricultural, industrial, and recreational purposes. EAA has demand and critical period management rules that allow it to impose pumping restrictions to limit groundwater withdrawals when aquifer levels drop below certain trigger points (established elevations of the water table) (EAA, 2006).

The restrictions allow the survival of the endangered species while providing water supply to the cities, towns, farms, and industries of the region. The restrictions and management authority derive from Texas State Senate Bill 1477 (Eckhardt, 2007), which basically created a special, unquantified value for the Edwards Aquifer and its flora and fauna as a matter of state government policy. This value is reflected in the management of the aquifer to balance the purposes of human use and endangered species in the ecosystem.

Sources:

1. Adapted from Edwards Aquifer Authority (EAA), The Edwards Aquifer; Manage, Enhance, Protect, 2006, URL: http://edwardsaquifer.org/ (accessed April 28, 2007).
2. Adapted from Edwards Aquifer Research and Data Center (EARDC), Threatened and Endangered Species in the Edwards Aquifer System, 2006, URL: www.eardc.txstate.edu/endangered.html (accessed April 28, 2007).
3. Adapted from University of Maryland-College Park (UMCP) Department of Meteorology, Edwards Aquifer Location Map, 1996, URL: http://www.atmos.umd.edu/~owen/CHPI/IMAGES/EA-location.html (accessed April 28, 2007).
4. Adapted from U.S. Environmental Protection Agency (USEPA), Effects of Sole Source Aquifer Designation, 2006, URL: http://www.epa.gov/region6/6wq/swp/ssa/effects.htm (accessed April 28, 2007).
5. Adapted from Eckhardt, G., The Edwards Aquifer Website; Texas Senate Bill 1477, 2007, URL: http://www.edwardsaquifer.net/1477.html#1.01 (accessed April 28, 2007).

National/Federal Government

In the United States, the federal government may perform functions similar to those of states where states have not obtained authority to implement federal laws or on federal lands. Policies for groundwater uses on federal lands may be based on the need to maintain instream flows for wildlife such as in national parks and reserves (Kimball, 1996) as well as for maintaining other surface and groundwater rights. The federal government has also demonstrated aquifer recharge with reclaimed waters (BurRec, 2000) and provided information to the public on groundwater use and quality (USGS, 1998). Federal policies on dewatering aquifers for mining purposes (e.g., coal production) may protect adjacent groundwater uses.

Exhibit 11.2 provides an overview of the types of policies that individuals, business, and governments at all levels might consider as steps to enhance management of groundwater sources.

ECONOMIC CONSIDERATIONS IN WATER SOURCE POLICIES

While the development of policies deal with many different aspects of groundwater, economic analysis offers a lens to evaluate policies with common economic features. These features will be explored in the next chapter in more detail. First, the policies are categorized with their economic aspects highlighted. Later, the criteria used to compare them will be defined.

Utilizing LR policies through conferring legal status through (a) property rights and (b) liability laws, and by providing community information. The first two categories of LR policies cover definition of rights in groundwater and due process for damages from misuse of groundwater. As described in Chapter 5, in many western states, property owners, individuals, and companies may hold the rights to water. In other states, particularly in the humid eastern United States, the state holds the groundwater (and all waters of the state) in trust and determines how they should be used. Rights in water use and damages from misuse may result in economic exchanges, such as selling or purchasing rights to use water and payments for property damage. Some laws may confer rights in a previously atypical way, such as creating natural rights of endangered species to coexist with human beings and other wildlife. If adequate habitat is not available because groundwater may not provide sufficient support to wetlands or baseflow of streams, then the wildlife cannot coexist. Thus, the wildlife has a right to an allocation of groundwater in those cases, which cannot be used for drinking water or irrigation at those locations.

Providing community and public information addresses a broad range of activities, including preparation of written literature available in hard copy and on the Internet, holding public meetings to provide technical and information exchange on groundwater use consequences for the communities, holding groundwater events such as a children's festival, neighbors sharing personal views, common-sense tips and moral, religious, and ethical concerns about groundwater use. A fundamental element of a market economy is the fully informed consumer and the free exchange of information satisfies that tenet. Such information may typically focus on the "wise use" of groundwater from a cost savings or conservation perspective as well as "lessons learned" of what to do and what not to do. Community information policies about groundwater are likely to have one of two basic foci: (1) to convince the audience that conserving or protecting groundwater should be a high community priority, and (2) to motivate the community for action taking specific conserving and protecting steps, assuming groundwater is a high priority.

Implementing RM practices. Risk is the probability of an adverse outcome (WHO, 2001, p. 258), so RM would focus efforts to reduce that probability. Establishing the efforts to manage risk may be part of an iterative process that

1. Evaluates resource condition and public health status.
2. Assesses risk, including potential for resource condition changes and environmental exposure to health hazards.

EXHIBIT 11.5 COMPONENTS OF A RISK MANAGEMENT POLICY

1. Determine Basic Controls for resource and health targets
2. Specify groundwater quantity/quality objectives and other management objectives
3. Define measures and interventions (requirements, specifications) based upon objectives
4. Define key risk points and audit procedures to evaluate the overall effectiveness
5. Define analytical verifications (process, resource conditions, public health)
6. Implement interventions and measurements
7. Establish resource condition and public health status
8. Assess resource susceptibility and environmental exposure affecting public health
9. Conduct assessment of risk and evaluation of acceptable risk
10. Cycle back to determine changes in Basic Controls

Source: Modified from World Health Organization (WHO), *Water Quality: Guidelines, Standards and Health*, Lorna, F. and Jamie, B. (eds.), IWA Publishing, London, U.K., 2001, 9.

3. Establishes resource and health targets, including accepted or tolerable risks.
4. Implements control approaches for the resource and human beings to maximize meeting groundwater quality and human health objectives (modified from WHO, 2001, p. 9).

The elements of one approach to RM policy are described in Exhibit 11.5. Risk management relative to the quantity of groundwater used typically would address extending the timeframe of use of a given volume of water or increasing the quantity available for its use for the economic and health benefits of the community, state or nation. Local practices might include providing or installing surfaces that allow percolation of precipitation, minimizing impervious surfaces, injecting clean water into the subsurface, constructing storm water retention ponds, and taking other actions that would recharge aquifers with water that would otherwise runoff. A federal demonstration program in the United States showed the results of some of these practices for increasing the volume of water in aquifer storage for future use (BurRec, 2000), which were evaluated from health and water quality standpoints (NRC, 1994).

In the United States and the European Union, groundwater quantity and quality may be protected through RM activities implemented through the wellhead protection programs of states and countries. In the United States, some communities have used wellhead protection not only to manage major anthropogenic sources of contamination in the area around production wells but also to ensure sufficient permeable area to recharge groundwater and provide an adequate quantity of water supply for the future. This practice may minimize the need to look for and incur the costs of alternative water sources or installation and operation of additional wells.

Offering economic instruments through (a) user charges, (b) subsidies, and (c) transferable water rights. The focus of this category is on fostering economic efficiency and using the price of water in the market (to the extent that one exists) to provide an efficient result. User charges usually relate to conserving the groundwater resource, often done through setting water rates by either local or state government. Subsidies can promote more or less use of the resource, depending on how they are applied. Community or state distribution of or tax credits for installation of water-conserving devices (e.g., flow restrictors for faucets and shower nozzles, low-volume toilets) are the examples of subsidies that promote less use (conservation) of groundwater. Below-market rates to finance agricultural investments that use water and business cost deductions for depleting groundwater that reduce the cost of water to the user are subsidies that encourage more water use. In the United States, this subsidy of water use in water-short areas has been a public policy to promote economic development in the agricultural sector. Transferable water rights refers to the establishment of water markets that would recognize a fuller value of water through prices set by sales and purchase agreements to facilitate efficient exchanges of groundwater and its alternative, surface water, although the two are one interconnected resource in many hydrogeologic settings and can be conjunctively managed in a watershed or river basin for cost-effective results. Furthermore, if costs to treat wastewater are high and water supply is priced using conservation rates, the industry may be induced to treat wastewater sufficiently to enable its on-site reuse.

Establishing PSs through (a) quantity limits and (b) technology standards. Quantity limit standards may apply during droughts or water emergencies. In these cases, households or industries may be limited to a certain quantity (ration) of water based on essential needs and functions. These conditions may actually reduce the costs of operation by promoting the identification and implementation of less water-wasteful practices. Technology standards address such requirements as well as installation specifications, allowable water flows through plumbing and water-conserving devices, and specific equipment for reuse and recycling of wastewater. The principal concern about setting technology standards relates to research identifying less costly technology over time, which may not be able to be implemented because of laws or regulations requiring specific equipment or practices of a static technology.

The range of policy approaches for groundwater sources of water supply is broad. The challenge is to select the policies that will fit in the institutional and political framework that exists in ways that provide the efficient use of an increasingly scarce resource. We will consider the criteria for these factors after the overview of the policies relating to the economic control of contamination of groundwater.

CONTAMINANT CONTROL POLICY

Policies in High-Level Overview

Controlling contaminants in groundwater has long been accepted as the approach for mitigating nitrate and coliform bacteria, which can cause prompt human physical illness. Attention to contaminants that were previously not as easily detected but had potential human consequences if ingested occurred intensively beginning in the mid-1970s in the United States and elsewhere in the world. At that time, scientists were examining groundwater for possible contamination by industrial chemicals and pesticides. In particular, government policy focused on uncontrolled chemical waste disposal sites that allowed the chemicals to percolate through the subsurface and reach the water table without degradation, and in turn be pumped out of the affected aquifers by water supply systems and delivered to homes for drinking water. Because of the intense anxiety about the effects of ingesting these contaminants, laws were quickly adopted to respond to these situations. The challenge in separating the overview of water source and contaminant control policies is that the circumstances in which contaminant concentrations were high and not amenable to prompt treatment created situations that effectively removed groundwater from future use, similar to depleting the affected aquifers. The obverse of this occasion is that the use of a water source is affected by its quality. For example, in the latter case, some groundwaters of the High Plains region of the United States are too saline for human consumption, but can be used for cattle watering. The various levels of jurisdiction have different as well as complementary roles in contaminant control policy as identified in Exhibit 11.6.

Local Level

At the local level and depending on the functions that the state or province has delegated to the local level, considerable information may be developed to inform local decision makers and the community. This information may cover identification of contaminant threats, implementing preventive and remedial actions, monitoring groundwater and drinking water quality, and prescribing locations in which commercial hazardous chemical use and handling may occur based on hydrogeologic

EXHIBIT 11.6 EXAMPLES OF TYPES OF JURISDICTIONAL POLICIES AFFECTING GROUNDWATER CONTAMINANT CONTROL

After each decision or policy, an indication of whether the action or activity is a LR policy, RM policy, EI or an environmental PS, or IRT one of those policies, is given. Some actions or activities may have aspects of more than one approach and this may depend on the context in which they are implemented. This list is not intended to be exhaustive or all-inclusive, but is provided as representative of the range of these policies.

Decision/Policy

Corporate or Local Property Owner/Operator

- Treat wastewater and discharge to sewer or stream or treat wastewater and inject into subsurface below the confining geologic layer underneath an underground source of drinking water (IRT: PF, RM)
- Reuse wastewater (IRT: EI, PS, RM)
- Treat wastewater and recycle (IRT: EI, PS, RM)
- Repair or replace damaged wells or well aprons (PF, RM)
- Avoid using, handling, or storing chemicals and other contaminants near wells (PF, RM)

Local Government

- Delineate wellhead protection areas (WHPA) for water supply wells and other groundwater recharge zones, identify potential contaminant sources, and establish WHPA management program to minimize contamination risk (PS, RM)
- Establish commercial zones for certain hazardous chemical use and handling away from the WHPAs and aquifer recharge areas (IRT: EI, PS, RM)
- Identify abandoned wells and properly close and seal them (PS, RM)
- Monitor ambient groundwater quality (LR)
- Establish hazardous waste recycling program (IRT: EI, PS, RM)
- Inform the community of contamination potential and threat and preventive and remedial responses (LR)
- Monitor and report on the quality of drinking water to the community (LR)
- Maintain emergency response capability for uncontrolled hazardous chemical and toxic substances releases (RM)

State/Provincial Government

- Define individual and state rights and due process for damages resulting from contamination of groundwater (LR)
- Set and enforce standards and consumer awareness reporting processes for contaminants in drinking waters delivered to consumers (PS)
- Provide drinking water consumers with an assessment of the susceptibility of their water supply system to contamination (PS, LR)
- Set and enforce standards for waste disposal on or in the ground and for injection of wastes underground by wells (PS)
- Provide guidelines for or regulate the establishment of WHPA programs (IRT: PS)
- Identify and provide funding for remediation of abandoned hazardous waste disposal sites (IRT: EI, RM)

EXHIBIT 11.6 (continued) EXAMPLES OF TYPES OF JURISDICTIONAL POLICIES AFFECTING GROUNDWATER CONTAMINANT CONTROL

- Set and enforce standards for hazardous waste generation, storage, treatment, and disposal facilities, and set standards for their operation (PS)
- Set and enforce standards for the storage, use, and disposal of pesticides, and other commercial toxic substances (PS)
- Set and enforce standards for underground and above-ground storage tanks for hazardous chemicals and toxic substances (PS)
- Set standards for wastewater treatment, discharges of storm water to retention and holding basins and drains, and releases from animal feedlots (PS)
- Establish and promote agricultural chemical and land management practices to minimize nonpoint source contamination (IRT: EI, PS, RM)
- Inform the public of contamination potential and threat and preventive and remedial responses (LR; IRT: PS, RM)
- Set standards to control volume and quality of fill materials to wetlands (PS)
- Monitor ambient groundwater quality (IRT: PS, RM)
- Transfer resources to local agencies to ensure implementation of minimum state program for controlling hazardous wastes and toxic substances in groundwater and drinking water (EI)
- Rely on judicial process to address groundwater contamination and damages to adjacent or affected individuals or properties (IRT: PS, RM, LR)
- Maintain emergency response capability for uncontrolled hazardous chemical and toxic substances releases, especially for communities not able to support their own response (IRT: PS, RM)

National/Federal Government

- Set and enforce standards and consumer awareness reporting processes for contaminants in drinking waters delivered to consumers (PS)
- Set and enforce standards for waste disposal on or in the ground and for injection of wastes underground by wells (PS)
- Provide guidelines for or regulate the establishment of WHPA programs (IRT: PS)
- Identify, set standards, and provide funding for remediation of abandoned hazardous waste disposal sites paid for by taxing hazardous chemical products (IRT: EI, PS, RM)
- Provide financial credits to farm owners to avoid production in wellhead protection areas (EI)
- Promote waste reduction and recycling ((IRT: EI, PS, RM)
- Set and enforce standards for hazardous waste generation, storage, treatment, and disposal facilities, and set standards for their operation (PS)
- Set and enforce standards for the storage, use, and disposal of pesticides, and other commercial toxic substances (PS)
- Set and enforce standards for underground and above-ground storage tanks and pipelines for hazardous chemicals and toxic substances (PS)
- Set standards for wastewater treatment, discharges of storm water to retention and holding basins and drains, and releases from animal feedlots (PS)
- Establish and promote agricultural, chemical, and land management practices to minimize nonpoint source contamination (IRT: EI, PS, RM)

(*continued*)

EXHIBIT 11.6 (continued) EXAMPLES OF TYPES OF JURISDICTIONAL POLICIES AFFECTING GROUNDWATER CONTAMINANT CONTROL

- Set standards to control volume and quality of fill materials in wetlands (PS)
- Review and, where appropriate, modify projects receiving federal financial assistance that may pose a contamination threat to aquifers that are designated as a community's or region's sole source of drinking water (PS, RM)
- Support research on the human health effects, detection technology, and treatment technology for contaminants, and hazardous and toxic contaminants in groundwater and drinking water (RM)
- Establish training requirements for pesticide applicators (PS, RM)
- Require testing and registration of toxic chemicals before companies sell them commercially (PS, RM)
- Develop a pollutant trading program (EI)
- Inform the public of contamination potential and threat and preventive and remedial responses (LR; IRT: PS, RM)
- Transfer resources to states to ensure implementation of minimum federal program for controlling hazardous wastes and toxic substances in groundwater and drinking water and for ambient water quality monitoring (EI)
- Maintain emergency response capability for uncontrolled hazardous chemical and toxic substances releases to support communities and states (IRT: PS, RM)

conditions. Since chemicals have become widely accepted in most cultures, the local level may maintain the capability to respond to uncontrolled chemical releases. Notification of local officials concerning hazardous and harmful contaminants used in or resulting from commercial processes is now routinely required. Community organizations may be helpful in disseminating information on groundwater contaminant prevention, threats, and responses. The action of corporate property owners will be vital in establishing and implementing company policies that control contamination of groundwater on site based on state and national regulations.

State Government

In the United States, groundwater is typically considered "water of the state," with the federal government regulating economic activities in interstate commerce that could affect water quality. State governments sometimes set standards for the release of contaminants and other hazardous chemical and toxic substances in the ground and groundwater or set their presence in drinking water to be more stringent than national minimum requirements that all states must adopt or rely on the federal government to implement. States may choose to adopt and enforce the federal minimum standards. State and national laws often give standing to sue for damages to individuals who have been harmed by contaminant release. In the European Union, member states have provided the ability for individuals who are harmed to sue and have recognized environmental endangerment and impacts to biodiversity as having legal standing (Clarke, undated). States may also determine where pesticides may be used based on the hydrogeologic conditions affecting their migration to groundwater and hydrologically connected surface waters. States have been on the forefront of promoting and implementing wellhead protection as a program to prevent contamination of groundwater used as source of drinking water. States may operate these programs through a range of agencies.

National/Federal Government

The principal priorities of the United States federal government in the control of contaminants and other hazardous and toxic contaminants in groundwater have been, but not limited, to

1. Set strict, joint, and severally liable requirements for contaminated sites.
2. Promote preventive actions through wellhead protection and regulation of waste injection into the subsurface.
3. Set standards for hazardous waste handling.
4. Establish requirements and provide funding through a tax on hazardous chemical products for remediation of abandoned hazardous waste sites.
5. Set standards for underground storage of chemical products.
6. Require training of pesticide applicators.
7. Require registration by corporations of their toxic chemical products before sales and use.
8. Set standards for wastewater, storm water, and animal feedlot releases (USEPA, 1990).

The European Union member states have similar policies in place (Clarke, undated). The EU Directive on groundwater protection goes even further, setting groundwater threshold values that trigger action by member states, including coordination with waste and chemical release (EU, 1979) directives (and incorporation in river basin management plans) (EU, 2006). While these policies have added costs to environmental response, by doing so, they have incorporated a measure of the value of human health and environmental protection in the cost of doing business across the nations.

Other actions of the United States government include transferring resources to states to ensure implementation of the federal minimum standards cited previously and for ambient water quality monitoring, promoting waste reduction, sponsoring research to detect and treat contaminants in groundwater and drinking water, and maintaining emergency response capability to respond to uncontrolled contaminant releases (spills) (USEPA, 1990). Many U.S. federal departments and agencies are responsible for implementing these policies, including the Environmental Protection Agency, Department of Agriculture, Department of the Army Corps of Engineers, and Department of Transportation. Considerable attention has also been given to remediating contaminated industrial sites ("brownfields") for other economically productive purposes by EU members (EC, 2007) as well as in the United States (USEPA, 2007a,b).

ECONOMIC CONSIDERATIONS IN CONTAMINATION CONTROL POLICY

Contamination control policy for the protection and restoration of groundwater covers a wide range of activity. Examining them by their type will enable us to focus on specific economic advantages and disadvantages in the next chapter. While some approaches seem to have greater advantages from an economic standpoint, this range of policies provides flexibilities to tailor environmental response to the institutional frameworks in states/provinces and localities while considering their economic consequences.

Utilize LR policies through conferring legal status through (a) liability laws and (b) property rights and by providing community information. Property rights are granted through the state and its subdivisions and may be limited as the determination of the state or community is in the best interest of society. Conducting an activity that contaminates a neighbor's groundwater without permission, thereby preventing the neighbor from using it would be a violation of that individual's right to use the property without encumbrance by another person. In liability law, state common law related to nuisance (an act harming or inconveniencing others), negligence (not exercising reasonable care resulting in injury to others), and strict liability (determination of responsibility for and extent of compensation for loss or damage resulting from one's actions to or on another) described in Chapter 5 have been specifically and extensively applied in courts to contamination of groundwater by one property owner affecting another property owner and the use of their property (Sax et al., 1986, pp. 919–924). People's right to use their land and its groundwater as they want is not absolute but relative since it flows across property boundaries (Haar, 1971, pp. 109–115, citing case law of Rose v. Socony-Vacuum Corp., 54 R.I. 411, 173 Atl. 627 [1934]). Additionally, the U.S. Congress clearly included past contributors (e.g., waste generators and transporters) to current groundwater contamination problems as liable for the costs of damages to groundwater and adjacent properties, and not just the current property owners (U.S. Congress, 1980).

Providing the public with the information about contaminants in its groundwater allows communities and their officials to make informed decisions about the best response to the circumstance to support minimizing the risk to the community. Many provisions of local, state, and national laws require these governments to inform the public about contamination of groundwater and other environmental media. For example, the Safe Drinking Water Act requires public water systems to inform consumers annually about exceedance of health-based drinking water standards, the Toxic Substances Control Act requires annual reporting by industry of toxic releases including those to groundwater, and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or Superfund) requires the communities to be informed about groundwater (or other environmental media) remediation at abandoned waste sites (U.S. Congress, 1986, 1991). Public information serves to help individuals and groups evolve their preferences about their desire for a clean, safe resource, and the amount of cost they are willing to accept or pay.

Implementing RM practices. Groundwater, once contaminated, is difficult and expensive to treat and clean up for use, so practices that reduce the risk of its contamination can have long-term beneficial consequences. The original European Union (EU, 1991) countries have long practiced protecting the area of land (recharge area) through which agricultural and industrial chemicals could percolate along with water from precipitation of such chemicals and then infiltrate to the water table to supply groundwater to wells. This practice in the United States, adopted from the EU, is called wellhead protection and is mandated in the Safe Drinking Water Act (as amended in 1986). The approach is to survey potential contaminant sources in the area most immediately recharging the aquifer in use and implementing a management program to reduce or eliminate the contaminant risk to the aquifer. Groundwater quality monitoring of the resource is part of this RM practice in the EU but not necessarily used in the United States completely. Other steps can also reduce this risk, including checking and repairing or replacing cracked well casing or concrete aprons around the wellhead to ensure that contaminants do not leak into the ground nearest to the well. Similar steps can be taken for springs.

The EU approach of using the "precautionary principle" might also be thought of as applying to an RM practice for groundwater protection. In this case, strict controls on the application of chemicals to the ground in wellhead protection areas minimize the potential of the aquifer contamination. This, in turn, reduces the cost of treatment for use as drinking water. Bottled water companies as local property owners may also be applying this principle when they buy large tracts of undeveloped land in the headlands of a watershed to ensure that no contaminants are used on the ground over the aquifer that supplies its wells or springs. In this case, the quality of the groundwater can be distinguished as being "natural" or "pure" and potentially command a higher price.

Offer economic instruments through (a) user charges, (b) emissions charges and taxes, (c) subsidies, (d) product charges, and (e) transferable discharge permits. Not many existing local, state, and federal policies fall into this category to control contamination of groundwater in the United States. Under the category of product charges, Superfund has been maintained by a tax on hazardous chemical products charged to their generators. Also, states may charge permit fees to business to release contaminants to groundwater and surface water that meet water quality standards. Farmers have received tax credits by not cultivating lands in wellhead protection areas if they signed up to do so in advance. While some federal programs provide funds to states to implement comparable programs to protect and restore groundwater and drinking water, the provision of these funds from the federal to state government is a pure transfer of tax dollars and not a subsidy. However, considering subsidies, the Environmental Protection Agency is authorized to provide grants to states to support below-market-rate loans to public water systems (publicly or privately owned) to ensure compliance with the health-based standards. Most of the public water systems reported to be out of compliance with these standards are small systems (serving 10,000 or fewer people) and use groundwater as their principal drinking water source (USEPA, 2001). These below-market-rate loans are a subsidy and are the result of U.S. Congressional policy to address concerns that small systems need special assistance to ensure protection of public health (U.S. Congress, 1976, 1980, 1986). Relative to transferable discharge permits, the U.S. Environmental Protection Agency's Office of Water has developed a watershed-based framework for possible pollutant trading (USEPA, 2007a,b). Exhibit 11.7 provides a general description of the pollutant trading process in the United States and how it might apply to groundwater.

Establish PSs through (a) ambient standards, (b) emission standards, (c) content standards, (d) technology standards, and (e) best practice standards. In the United States, most of the local, state, and federal activities fall into this category. The USEPA set ambient standards for groundwater that are sources of drinking water into which wastewaters are injected requiring the health-based

EXHIBIT 11.7 POLLUTANT TRADING IN THE UNITED STATES

What is water quality trading?

Water quality trading is an innovative approach to achieve water quality goals more efficiently. Trading is based on the fact that sources in a watershed can face very different costs to control the same pollutant. Trading programs allow facilities facing higher pollution control costs to meet their regulatory obligations by purchasing environmentally equivalent (or superior) pollution reductions from another source at lower cost, thus achieving the same water quality improvement at lower overall cost.

How does water quality trading work?

While trading can take many different forms, the foundations of trading are that a water quality goal is established and that sources within the watershed have significantly different costs to achieve comparable levels of pollution control.

Where will water quality-trading work?

Where watershed circumstances favor trading, it can be a powerful tool for achieving pollutant reductions faster and at lower cost. Water quality trading will not work everywhere, however. Trading works best when

1. There is a "driver" that motivates facilities to seek pollutant reductions, usually a Total Maximum Daily Load (TMDL) or a more stringent water quality-based requirement in a National Pollutant Discharge Elimination System (NPDES) permit.
2. Sources within the watershed have significantly different costs to control the pollutant of concern.
3. The necessary levels of pollutant reduction are not so large that all sources in the watershed must reduce as much as possible to achieve the total reduction needed—in this case, there may not be enough surplus reductions to sell or purchase.
4. Watershed stakeholders and the state regulatory agency are willing to try an innovative approach and engage in trading design and implementation issues.

How could water quality trading apply to groundwater?

Groundwater quality is affected by both point (a specific location, such as buried waste) and nonpoint (diffuse and possibly many locations, such as pesticides applied to lawns or farmlands) sources of pollution. As groundwater flows, contaminants from polluting activities move in the subsurface toward discharge points or zones, such as a well (or many wells) and streams, lakes, wetlands, or coastal zones.

(*continued*)

EXHIBIT 11.7 (continued) POLLUTANT TRADING IN THE UNITED STATES

A Total Maximum Daily Load for a waterbody or a Drinking Water Standard could be set as the "driver" for which polluting activities must be designed to meet. For groundwater, this setting of the "driver" may be informed through modeling of the subsurface contaminant flow for a watershed or river basin. This modeling would require significant and detailed information about groundwater and the subsurface in the area under evaluation and about the contaminants of concern. Polluting activities contributing to the contaminant load of subsurface groundwater flow may then be identified and costs may be calculated for each one to achieve the "target" load by modifying its point or nonpoint pollution practices. For the target load to be achieved, in some cases, it may be more cost-effective for some locations to treat or eliminate the pollution than others. In that case, pollutant trading might occur among the owners of the polluting activities.

As an extension, use of the subsurface environment for disposal of carbon dioxide releases to mitigate global climate change raises issues about valuing this subterranean zone. Chapter 12 will address this subject further.

Source: U.S. Environmental Protection Agency (USEPA), Water Quality Trading, 2007b, URL: http://www.epa.gov/OWOW/watershed/trading.htm (accessed August 10, 2007).

drinking water standards to be met at the point of injection. For hazardous waste disposal sites, contaminants measured at the disposal unit boundary by monitoring well cannot be statistically significantly different from those contaminants measured in the ambient environment near the unit. Superfund site remediations also employ drinking water standards or an alternate standard to be met for *in situ* requirements in contaminant cleanup of groundwater. Some pesticides may have restrictions on use tied to their occurrence in ambient groundwater. Content standards apply to the concentrations of contaminants allowed in drinking water supplied by public water systems. USEPA sets health-based maximum contaminant levels or treatment technique requirements for over 90 contaminants that may be found in drinking water. Emission standards are utilized in the underground storage tank program, which also combine technology standards for containment. Basically, no release of contaminants from the tanks is permitted. Modern underground tanks utilize a double-wall technology and monitoring in the space between the two walls to determine if a leak has occurred in the first wall requiring replacement of the tank to ensure no release to the environment. Likewise, hazardous waste generators, storers, transporters, treaters, and disposers are required to follow technology standards for such things as design and construction of storage and disposal facilities. Farmers follow best management practices to minimize nonpoint source pollution to aquifers, streams, lakes, and estuaries. Best practice standards can also guide the implementation of the wellhead protection program and the training of pesticide applicators. Thus, a range of these policy approaches have been applied to maintain the services of groundwater.

CRITERIA FOR POLICY EVALUATION

To obtain an economic comparison of these policies affecting groundwater, criteria should be applied that incorporate factors reflecting economic principles. These principles include adequate information about alternatives and their value to the persons affected (as complete information as possible for decision making), balancing marginal environmental results and marginal costs (efficiency), incorporation of social costs and benefits (full social effects considered), and fairness to the persons and groups affected (equity). Other more specific principles could be identified within these fundamental ones, such as pricing water at its marginal cost, including costs of external effects and marginal abatement costs (MACs) for pollution control to be at or near marginal damages (MDs) from the pollution. The criteria by which these policies might be evaluated and compared include (modified from Turner et al., 1993; Field, 1994; Schiffler, 1998; Daly and Farley, 2004):

1. Ecosystem scale
2. Positive ecosystem response
3. Equity
4. Economic efficiency or effectiveness
5. Dynamic incentive
6. Low information requirements
7. Low administration cost
8. Agreement with moral precepts

These criteria can be used to compare existing policies and to evaluate the effects of future approaches to use, protect, and restore groundwater, as well as other environmental media.

ECOSYSTEM SCALE

As evident from the preceding chapter on macroeconomics, the ecological "scale" of a policy or project may be a major factor in its development and implementation. In ecological economics, scale emerges as the first critical aspect of policy that should be considered since it is a major factor affecting the other criteria listed above. Scale relates to size of the aquifer, extent of the area affected, number of people or amount of flora and fauna benefited or impacted, amount of groundwater produced, uses of groundwater affected, and many other elements related to a policy. From the perspective of the attention on global climate change and effects on people and resources around the world, scale is a critical factor to be considered first before determining the significance of the other policy evaluation criteria. Importantly, ecosystem scale relates to a clear understanding of the objective in using the resource and the extent to which achieving the objective is likely to affect the resource for either quantity or quality factors. Whether the objective and its effects are clearly articulated to and well understood by the affected population may influence the perspective of the costs and benefits of a policy or project, especially as the effects transcend boundaries at any level.

Ecosystem scale was addressed extensively in Chapter 2. To supplement if understanding this criterion, please refer to Chapter 2 for additional information.

POSITIVE ECOSYSTEM RESPONSE

Alternative policies directed toward the same objective may have different probabilities for achieving ecological results. These results, whether they are production of a certain quantity of water or restoration of an aquifer to meet drinking water standards, are the benefits from expenditure of scarce resources. The likelihood of obtaining the expected or required results should be factored into evaluating alternative policies and subsequent investments to respond to aquifer depletion or contamination by individuals and corporations. Being efficient at achieving the wrong result is not the best use of resources.

EQUITY

Considerations of equity deal with ensuring that environmental programs respond to each segment of society fairly. Programs addressing preventing contamination to, protecting and restoring groundwater for drinking water sources must carefully evaluate equity, since most water supply systems in the United States serve populations of 10,000 or fewer people (58% of such systems serve 500 or fewer people) and are groundwater supplied and often in rural areas. While well-to-do small communities exist, they are more the exception, in this case. It is a moral, and for some a religious, concern as to how these people and communities are treated. Providing benefits to the largest number of people most easily reached from a cost-effectiveness perspective may leave these less-well-off communities more disadvantaged. If a groundwater supply or remediation program relies on a flat tax or user charge (i.e., the same tax rate or charge per unit of value of water purchased or quantity of water restored), people with less income will pay more of their income for a necessity such as water than wealthier consumers. This circumstance is referred to as a regressive tax or charge. Small water systems lack economies of scale to bring per unit costs down to a more affordable level. In larger wealthier communities with a low-income population, declining block rates for water use might also be considered regressive. In these situations, the first units of water are assigned a price higher than units of the second block of water use, so the marginal price charged for additional units is less, even though more water is consumed. Therefore, the distribution of costs and benefits is an important criterion for groundwater policy development.

Equity and distributional aspects also relate to generational effects and their inherent rights to water and its services. Intragenerational equity provides for fair and just treatment with the current time typically and affects people across income, ethnic, cultural, and other lines in the present generation. Intergenerational equity poses the same interests across generations into the future. Fair and just social and economic outcomes are the center of this criterion for broad acceptance within the larger society. Decisions about equity and distribution should be made in advance of evaluating economic efficiency, since in a Pareto-optimizing world, if distribution is not addressed, a group of people will potentially be made worse off with a particular policy and the cost of responding to them will not have been included in the evaluation.

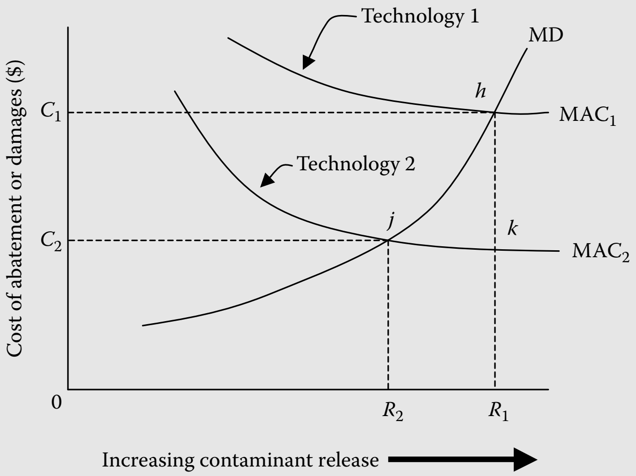
ECONOMIC EFFICIENCY OR EFFECTIVENESS

Efficiency in the context of groundwater is the balancing of marginal environmental results and marginal costs for the services of the resource (Field, 1994, pp. 181–183). While we may not be able to determine precisely where that balance point is, we should attempt to come as close as possible to it. For groundwater use, this balance is between price reflecting known alternative demands for the resource and marginal costs including externalities comprising the social costs (subsidence, loss of wetlands, and other effects). For contaminant control, MACs should balance with MDs.

Routinely, we do not have sufficient information to estimate damages (e.g., incidence of illness or loss of habitat). In these cases, we evaluate cost-effectiveness as the criterion. For a policy to be cost-effective, it must provide the greatest environmental result (e.g., more water or least contaminant release) for the least cost (e.g., least money spent or lowest damages). An efficient policy is cost-effective, but the reverse is not always true. The least-cost program does not always balance costs and benefits.

In program decisions, maximizing the environmental result with the least resources expended is important, choosing the cost-effective alternative to incorporate the best information. Exhibit 11.8 shows two different functions for MACs. MAC_1 indicates that abatement costs for *Technology 1* are efficient relative to addressing MDs at intersection h; i.e., this is an efficient outcome because MAC equals MD for the next unit of contaminant release reduced. First estimates may be high or low, depending on the factors used to derive them. However, technology applications exist in competitive markets, which may serve to bring costs of abatement down. If the cost estimate is high in this case and those costs are used to set the cost-effective contaminant release level at R_1, this level will be too high, not maximizing the environmental result and not protecting groundwater most effectively. MAC_2 represents the function that considers hypothetical (in this case) technological advances of *Technology 2* for abatement, which would reduce contaminant releases at a lower cost shown by intersection k. At the contaminant release level of R_2, the technology represented by MAC_2 can more cost-effectively abate the release than *Technology 1*. From an efficiency standpoint, *Technology 2* is also capable of a more efficient outcome indicated at the intersection of MAC_2

EXHIBIT 11.8 EFFICIENCY AND A MARGINAL ABATEMENT EXAMPLE



and MD at *j* with lower MDs from a social perspective. Given scarce resources to allocate to many potentially worthy projects, it is important to maximize the effects of their expenditure. The limited resources of developing countries and any nation with an economy in recession or depression point to the significance of this criterion.

DYNAMIC INCENTIVE

Policies recognizing alternatives or that long-term solutions may be less costly and arrive at the same or improved environmental results provide incentives for better outcomes. Technology is constantly improving in a wide array of fields applicable to environmental quality. Policies should not solely rely on governmental requirements, but also encourage private sector response to reduce costs or invest in research for less costly treatment or production technology as indicated in Exhibit 11.8. Policies that require specific technological application, rather than set objectives for resource use or treatment, inhibit incentives for improved efficiency.

LOW INFORMATION REQUIREMENTS

The costs of obtaining and maintaining data to evaluate the policy should not be high. If it is too costly to gather data, such as through groundwater monitoring, to tell the program manager whether he is getting the results he expected, he may not spend funds to collect the complete information needed. The manager will make future investment decisions without knowing their appropriateness or cost. Individuals and corporations responsible for reporting the results may stop sending the data, and perhaps ignore collecting the data in the first place to reduce their costs.

LOW ADMINISTRATION COST

The cost of managing program implementation, including enforcement, should be reasonable. While program results are to be maximized with the available resources, if inadequate attention to enforcement occurs, compliance by the target group will slip. Administration and enforcement costs need to be balanced with results based on health and environmental necessity. Furthermore, challenges to uphold enforcement in court take time and money. Thus, enforcement should be straightforward with easily measured and reported targets.

AGREEMENT WITH MORAL PRECEPTS

The program or project should be within acceptable bounds for the community or country relative to moral (Field, 1994, pp. 188–189), ethical, and sacred (Chapelle, 2000, pp. 13–18) values and considerations. These values are reflected in a community's tastes and preferences and the choices the consumers make among alternatives. Moral considerations are involved in concern for the appropriate response to pollution or mining or groundwater and the responsibility of polluters or producers not to harm others in pursuit of their objectives. Ethics, drawing on moral perspectives, has guided countries with environmental laws to prescribe a code of conduct embodied in those laws that provides direction, sets responsibility for actions, and prescribes consequences relative to contaminating groundwater and other environmental media, or extracting groundwater to excess. The belief that water as one part of the hydrologic cycle essential to life is a portion of a divine Creator's gift to the world, as, for example, in the Judeo-Christian, Islamic, and Native American religions, and plays a prominent role in these religions' histories, practices, and traditions. As a result, water has a sacred quality that is treated with reverence in the present and for the future—a foundational consideration of moral precepts and ethical response to the condition of groundwater and water in general. If these core values do not exist, the policies to protect water from contamination or wasteful use may be eventually ignored or overturned.

Understanding these criteria, the next step is to examine the economic implications of the policy types that affect groundwater as a water source and sink for contaminants. The first policies covered stem from old British common law addressing liability and property rights. The second investigation is that of providing information to people about groundwater to guide their actions in their communities. Third, we will evaluate policies that provide economic instruments to guide use and protection for groundwater. Finally, we investigate use and contaminant control standards approaches relevant to groundwater and their effects relative to ecosystem scale, equity, efficiency, and other criteria.

SUMMARY

Corporate, local, state, and federal policies can be numerous and complex. They can be cast in a framework for economic analysis. This framework includes categorization of policy as

1. Conferring legal status through (a) liability laws and (b) property rights.
2. Providing community information.
3. Managing risk.
4. Adopting economic instruments through (a) user charges, (b) emissions charges and taxes, (c) subsidies, (d) product charges, and (e) transferable discharge permits or water rights.
5. Establishing standards through (a) quantity limits, (b) ambient standards, (c) emission and content standards, and (d) technology standards.
6. Setting performance standards.

These policy types can then be evaluated through the economic criteria of

1. Ecosystem scale
2. Positive ecological response
3. Equity
4. Economic efficiency or effectiveness
5. Dynamic incentive
6. Low information requirements
7. Low administration cost
8. Agreement with moral precepts

while considering adequate information about alternatives, fairness to the persons and groups affected, their value to the persons affected, balancing marginal production and treatment costs with marginal health and ecosystem effects, and incorporation of social and long-term ecosystem costs and benefits. The next steps will be to compare the policies with the tool of the criteria to see the strength of their economic underpinnings.

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12 Economic Analysis of Groundwater Policy

With the most readily available groundwater resources being depleted through use or contamination throughout the world, policies affecting the allocation of this resource require careful economic analysis. Policies affecting other resources such as mineral production or wildlife (e.g., endangered species protection laws) may have unintended economic consequences for groundwater in some cases. The best informed policy formulation and implementation must stand on the recognition of the policies' relationships to human needs and the ecosystem on which we rely as well as the fundamental economic linkages affecting groundwater as both a water source and waste sink. Economic analyses must consider not only the obvious market effects, but also the nonmarket and ecosystem effects, which may be of a longer-term consequence.

POLICY EVALUATION

The economic consequences of the range of policies presented in Chapter 11 are varied, some potentially raising costs to the consumer, others possibly reducing costs. As indicated previously, policies setting or affecting prices for water supply have resulted in a wide range of consumer costs for drinking water depending on the location. At the corporate level, installing a well (or wells) for self supply may be a decision based on the desire to control factors for a stable production process to manage future costs or requirements for a long-term water supply of reliable quality (assuming the production process is sensitive to changes in water quality). Production processes could include manufacturing as well as agriculture. Corporate policies to recycle and reuse wastewater may increase costs if water treatment is needed for water use; however, companies can vary inputs to production based on costs, with water usually being a small portion of the price of the delivered product (Gibbons, 1986; Young, 2005). In industrialized countries around the world, policies for waste management have resulted in municipal solid waste being the largest volume of waste typically disposed by landfilling (Turner et al., 1993), which may pose a potential threat for groundwater contamination. As previously noted, in the United States, policies permit the largest volume of wastewater to be disposed by underground injection, presenting potential challenges for future groundwater protection if not properly managed. Most likely, governments evaluated many environmental and economic criteria before establishing these policies at that time.

With these considerations in mind, we will examine the policy types affecting groundwater based on the criteria previously identified in Chapter 11. The first policy type to be evaluated will be that of local relational policies: having legal status for groundwater use through property rights and liability laws and providing community information. This discussion will be followed by consideration of managing risk, establishing standards, and then offering incentives through economic instruments.

NOTE ON RELATION OF CHAPTERS 12 AND 13 ADDRESSING ECONOMIC EVALUATION

This chapter "Economic analysis of groundwater policy" and Chapter 13 "Cost–benefit information and analysis" support each other in critical ways. This chapter principally relies on partial equilibrium analysis defined in Chapter 1 as "an evaluation of a small part of the economy, such as one market or industry, without considering changes in the rest of the economy." The analyses in this chapter, while hypothetical, draw on the fundamental economic principles in Chapters 8 and 9 to aid in understanding how market and non-market factors may affect the allocation of groundwater and its services in efficient ways. As an increasingly scarce resource, freshwater sources of groundwater and surface water are being dealt with in a more competitive, market-like circumstance. The partial equilibrium analyses in this chapter are typically portrayed in graphical form and show only a static or short-run result. The approaches to analyses of costs and benefits in Chapter 13 are a range of tools that the economic analyst can use to research, define, and estimate specific costs and benefits. Since water is not always treated as existing in a competitive situation with prices set in a market, some of these tools, such as contingent valuation, assist the analyst in estimating its value to society when competitive prices cannot be observed. The tools of Chapter 13 may be used to estimate and calculate some of the results displayed graphically in this chapter.

LOCAL RELATIONAL POLICIES

Local relational policies include rights to use groundwater and liability from misuse of groundwater from excessive pumping or contamination of the resource. Both of these legal approaches affect groundwater users adjacent or near each other and even more distantly depending on hydrogeologic conditions. The third local relational policy, community information, also potentially affects adjacent or nearby groundwater users with one person or a group informing another for the possible benefit of the community of water users through facts and data being more commonly understood and used in decision making.

Ecosystem Scale

Local relational policies are focused on establishing rights and communicating among community water consumers in the immediate area affected by the policies on typically a case-by-case basis. Their ecosystem scale can be fairly limited. However, common law and scientific understanding are broadly applied. As a result, the ecosystem scale of these policies may be extensive. For groundwater, applicability may be on an aquifer-wide level and, therefore, these policies may have significant effect. A shortcoming of these policies is that they do not necessarily establish a standard of use or priority to maintain the natural capital in groundwater, nor for minimizing energy use and greenhouse gas emissions associated with pumping and transmitting groundwater. Ecosystem effects of local relational policies may need greater research on positive outcomes for the larger resource.

Property Rights and Liability Law for Water Sources

The ecosystem scale of property rights and liability law is usually limited geographically. The focus of legal challenges often is between adjacent property owners, but may also include associations of challengers to a particular property owner. These laws may be aimed at more obvious wasteful or harmful practices associated with water, which may be isolated from more profound water use and contamination. However, this circumstance is changing as groundwater has been treated as a commodity to be piped to distant locations to provide water supply. In a larger context of water rights and use liability, nations are concerned about extensive pumping along their boundaries and the economic effects of transboundary water withdrawal limiting their respective citizens' water available for use. Groundwater pumping by many well owners/managers along state and national boundaries may be at a large scale, with states challenging each others' right to pump and use subterranean waters that may have been in storage for long periods or may be slowly migrating and not readily observable. Because of the typical slow movement of groundwater, replacement (replenishment) of groundwater drawn away by adjacent users may be difficult to facilitate and in arid regions even more problematic. Many adjacent groundwater pumpers can deplete extensive zones in large aquifers, also causing loss of habitat for underground and surface water organisms in addition to loss of future human water supply. The effects of these rights and laws may thus be somewhat serendipitous and any specific ecosystem consideration unplanned and having future unintended and uncontrolled consequences.

Property Rights and Liability Law for Contaminant Control

Chemical waste releases have historically been a problem that has affected groundwater and contributed to numerous contaminated sites around the world. For example, in the United States, 1644 abandoned waste (Superfund) sites being remediated have contaminated groundwater by a range of wastes and chemicals (USEPA, 2002). Contamination of groundwater is usually thought of as local. In the context of property rights and liability law, groundwater contamination would then be between one contaminator and the owner whose water would be contaminated or threatened. Groundwater movement can transport contamination between adjacent properties in such cases. If the time frame is short, the contamination may not travel far and so the ecosystem scale may be limited. However, if a class of contaminators is large and widespread or the timeframe is long, the ecosystem scale may be extensive, prompting legal challenges of all types of groundwater users whose resource may not be available for future supply and use. Likewise, protected wildlife within a large underground zone, such as endangered species, may be threatened by the outcome of rights and liability challenges associated with contaminant releases. Local liability laws may be ineffective at the larger ecosystem scale unless used on classes of contaminators who would affect extensive areas and associated aquifers or portions of aquifers.

Community Information for Water Sources

Community information focused on ecosystem scale of groundwater sources may be either narrow and local or comprehensive. Local ecosystem scale information may include only a particular concern such as aquifer depletion and individual steps to reduce it. More comprehensive approaches might include identification of alternative water sources and their infrastructure, response to aquifer deletion of other communities and success in dealing with it, and description of extensive depletion effects to industry and wildlife. To ascertain the effectiveness of community information on the largest user groups, communities would need to evaluate responses of these groups to the information. Groups with the greatest discretionary income may engage in water using activities such as lawn and garden watering, or companies in which water use is large but small in the overall production process, which have large-scale effects but limited motivation to change usage patterns. To be most useful in addressing ecosystem scale, care should be taken in using community information to make sure that it is accurate and in accord with the best scientific understanding to appropriately affect water source scale issues that are of great interest to particular user groups. Providing information through many communities potentially expands the ecosystem scale effects.

Community Information for Contaminant Control

The assessment of community information provision for contaminant control is similar to water source for ecosystem scale. The focus may be highly local or broader and more comprehensive. Since most people use products that may have contaminant or residual effects, care should be taken to motivate action and not demotivate it. Comprehensive approaches to providing information that considers larger-scale factors may also focus on contaminant generation in the manufacture of disposable products and on the identification of less-contaminating alternatives that achieve the same objective. For example, simpler products may generate less contamination in production, which lessens the scale of potentially affected areas and aquifer zones.

POSITIVE ECOSYSTEM RESPONSE

Positive ecosystem response for this or other categories of activities must be evaluated on ecosystem assessment. This assessment must recognize the interrelation of factors that may be both resources and sinks as well as other aspects of the ecosystem that are not obviously connected to the focus of a particular activity but may have a bearing on ecosystem response and the near- and long-term use of groundwater, in this case. In addition to improved water availability for people, and flora and fauna, positive ecosystem response may include minimizing the ecological footprint of groundwater production, use, and contamination. Mitigating the size of the ecological footprint related to groundwater as water source or contaminant sink translates to reducing energy use and greenhouse gas emissions in pumping, treating, and transmitting groundwater, including reducing water transmission losses that require more energy to move the additional water in replacing that which was lost. Additionally, reducing resource consumption and making communities more sustainable have a positive effect on communities' social framework and reinforce orderly government and institutions that support the communities. Direct measurement or steps taken to project ecosystem response will contribute to understanding these effects.

Property Rights and Liability Law for Water Sources

Property rights and liability law, unless focused on particular ecosystem receptors needing water, may be limited in ecosystem responses for groundwater. Laws directed at particular existing concerns or potential threats of narrow focus, such as ecosystem habitat loss or wasteful use at particular sites, may be more successful. This limitation may not be applicable when these legal frameworks are deployed for protecting water needs of groups of organisms and animals at harm, such as endangered species, across many properties drawing on the same aquifer. Preventing excessive pumping through property rights and liability law may be possible where threats can be adequately modeled and demonstrated. Rights may need to be aligned to take into account the requirements of the ecosystem as research identifies them, such as for endangered species. Depending on the community or nation, changing laws and legal practices to recognize hydrologic principles may take a long time but may be successful in a more comprehensive approach even if at small scale sites and in a way that does not necessarily consider the larger ecosystem. Communities protecting recharge zones and providing artificial recharge to aquifers through rights and liability law may enjoy a positive ecosystem response even though the extent of the response may be limited to a small area in a state or nation. However, typically, the ecosystem response is not the focus of these rights and laws.

Property Rights and Liability Law for Contaminant Control

Positive ecosystem response based on property rights and liability law will rely on legal steps to prevent groundwater contaminant in the first place and on contaminant remediation. When one property owner's activities threaten adjacent resources of other owners and users, contamination modeling may demonstrate how to prevent groundwater contamination and serve as an example for other similar situations. Preventing the contaminating events would reduce the need for the ecosystem to respond and, in the case of groundwater, protect its quality. Should a contaminating event occur, these legal frameworks may be applied to limit their effect on the ecosystem, but the instances at issue would need to be discovered first, remedial engineering employed, and time to reuse the resource taken. Damage would in these circumstances be done to the ecosystem, which may be widespread or local. In the cases of large classes of contaminants applied over large areas of concern, damage could be extensive. Ideally, the threat of legal action would dissuade potential contaminators, but this threat has not had perfect success. People and companies are regularly searching for ways and places to dispose of waste and residuals from production and use of resources, most of which are anticipated to be legal. So positive ecosystem response may be in question beyond a local situation being resolved through rights or liability determination and certainly unplanned under the application of these rights and laws, since they do not necessarily focus on the effects of the ecosystem, but rather on the results of human interaction through the use of the resource as a sink.

Community Information for Water Sources

Actions taken to provide community information to affect water source demands and use should have a positive ecosystem response if the negative aspects of use of groundwater can be measurably mitigated. Reduced groundwater use may translate into many ecosystem effects, including less depletion with more water available for future users and for times of drought, less land subsidence, less habitat loss in wetlands and streams, and, therefore, more wildlife and biodiversity. If many communities provide correct information about the positive effects of mitigating excessive or wasteful water use, the ecosystem effect may be much more extensive. To maximize the positive effects, the community messages may be customized for particular audiences and groups within communities. Community information approaches typically assume and rely on the positive responses of the significant or targeted populations to take "sustained" action over long periods of time. Given the typically long periods of time for the resource to respond, the results of this policy are uncertain without long-term concerted attention of the community or communities and a focus on measurement of aquifer and ecosystem response to provide feedback for further attention and action.

Community Information for Contaminant Control

Likewise, community information to influence contaminant release and control may have a positive ecosystem response regardless of the extent of such an effort as long as contaminant release is reduced. Reduced contaminant release to the subsurface has the potential to maintain aquifers as a freshwater source, rather than reducing the availability of the resource from contamination. Reduced contaminant release puts fewer humans and less wildlife in jeopardy of potential illness, disease, and death.

EQUITY

Property Rights and Liability Law for Water Sources and Contaminant Control

Low-income or disadvantaged property owners and small businesses generally have fewer resources, and therefore less flexibility to reduce consumption or waste disposal to minimize externalities. However, because they may consume less and have less to dispose, they may not be sources of significant externalities. The potential for reduced consumption and disposal from low-income and disadvantaged property owners should be considered in deciding how to implement property rights and liability laws. The strength of these rights and laws is that they protect all individuals if established and implemented equitably at the outset. In most societies, low-income individuals or businesses may need the support of government-assisted legal representation to ensure that they are not taken advantage of by entities that may in some cases have wasteful water habits and generate more waste from greater consumption of products.

Community Information for Water Sources and Contaminant Control

Community information for water sources and contaminant control may be a benefit to all in a society. The Groundwater Foundation has demonstrated these benefits through its efforts to educate, inform, and collaborate support to communities across the socioeconomic spectrum in protecting their groundwaters.

ECONOMIC EFFICIENCY OR EFFECTIVENESS

Property Rights and Liability Law for Water Sources

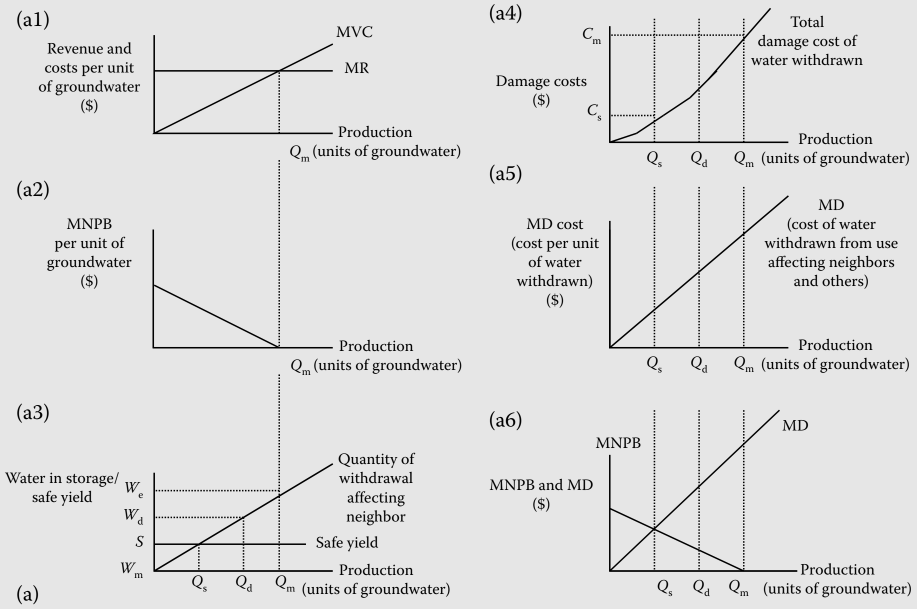
Economic analysis of local relational policies for water sources considers ownership of the groundwater and its use or abuse relative to adjacent or nearby users. Having legal status for water use and contaminant release means holding property rights to the groundwater or to discharging to the water body, as well as responsibility for conducting associated activities with those rights in a way acceptable to the community.

To start our investigation, we will first consider a simple hypothetical case involving two groundwater users, a water seller, who sells his water to everyone else, and his neighbor, who uses groundwater from her wells to supply the needs of her family members who live with her on a large farm. Both have rights to unlimited water use on their properties. In this hypothetical locality, the water market is good and the water seller sells everything he can produce for any purpose and distributes it by pipeline to water systems, by bottle, and by tanker truck. His high-capacity well runs 24 h per day everyday. The farmer has needs year around but has expanded need for groundwater during the summer for crop irrigation. The farmer found that the water table was dropping and that one cattle-watering well was dry and her overall pumping costs had risen for the other wells. Neighboring groundwater users discovered similar results. Additionally, the streams that normally flowed even during times of low or no precipitation were now dry. Consultation with the local geological survey determined that although the water table had declined, it was not yet at a level that would be considered critical to continual long-term use, the safe yield level, even though precipitation had been less over the last several years, while the well screens of most users were still below the current water table. With this situation described, we consider the economic relationships between the neighbors. Exhibit 12.1a will help in exploring this situation.

Graph (a1) for case (1) shows that the water seller should produce and sell the groundwater until his marginal variable costs (MVC) of operating, such as labor, electricity, and pump house maintenance, just equal his marginal revenue (MR). This operation puts him at a production of Q_m, maximum quantity. His maximum marginal net private benefit (MNPB) (MR less MVC) is the area under the MNPB curve in graph (a2). Graph (a3) presents a slightly different picture for his operation, since his volume of pumping has affected the aquifer by lowering its water table approaching a point W_d, with production of Q_d. The neighboring users found their costs rising from having to install new wells to replace dry ones and from added pumping costs (collectively termed "damages") (shown in graph (a4)), including the loss of local fishing because of dry streams. Their marginal damage (MD) costs (the rate of increase in total damage cost) increased from the expanding water seller's production, as shown in graph (a5). The neighbors agreed to sit down and negotiate with the water seller, threatening to take him to court for their losses if he did not consider their costs. With the assistance of a local hydrogeologist, they negotiated a long-term safe production level, Q_S, which would allow him to have a profit while the community would incur minor costs of C_S shown in graph (a4), but including return of the fishing stream.

EXHIBIT 12.1 PRODUCTION AND RESOURCE EFFECTS

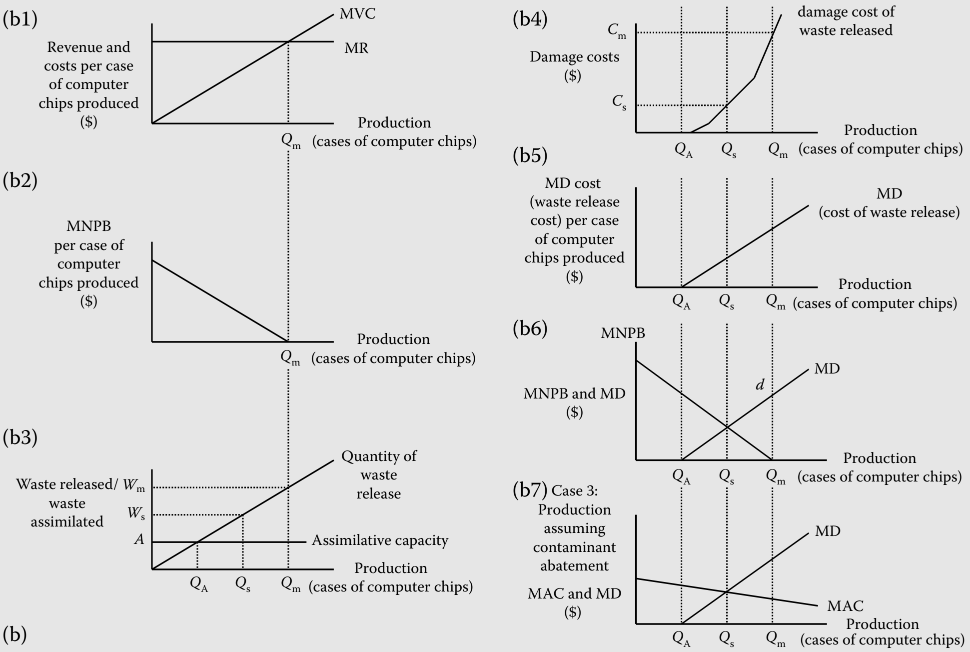
(a) Case 1: Production assuming no water use limit



Source: Modified from Turner, R.K. et al., *Environmental Economics: An Elementary Introduction*, The Johns Hopkins University Press, Baltimore, MD, 1993, 149. With permission.

EXHIBIT 12.1 (continued) PRODUCTION AND RESOURCE EFFECTS

(b) Case 2: Production assuming no contaminant abatement (graphs b1 through b6)



Source: Modified from Turner, R.K. et al., *Environmental Economics: An Elementary Introduction*, The Johns Hopkins University Press, Baltimore, MD, 1993, 149. With permission.

Note that in graph (a6) reflecting the final negotiated position, the water seller has lost output from Q_S to Q_m under the MNPB curve. However, the neighbors were willing to sue him for damages far exceeding his net profit, which is represented by the area under the MD curve to the right of Q_S. Thus, the intersection of the MNPB and MD curves established the level of production for the water seller, Q_S, and his net profit. At this intersection, the MNPB just equals the MD, an efficient economic outcome.

This analysis of a simple example is the product of the theorem defined by Dr. Ronald H. Coase in 1960 (cited in Turner et al., 1993, and Field, 1994). Coase believed that government intervention was not necessary to obtain an efficient outcome in cases of pollution (or, by extension, other externalities, such as depletion or mining of a groundwater source). Rather, the polluter (or depleter) and the injured parties, as long as one or the other of them had property rights in the resource being used or polluted, could arrive at the economically efficient outcome through bargaining, as in the example above. Field (1994, p. 197) identifies the minimum conditions that would have to exist for such an approach to work toward an efficient result:

1. Well-defined, enforceable, and transferable property rights
2. A reasonably efficient and competitive system for interested parties to confer and negotiate the use of these environmental property rights
3. A complete set of markets for private owners to capture all social values associated with the use of an environmental asset

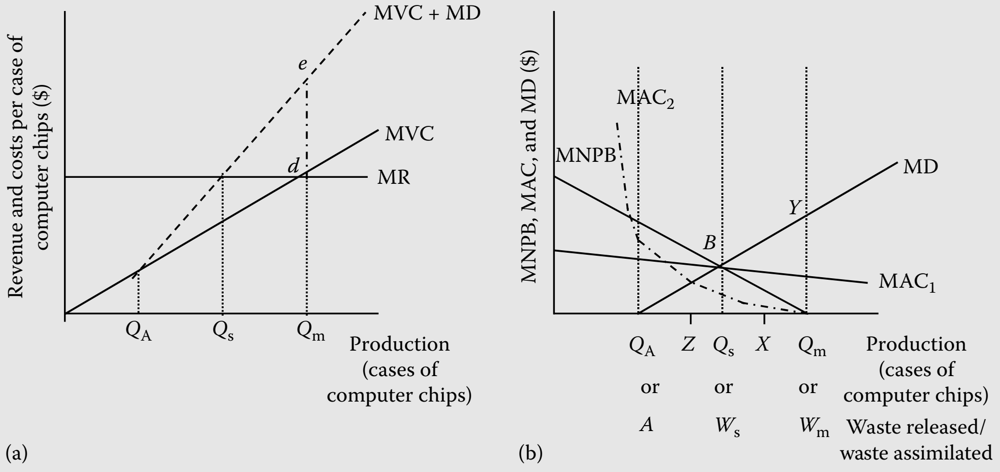
The approach of the Coase Theorem, while attractive in its apparent simplicity, has challenges in terms of its implementation. Competition is not perfect, as government involvement in the economy is required to ensure equity and other interests are represented. Markets for groundwater are typically not competitive. Transaction costs of getting both parties together are high, especially if there are a very large number of individuals who have been damaged. Thus, what may seem like a reasonable and straightforward process may in fact be long and tortuous.

Next, in considering the groundwater contamination side of a similar situation, dealing with hazardous waste cleanup at abandoned waste sites in the United States and Europe as well as other countries has shown that not only is it difficult to identify all the persons who have suffered by contaminated groundwater, given the vagaries of pathways of the subterranean environment, but also challenging to identify all the past contributors to an abandoned chemical disposal site.

Property Rights and Liability Law for Contaminant Control

A similar analysis of property rights and liability laws that might support contaminant control for groundwater is outlined in Exhibits 12.1b and 12.2. Exhibit 12.1b assumes no contaminant abatement, just a hypothetical negotiation between the groundwater supplier of drinking water to adjacent property owners and a computer chip manufacturer disposing of wastes in an on-site landfill that leaches to groundwater, which supplies the property owners with drinking water and maintains a wetland and productive estuary nearby. The profit-maximizing company desires to produce Q_m cases of computer chips, shown in graph (b2). Graph (b3) indicates that the subsurface could tolerate waste releases up to A on the vertical axis at a level production of Q_A with no known costs to adjacent property owners. Above a production level of Q_A, contaminants begin being observed in drinking water, but below levels of health concern. However, once production reaches Q_S in graph (b4), contaminant levels in groundwater have been shown to exceed the accepted maximum contaminant level increasing health concerns and requiring the water supplier to use an alternate water source at a higher cost. The water supplier along with the property owners who are concerned about their property values and the local park district, which is considering establishing the wetland as a wildlife refuge, have decided to enter into negotiations with the company to arrive at a solution in all of their interests. They arrive at the negotiated point of intersection of the company's MNPB curve and the MD curve of the water supplier, neighbors, and park district (see graph (b6)).

EXHIBIT 12.2 PRODUCTION AND RESOURCE EFFECTS—ASSUMING CONTAMINANT ABATEMENT CONTROL



In Exhibit 12.2, graph (a) shows that adding the MD curve of the community to the MVC reflecting the plant operating and maintenance cost of an additional unit of production) curve of the company, they can arrive at the same solution when compared with the MR curve of the computer chip company. The segment *d-e* in graph (a) is the same as that of segment Q_m-*Y* in (b) and of segment Q_m-*d* in Exhibit 12.1(b6) (although not precisely to the same scale in each graph), measuring the MD to the community of the maximum production or maximum waste released. The result is Q_S, the socially efficient production level, since MD are accounted for the neighbors', water supplier's, and park district's interests. The discussion below describes circumstances contributing to this outcome.

In arriving at the efficient production level, Q_S, the company had to consider another important factor: contaminant abatement. The company would need to install and operate more pollution control equipment. This added information is given by the marginal abatement cost (MAC) curve, MAC_1, in Exhibit 12.2b. MAC_1 intersects as closely as possible with the MNPB and MD curves in this case, at point *B*, only for the purposes of an idealized efficient result, which a company would want. MAC_1 also needed to be below the MNPB for the company to operate at a profit. Note that to the right of point *B* in Exhibit 12.2b, MAC_1 is above MNPB and the company would not want to operate in this area of the graph. The convergence of these three marginal curves in this example is ideal, not typical. Most presentations of this outcome assume that the MAC lies below the MNPB in the area of interest on the graph, as is the case with MAC_2 (the dash-dot-dash line in 12-2 (b)).

The ideal graph 12-2(b) result makes other points. The area bounded by the triangle Q_m Q_s *B* in (b) is output lost by the company if no waste release abatement were required. If the company had chosen to operate at a production point represented by *X* on the horizontal axis, the community would have faced considerable damages, well in excess of the company's MNPB. Below (to the left of) Q_A, the community was not affected by the waste release, since the conditions in the subsurface environment were not so contaminated that natural degradation could break down the contaminant to apparent safe levels. Also, because the production levels are associated with waste release levels, the horizontal axis of (b) can be labeled with the "waste released/waste assimilated" notations, *A*, W_s, and W_m.

Further consideration of the company's operating position should occur in light of a MAC that is less than the ideal, as presented above. If the MAC that the company faces is MAC_2, several other points can be made. First, the company would not consider operating in the area where the MAC was greater than its MNPB; costs would be greater than benefits to the company, which does not make economic operating sense. If the company were to operate only to make a profit (benefit) and ignore social costs of its production, then Q_m bounds the point at which it would implement waste release abatement. This point also marks the condition of maximum waste release, W_m. The company can only afford to operate over the long term if its MAC is less than or equal to its MNPB, assuming that its MNPB represents the "preabatement" operation in which it did not account for damages to the community and associated abatement costs. As long as its MNPB was positive or zero, it might operate at *Z*, the intersection of the MAC_2 and the MD curves, where the MD equal the MAC. This would be the logical management choice of production and waste release because the company had to recognize, based on negotiation with the community, the MD to society that it was creating. However, as long as the MNPB curve remains fixed, the company might operate anywhere along the MD curve up to Q_s for MAC_1 and between the MNPB curve and *Z* for MAC_2 if these were two real MAC curves, since the MD are less than the marginal costs and the company still operates at a profit for each additional (marginal) unit of production.

Returning to Exhibit 12.1b, graph (b7), imposing the MAC curve on this graphical analysis, the MAC curve ideally crosses the MD curve at Q_s. It could cross it anywhere to the left of Q_s and the company would operate at a profit based on the location of the MNPB curve in graph (b6). The company would not desire to operate at a point where the MD are greater than MNPB, to the right of Q_s.

With liability laws operating in the contaminant release realm, other costs must be included in the analysis. To observe contaminants in groundwater, monitoring must take place. Because of the "out-of-sight" nature of groundwater, this monitoring may be extensive and would have to be paid for by someone (usually a company, government, or possibly both). Monitoring is expensive and, as noted in Chapter 6, monitoring wells must be installed before sampling can even be initiated. The "burden of proof" requirements are substantial in most instances, and the information associated with demonstrating the proof that injury occurred can also be time consuming and expensive. First, the plaintiff must demonstrate that his/her injury can be traced to a specific contaminant release, which may be very difficult. Second, the release must be associated with the defendant. Additionally, bargaining over the outcome of a pollution case may take enormous time and expense.

The principal point to be made relative to property rights and liability law pertaining to groundwater is that utilizing the fundamental economic relationships provides an efficient result, at least in the idealized cases. If several outcomes are evaluated toward achieving the same objective, conclusions can be made about which one is most cost effective. However, an efficient result may not be acceptable within the community or for other reasons of a political nature. Be that as it may, efficiency evaluations associated with property rights and liability law applied to groundwater can be used to inform the larger decision process to move toward an efficient outcome. If court suits make monetary awards in property rights and liability cases, these awards raise the cost of ignoring effects on adjacent property owners and other individuals of causing less water availability or poor groundwater quality.

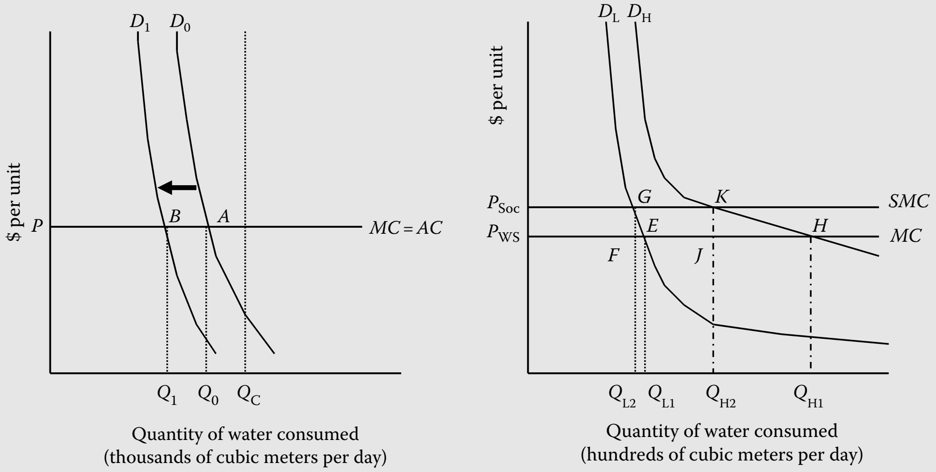
Community Information for Water Source

People in communities concerned about the long-term use of their groundwater resource may share information about the use and conservation of water. This interest in maximizing the use of the water source or making it available to future generations may be motivated by physical necessity, actual measurement, idealism, concern for the environment, or religious inspiration. More recently, interest in sustainable resource management has furthered this focus (for example, see Daly and Farley, 2004). The result of sharing information about the groundwater supply and its role in the community is typically an effort to reduce the demand for water. The motivation could be that if demand had grown as a result of increased preference for water use, as depicted in Exhibit 12.3, shifting the demand curve, D_0, to the right along the MC supply curve, use may have expanded to be too close to Q_C (a critical level of demand that would jeopardize future use) at which time the well may have to be deepened or another water source developed at community expense.

Exhibit 12.3 describes the response if the sharing of information to reduce water use is successful in the long term. In panel (a), the result of community information is to reduce demand from Q_0 to Q_1. In the example of panel (a), the water supplier is assumed to be on the supply curve MC. In the range of interest on the graph, MC is flat, meaning that MC = average cost (AC) = price (P). That is, each unit in this range sells for the same amount. In this case, the water supplier receives less revenue, the reduction represented by the rectangle $Q_0\, AB\, Q_1$, when water consumption is less. The reduction in revenue may motivate the water supplier to raise the price of water if all costs are not being covered at price P (a price increase may be a further inducement to conserve water, which will be addressed later).

Some effects of sharing information to reduce water use may have variable results on different groups of consumers. Panel (b) of Exhibit 12.3 suggests that if users initially stay on their demand curve, outcomes between low- and high-income water consumers (or small and large industrial water users) could be significantly contrasted (note that the Q scale on the x-axis is not the same in panels (a) and (b)). The demand curve, D_L, is operative for low-income consumers who may have less discretion in their water use. If they respond to community information to reduce water, and

EXHIBIT 12.3 ECONOMIC EFFECTS OF COMMUNITY INFORMATION AFFECTING GROUNDWATER QUANTITY USE



(a) Community information directed at preferences for reduced water demand

(b) Variable effects of community information among water user groups

Note: x-axis scales for Q, quantity of water consumed, is different in panels (a) and (b).

we recognize that they have limited options for doing so, indicated by their inelastic demand in the range of interest (moving from position E to F on the P_{WS} curve or to G on their demand curve if price is increased to induce conservation), their reduction may be from consumption position Q_{L1} to Q_{L2}. These consumers can try to take shorter showers, use less water bathing, or install free shower flow restrictors, but other possibilities to reduce water use may be constrained by their ability to purchase other means of doing so. Note that F represents a shift in demand similar to Exhibit 12.3, panel (a).

On the other hand, high-income consumers may have water uses that are more discretionary and can be adjusted by lifestyle changes and by investing in equipment to accomplish a reduction in water use. For example, lawn watering can be cut, car washing may be reduced, and, significantly, purchases of water-conserving appliances (shower flow restrictors, low-flush toilets, and washers with water-conserving settings) can decrease water use. These types of water use and possible ability to accommodate conservation are reflected in the more elastic portion of their demand curve (D_H) in the area of interest and a change in water demand position from H to J or to K if the price is increased. Position J represents a shift in demand similar to the portrayal in Exhibit 12.3, panel (a). A much larger reduction in the amount of water use is shown for the elastic portion of the high-income demand curve, given by the change in quantity consumed from Q_{H1} to Q_{H2}. The social costs to both groups in making such changes are reflected in the price curve of P_{Soc} above the water supplier price of P_{WS}. The difference in the two curves is the additional cost to the community to make adjustments to conserve and in response to community information that water conservation may sustain the groundwater supply for future use. Recognizing that not all individuals (or businesses) may be able to reduce water use to the same extent may be important in implementing community information campaigns targeted at different users. This understanding also considers the equimarginal principle of economics: at the given price for water use, consumers will have different results if they are implementing use reduction measures, based on ability and willingness to pay the costs to apply those measures. If water price, income, and other economic factors remain the same, and the adjustments become permanent, the change in water demand from community information may be reflected in the shifting of the demand curves, as indicated in panel (a), assuming people act on the information they receive.

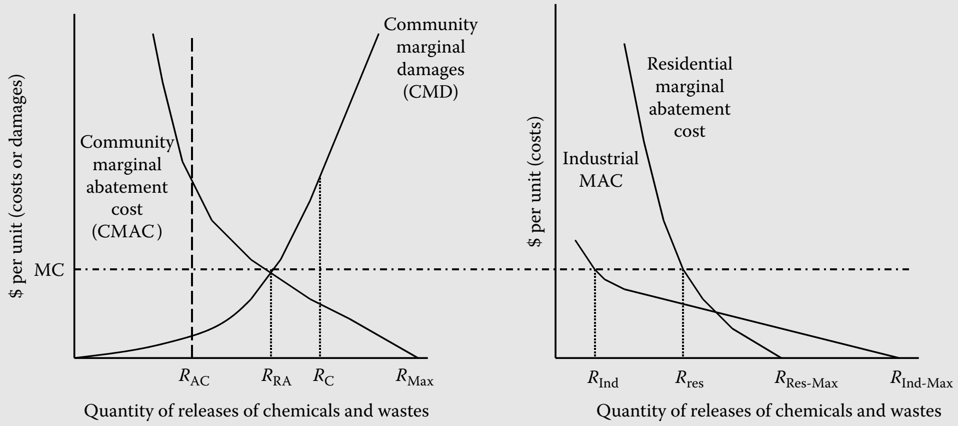
Community Information for Contaminant Control

Communities face potential and actual contamination of their groundwater from a range of sources, including the activities of residents, business, and industry (USEPA, 1990; UNESCO, 2003, pp. 10–11). Economies around the world have become heavily dependent on chemicals for cleaning and processing their products and consumption activities, including household needs. Residents may apply chemicals to their lawns. People relying on individual septic systems for domestic waste treatment may be flushing household chemicals out of their houses and directly into the ground with little or no treatment, depending on the successful operation of the septic system. Businesses, including agriculture, rely on chemicals to increase productivity, which once used, the residual chemical is dealt with as a remaining waste for disposal. Some industries likewise use chemicals, which may be released to the ecosystem and groundwater by waste lagoons and injection wells. Communities may also construct and maintain stormwater retention ponds, which collect runoff with chemical residuals from many activities, such as pest control, roadway residues, and other residential and commercial functions, which are allowed to percolate and infiltrate through the subsurface to groundwater. These and other activities may have a detrimental effect on groundwater quality.

Many of the activities having adverse groundwater quality effects may also have discretionary aspects that community information focused on reducing risks of contamination may have influence in lessening contaminant releases to groundwater and the ecosystem. Some activities may have lower costs to implement than originally thought. For example, businesses may be able to reduce the volume of chemicals stored on site by more carefully managing their production needs, minimizing the possibility that chemical stocks could leak from the site and contaminate groundwater (USEPA, 1996). Likewise, residents using chemicals in their homes for pest control and cleaning may be able to switch to biodegradable products, or to target their uses rather than applying them widely. Collection and recycling of waste oil may be practiced in both the residential and commercial/industrial sectors. In all cases, markets for wastes and means to recycle must be the available alternatives, in some cases, provided by the community recognizing the social costs and benefits of reducing wastes released to the ecosystem.

The economic effects of community information affecting groundwater quality are considered in Exhibit 12.4. The level of overall chemical and waste releases will vary based on the society and culture. Exhibit 12.4, panel (a), shows a “community marginal abatement cost” (CMAC) curve sloping down to the right and intersecting the x-axis at the point R_{Max}, at which point no chemical residuals or wastes are reduced. The CMAC intersects the “community marginal damages” (CMD) curve at R_{RA}, where releases are accommodated to the point that balances community abatement and damages. In this hypothetical situation, the community has engaged local scientists to establish the assimilative capacity of the subsurface and groundwater for releases of chemicals and wastes, R_{AC}. At R_{AC}, it is expected that community damages will be at or near zero, because the subsurface environment can degrade or make innocuous the lower concentrations of the range of chemicals and wastes released to it by the community. To the right of R_{AC}, with increasing waste quantities released, damages to individuals in the community occur. The MAC per unit of release exceeds the MD. The community-efficient outcome is R_{RA}, as long as the community is willing to accept some damage (for example, higher levels of nitrate in groundwater, but below the drinking water maximum contaminant level) for the opportunity to have the waste-releasing activities that it wants to accept, such as lawn fertilizing, crop production, or individual septic systems. At the point R_{C}, critical standards are breached, such as drinking water maximum contaminant levels, which pose

EXHIBIT 12.4 ECONOMIC EFFECTS OF COMMUNITY INFORMATION AFFECTING GROUNDWATER QUALITY



(a) Community information directed at preferences for reducing contaminant sources

(b) Hypothetical variable response to community information among contaminant sources

Source: Adapted from Field, B.C., *Environmental Economics*: *An Introduction*, The Johns Hopkins University Press. Baltimore, MD, 1994, 207, 215. With permission.

increasing health problems, as noted by the sharp upward rise of the CMD curve. The community would ideally want to balance marginal abatement and damage costs below this point anywhere to the left of it.

The CMAC curve may have several components, at least residential and industrial components, to consider. This aspect of the analysis may influence the most effective way to implement a community information program to achieve its results to reduce the effect of contaminant sources potentially affecting groundwater. CMAC, in addition to the actual changes in abatement, may also incorporate the costs of the community information program. For any particular community, the relative relationships shown in panel (b) of Exhibit 12.4 may be different. Barbash and Resek have shown that groundwater quality results vary significantly based on domestic or industrial sources of contaminants (Barbash and Resek, 1996, p. 245). In panel (b), the industrial sources have a somewhat more elastic abatement cost curve, suggesting that slight application of efforts to reduce that sector's contaminant release could yield significant decreases in those releases for this hypothetical case. The residential sector's abatement cost curve in this example is less elastic. (The reverse of the situation may be true in reality and would need to be assessed in each case.) What might this imply about residential abatement costs if this were an actual situation? Each resident acting independently has his or her own abatement costs for reducing contaminants, which on a per unit basis are considerably larger than an industry acting centrally to reduce them.

Which sector could most efficiently reduce contaminant releases to groundwater? In the hypothetical situation of panel (b), each sector would ideally act within the community based on the equimarginal principle that the costs to abate releases at the margin would be equal. In this case, if each sector responded based on their MAC being equal, the efficient release would be at point R_{RA}. In the ideal case, this point coincides with the intersection of the residential and industrial MAC curves, and the MC curve. In reality, this matter would take considerable research within the community to figure out how this would occur. In this hypothetical community, residents would release R_{Res} and industry would release R_{Ind}.

REMAINING CRITERIA FOR EVALUATING LOCAL RELATIONAL POLICIES

Having considered ecosystem scale, positive ecosystem response, equity, and economic efficiency and effectiveness of local relational policies, we consider the other previously identified evaluation criteria:

Dynamic Incentive

Property Rights and Liability Law for Water Source and Contaminant Control

These laws may be inflexible such that they cannot induce cost-effective results in the long run, but deal with the current situation of externalities only. The laws do not in and of themselves promote research for more efficient solutions. However, the threat of a legal suit under property rights and liability laws may induce investigation and research if situations generating or potentially causing the externalities of concern are widespread, such as has been the case with groundwater exploitation and contamination in the past. More economically efficient outcomes may result.

Community Information for Water Source and Contaminant Control

The dynamic incentive of community information applied to groundwater by the nature of the resource may be localized but may be dispersed over such disparate decision makers that long-term adjustments in water consumption and contamination may be spawned, but whether the results are cost effective and prompt research into more efficient methods of managing groundwater is speculative. If community information campaigns occurred in a sufficient number of places to obtain greater interest in research to facilitate more efficient long-term solutions, this latter conclusion might be different.

Low Information Requirements

Property Rights and Liability Law for Water Source and Contaminant Control

Individual and legal negotiations may require substantial amounts of information depending on the nature and requirements of the property rights and liability law and the court system in administering them.

Community Information for Water Source and Contaminant Control

Activities associated with community information must consider getting their message on groundwater consumption and contamination across to their intended audiences briefly and succinctly. Therefore, it must focus on the most important information and deliver it clearly. Community messages can be successful with low information requirements, but they must be based on the best scientific information and nurtured over time, often through volunteers relying on voluntary action by the targeted audience. Tracking feedback from measuring community response and associated groundwater conditions may have significant data-gathering requirements, but this is likely location and condition specific.

Low Administration Cost

Property Rights and Liability Law for Water Source and Contaminant Control

Administering negotiations among property owners or legal deliberations through the courts can have very high costs. The outcome of the legal cases involving the law on abandoned waste sites in the United States has been very expensive. Likewise, legal challenges for water property rights represent a significant legal field of business. In both cases, legal fees raise the administrative costs.

Community Information for Water Sources and Contaminant Control

Typically, community information campaigns have low administrative cost when compared with other policies. As noted above, they often rely on volunteer efforts, which may have significant social costs that are unrecognized in the marketplace but account for in-shadow pricing. Community information may also be transferred from one person to another through social interaction without added administrative cost.

AGREEMENT WITH MORAL PRECEPTS

Property Rights and Liability Law for Water Source and Contaminant Control

Typically, property rights and liability laws were derived from a common law, which reflected appropriate relationships of individuals in society and was derived from religious precepts that were codified in the secular law. These laws also apply to relationships dealing with the consumption and contamination of groundwater.

Community Information for Water Sources and Contaminant Control

Likewise, community information policies often seek to correct relationships that are out of balance, such as using groundwater in large quantities or as a waste disposal sink so as to preclude others' use rather than conserving it for future generations. The consideration of sharing and use of a resource by others aligns well with religious and societal precepts of fair and appropriate treatment of others' interests.

RISK MANAGEMENT FOR WATER SOURCE AND CONTAMINANT CONTROL

Risk management for water source and contaminant control of groundwater involves choosing the risks an individual, corporation, community, or nation might carry, and importantly determining the risks to be avoided or reduced and conducting specific functions and processes to do so. Risks to be avoided or reduced for water sources might include loss or depletion of an aquifer used for water supply. For contaminant control, these might be irreversible contamination of an aquifer over the planning horizon of a community or avoidance of consuming contaminated groundwater to avert possible disease (WHO, 2001).

ECOSYSTEM SCALE

Risk management, though important to the viability of groundwater sources for quantity and quality purposes, is typically implemented on a case-by-case basis. Risk to an entire aquifer is rarely a management consideration but should be examined. This risk depends on aquifer size and number of users, as in the case of the Ogallala Aquifer, in which case much of the aquifer was in risk of depletion from the groundwater withdrawal of thousands of irrigating farms. While laws may be implemented across states or nations, risk to natural capital in groundwater is usually a concern for a portion of an aquifer for which a permit may be issued for production or disposal, with controls identified in the permit. Risk to the larger aquifer as a management unit is not operationalized at that level, thereby creating risk to the perpetuity of aquifer use.

POSITIVE ECOSYSTEM RESPONSE

Managing risks typically obtains a positive ecosystem response. This has been the case in the regulation of underground storage tanks in the United States where it was clear that most tanks in the subsurface would eventually deteriorate to the point of leaking and should be removed before they did leak. The cost of remediating lost gasoline and other chemicals in groundwater is large compared with the cost of replacing the tanks with new technology that mitigates the loss of chemicals and their impact on groundwater. A portion of the ecosystem response could be evaluated in an "avoided cost" benefit framework.

EQUITY

Risk interventions may affect different socioeconomic groups variably. This is particularly true if some groups do not understand the nature of the risk and its cost to them. Certain interventions may treat all groups similarly, such as in the case of treating groundwater before delivery to all customers, regardless of their income levels or other differences. Policy formulation should be sensitive to these criteria since not doing so may result in significant risk to populations who may have the least ability to avert or avoid the risk, creating potentially substantial health and environmental costs for them. An example is the disposal of industrial waste from the 1950s to the 1970s contaminating soil and groundwater on lands of the Ramapo Mountain Indians in New Jersey, which has twice been declared a Superfund site to ensure its cleanup because of continued discoveries of wastes. The Ramapo Indian Nation exists with low income and continuing illnesses (Stodghill, 2007).

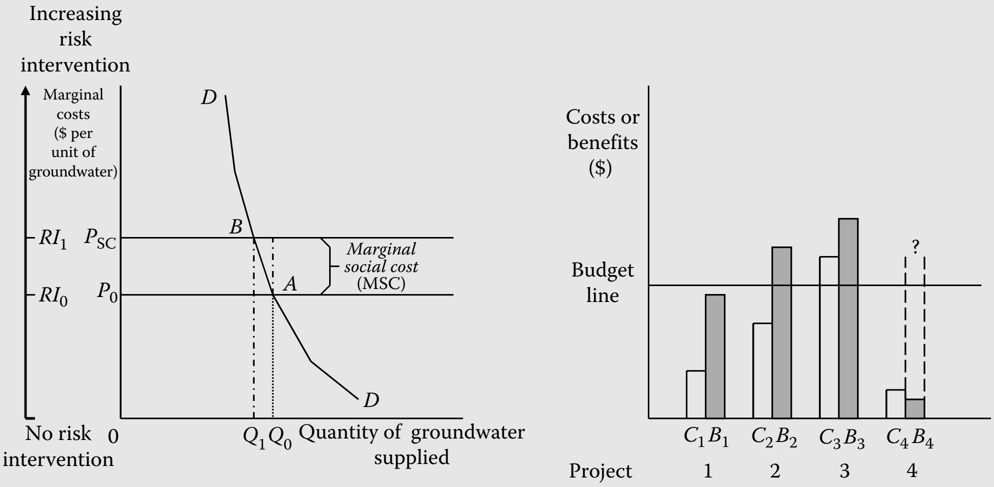
ECONOMIC EFFICIENCY OR EFFECTIVENESS

Economic analysis of risk management policy focuses on interventions at key points of risk for the resource or public health. Since multiple risks may potentially affect the resource condition or the public's health from groundwater consumption, multiple interventions (also referred to as the "multiple barrier approach" in a public health context) may be taken. With respect to groundwater quality, the highest priority contaminant risks are from human and animal fecal bacteria and from naturally occurring heavy metals, and other anthropogenic sources in pumping and recharge zones most immediately around wells, often referred to as wellhead or source protection areas. The interventions, or risk management actions, can be examined from the perspectives of economic efficiency and effectiveness. From an efficiency standpoint, we can evaluate the effect of local risk intervention on the price of water. Considering cost effectiveness, we can compare the costs of different actions or sets of actions addressing the same objective or set of objectives.

Since the risk to the resource or public health is the probability of an adverse outcome for these endpoints, we should consider the nature of these outcomes. From a source water quantity standpoint, an adverse result could include the lowering of the groundwater table, increasing pumping costs, and possibly resulting in the need to install deeper wells for long-term continuity of supply. In the groundwater quality realm, contamination of the resource may necessitate groundwater treatment, either in situ or after withdrawal from the well before use. In either case, this would increase the cost of using water. If the risk management approach is sufficiently comprehensive to consider the susceptibility of the resource to known or future contaminant sources, the intervention may be to move the contaminant source through zoning or controlling the land use in the recharge area of the well so that the probability of future contaminating events is very low. In the case of the latter set of actions, the community may have social costs that are not incorporated in the price for acceptable quality water, but are costs to it that could be evaluated on a per water unit basis. In some cases, the intervention may have been accomplished by a different agency than the water supplier, so the full costs of action are not included in the price. Exhibit 12.5, panel (a), shows the results of these actions on water price. Exhibit 12.5, panel (b), compares the cost effectiveness of different actions with a budget constraint.

In Exhibit 12.5a, more risk intervention is shown the second vertical axis on the left, such as the movement from position RI_0 to RI_1. The economic efficiency of the risk intervention policies in Exhibit 12.5a suggests that (if $P = MC$ and represents the supply curve in the range relevant to the analysis) as price goes from P_0 to P_{SC}, the quantity of groundwater to be supplied would be reduced from Q_0 to Q_1. This is only the case if the water supplier is the agency that conducted the interventions and incorporated them into the price of the delivered water to the consumer. The marginal social cost (MSC) of the intervention, that is, the additional cost of the action for

EXHIBIT 12.5 ECONOMIC EFFICIENCY AND EFFECTIVENESS EVALUATION OF RISK INTERVENTION TO CONSERVE OR PROTECT GROUNDWATER QUANTITY OR QUALITY



(a) Efficiency effects on water price when risk interventions are incorporated into water supply costs

(b) Cost effectiveness of different risk interventions with a budget constraint

each unit of water that may be sold, is equal to the difference P_{SC}–P_0. If the agency that carried out the risk interventions is not the water supplier and the social costs of the interventions are not recovered in the price of the groundwater sold, but through other public revenue sources, then the price charged to consumers stays at P_0 for the quantity Q_0. In the latter case, if the social costs of the actions are paid for by the community at large and not by the water users, the full cost of receiving safe water is not recognized by the consumer in the price she pays. The community is subsidizing the risk reduction.

Considering the cost effectiveness of different risk interventions, Exhibit 12.5b compares four intervention projects that are different but address the same risk reduction objective. By the inspection of the graph, Project 1 has the greatest benefit to cost ratio (B_1/C_1), except that Project 4 seems to have a larger ratio if nonmonetizable benefits are included in some way (in this case by the dashed bar). Project 4 reflects that the quantifiable benefits indicated by the solid B_4 bar are small, even less than the costs. Considering the perceived unquantifiable benefits of the dashed B_4 bar, the bar for B_4 suggests an even greater benefit to cost relationship. Projects 1, 2, and 4 have costs within the budget line constraint for this community's risk intervention activities. Inspection of graph (b) indicates that, if only considering projects with monetized benefits exceeding costs, Project 1 appears to be the most cost effective and has the highest benefit–cost ratio. Project 3 is clearly too costly at this time. Project 2 by inspection appears to have a similar benefit–cost ratio to Project 1 and has costs within the budget line constraint, but is more costly than Project 1.

This example shows that

1. If maximizing the monetized benefits per monetary unit cost is a major criterion for project selection, Project 1 should be chosen
2. If choosing the project with the greatest benefits is the objective, Project 3 should be selected if no budget constraint exists
3. If only projects that are within the budget constraint and have monetized benefits exceeding costs must be chosen, then the community could decide between Project 1 and 2

Often, perceived benefits are considered in evaluating and selecting projects and are often associated with an individual's or group's weighting of risks. Perceived benefits may be greater for a project when compared with others, and this factor may be important in the decision-making process. Reflecting perceived benefits is challenging in a framework of strict comparison of monetized benefits and costs when selecting projects. Budget constraints are usually an essential consideration in selecting projects and may not be part of a strict cost-effectiveness analysis.

In considering risk management, the degree of risk taking or risk aversion is a factor based on perception of costs and benefits (Atkinson et al., 1992). Benefits may be valued by the risk taker but difficult to quantify or monetize. What form of risk taking might apply to groundwater? In arid environments, high-volume use in the present may risk a long-term source of water or the introduction of contaminants of unknown consequence to groundwater may risk future use.

Economic analysis of risk management for groundwater could also be evaluated using an "avoided cost" benefit methodology. The risk avoided could be compared among projects or programs. The projects or programs with the greatest risks avoided based on monetized results might be the ones that are then evaluated on the basis of the costs to implement the risk avoidance.

Dynamic Incentive

If the risks to be addressed are of the same kind, such as the range of solvents in the groundwater of a region or water shortage affecting a watershed, and occur in numerous places or have many potential purchasers of an intervention device or response mechanism, then the market may stimulate research into the interventions and competition among them to lower the price.

Low Information Requirements

This factor applied to managing risks to groundwater depends on the nature of the risk and the ecosystem setting. Considering the example of underground chemical storage tanks again, sufficient information was obtained from the early identified problems with those tanks that were leaking that subsequent interventions were often done with much less information gathered if no leak problem was suspected. Information requirements would need to be evaluated if their magnitude is to be determined.

Low Administration Cost

Often risk interventions for groundwater can be managed through existing environmental programs, minimizing the administrative cost.

Agreement with Moral Precepts

Identifying potential problems (risks) and reducing or eliminating them before they manifest themselves and cause greater costs is typically viewed as a responsible and morally appropriate action in communities.

ECONOMIC INSTRUMENTS FOR WATER SOURCES AND CONTAMINANT CONTROL

Economic instruments act through the marketplace and indirectly affect risk to people or the resource through pricing mechanisms. Using economic instruments to influence resource use and ecosystem results focuses on pricing to balance the actions of producers and consumers in the marketplace. The principal positive results of marketplace pricing are the "signals" of production cost given to consumers and the consumers' value of the producers' output (Turner et al., 1993, p. 143). However, the product in this case, groundwater, is not free for either use or as a means of residual management but may be treated as free in the market process. In the context of these economic instruments, groundwater is a public good priced as a private commodity. Use of the product can impose costs on others, as noted above. Disposal of chemicals and wastes in groundwater can create costs for other users desiring the resource to be of a particular quality. These costs are considered a “loss of welfare” to those experiencing them. Economic instruments may provide incentives, using prices in the market, which can be targeted to facilitate specific outcomes such as reduced use of groundwater or waste releases to it.

Incentives through economic instruments can be produced in two principal ways (Turner et al., 1993, pp. 143–144):

1. Revamp markets to include the value of resource and ecosystem products and services in prices of intermediate or final goods and services that consumers purchase; such an approach may involve setting objectives responding to ecological balance for the use of the resource and treatment of contaminant releases.
2. Establish markets for formerly free resource services.

Both of these approaches would need to be taken by a central decision-making authority that could take action to intervene in markets: local, state, and federal governments. The rationale for revamping and changing markets to recognize the value of free resource and ecosystem products and services include the following:

a. Market incentives are more efficient than standards set under a “command-and-control” (CAC) approach.
b. CAC requires advance information that the regulating authority must set up processes to obtain but is already held by the resource user or contaminant releaser.
c. The marginal costs of reducing releases vary by contaminant releaser with the possibility that the entity with least costs per abated unit can implement its abatement technology to reduce more contaminant at least cost to the economy.
d. Using the market incorporates the “polluter pays principle,” adopted by the Organization for Economic Co-operation and Development (OECD) in 1972, on a group of twenty-four industrial countries and the Commission of the European Community, plus Yugoslavia. The significance of this point is that by adopting this principle across the international realm, no country would serve as a disposal place (“dumping ground”) for contaminants to attract more industry at the expense of other countries and potentially to the detriment of that country’s people who may be harmed by the contaminants being concentrated there. This principle corrects a “market failure” by motivating users of free resource and ecosystem services to incorporate their value in the price (or at least a significant component of the price) of their goods and services, internalizing the costs of use or ecosystem deterioration, including damages to those harmed by pollution. The adoption of this principle may also be viewed as determining not to subsidize polluters. By extension, a similar principle of “user pays” may broadly address costs of overuse of irreplaceable, nonrenewable resources by users taking “free” ecosystem products and services in their price for those goods. (For further discussion, see Turner et al., 1993, pp. 143–156 and Field, 1994, pp. 226–261.)

The range of economic instruments, as indicated in the previous chapter, includes

a. User charges and taxes
b. Emissions charges and taxes
c. Subsidies
d. Product charges
e. Transferable discharge permits or water rights
f. Marketplace bidding for formerly free services

No particular policy approach will probably be most favorably applied to every similar condition (Field, 1994, p. 226; Schiffler, 1998, pp. 340–342). Thus, a combination of economic instruments should be considered to affect groundwater goods and services and other ecosystem factors related to them.

ECOSYSTEM SCALE

Economic instruments by their nature are market based. Since the market undersupplies public goods such as the services of groundwater, the effect of market-based approaches in maintaining natural capital of the ecosystem may be limited. The European Union has found their use limited but increasing among member states (Ecotec, 2001). With the focus of the instruments on efficient transactions, it is not necessarily clear that economic instruments will be effective in maintaining natural capital in groundwater across time and locations. Typically, these instruments are implemented through jurisdictions that in most cases will not coincide with aquifers as the target for results. The instruments could be employed over multiple aquifers contributing to a macro-level response, but that application would depend on political cooperation across jurisdictions. If market pricing is implemented to influence the quantity of the water source used for the release of contaminants to the subsurface across a state or nation, some effect on maintenance of natural capital in groundwater is expected. Otherwise, without a larger objective for the resource, large-scale ecosystem effects would be unplanned with potentially uncertain and unexpected results.

POSITIVE ECOSYSTEM RESPONSE

All of these policies may improve the quality and quantity conditions of groundwater and the subsurface environment, but that may not be the principal objective of such policies. Rather, the ecosystem results that may be accomplished under them may be variable and uncertain because the focus of the application of these instruments is on economic efficiency. Groundwater quality and quantity improvements are only potential secondary effects, and their incidence may not necessarily occur where the resource is under stress by water demand or contamination. Therefore, these policies may not be successful in targeting particular locations or circumstances of resource challenge.

The extent to which some approaches encourage conservation of groundwater use or reduced waste disposal underground that may minimize the throughput of groundwater and resources that become residuals, followed by the promotion of maintenance of natural capital in groundwater, will be discussed in detail in subsequent chapters.

EQUITY

Equity and distributional issues are a concern for economic instruments and their Pareto efficiency. If an individual or group cannot be compensated through use of the instrument by the gainers in some way, an examination of whether costs are borne by groups of lower income or otherwise disadvantaged is a concern.

1. User, waste release and product charges and taxes, and subsidies—All of these policies have distribution effects such that low-income users are charged or subsidized at the same rate as high-income users, which is regressive. The focus is on the current generation, not future generations necessarily. Charges, taxes, and subsidies that result in conserving groundwater quantity and protecting groundwater quality do provide for future generations' needs, but the extent to which this occurs is not within the scope of these instruments.

2. Transferable discharge permits—These policies may leave locations of highest need in a worse condition since they might not be able to afford permits and their requirements. Intergenerational protection of the natural capital in groundwater may be protected, but this is not the specific focus of this instrument and may not provide the equity result that this concern raises.
3. Markets for formerly free services—Bidding on formerly free services of groundwater may be a regressive circumstance for low-income individuals and businesses. Low-income groups may be worse off because of lack of access to groundwater. If bidders have uncontrolled use of the resource they have purchased, intergenerational concerns may never be addressed in the effort to maximize profit and take advantage of rent from an increasingly scarce resource.

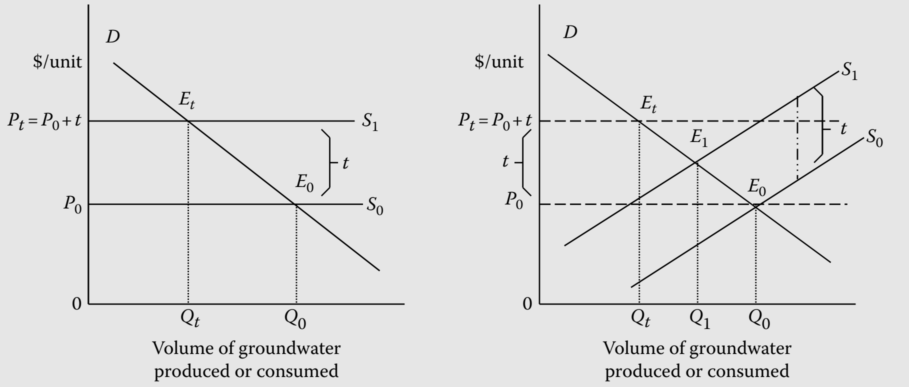
ECONOMIC EFFICIENCY OR EFFECTIVENESS

Water Source User Charges and Taxes

User charges and taxes are different institutional approaches to correct market failure when the resource demand, in this case of water source use, does not have adequate market signals to reflect water scarcity for more efficient allocation. These approaches have the same outcome for the consumer for either the product or the service of the resource. User charges are fees or payments for using a property or service, that is, groundwater and its services, such as water supply and wastewater conveyance. User charges could be assessed based on units utilized, frequency and time of use (during the day or seasonally), and duration of use. Groundwater use could also be taxed based on the unit(s) purchased or consumed. Taxing authority in certain states may be limited to the state, county, or municipal levels. However, charging for use of a property or service may be done by any unit of government for a product or function rendered, which is within its control.

Exhibit 12.6a portrays the result of applying a user charge or tax, t, and in which P_0 reflects the average cost to the groundwater supplier charged to consumers along its supply curve S_0 before the

EXHIBIT 12.6 ECONOMICS OF USER CHARGES AND TAXES ON GROUNDWATER USE



(a) User charge or tax with horizontal supply curve (b) User charge or tax with upward-sloping supply curve

Note: Assume that all units in both graphs are the same and the user charge or tax, t, in both are equal.

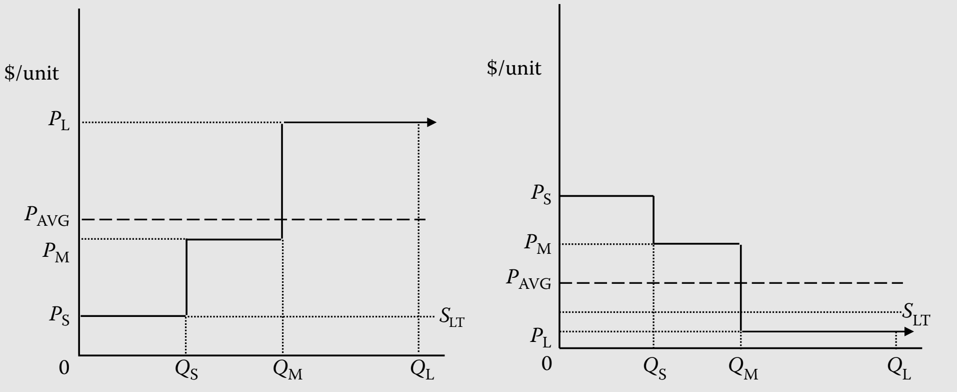
imposition of a tax. The demand curve, D, gives the local demand for groundwater, which intersects S_0 at Q_0, the quantity used by consumers prior to a tax being applied. The tax, t, raises the price of groundwater to P_t, that equals the original price, P_0, plus the tax, t. Consumer response to the tax is to reduce consumption from Q_0 to Q_t with the loss of service of $Q_0–Q_t$ of water. If preferences for water do not change in this example and if the tax goes to the water supplier, the revenue changes from the area under the demand curve of $0\ P_0\ E_0\ Q_0$ to $0\ P_t\ E_t\ Q_t$, which depending on the drawing may be more or less than originally received at price P_0 (inspection of the drawing suggests in this case that it may be less). An equivalent effect on consumers occurs, paying before the tax an amount equal to $0\ P_0\ E_0\ Q_0$, and now paying $0\ P_t\ E_t\ Q_t$ for less groundwater.

In the case of an upward-sloping supply curve for water, say in the case where the water supplier had to buy water from a neighboring municipality to meet greater demands at certain times, and assuming the same demand curve relationship, the quantity reduction in consumption may be less, as shown in Exhibit 12.6b. With an upward-sloping supply curve and the same tax as in (a), the new equilibrium is not at E_1, the intersection of, or balance in, supply and demand, but at E_t, because of the amount of the tax added to the price, now P_t. While the consumer surplus, the area between D, the demand curve, and the line P_0 represented an efficiency gain for consumers, the tax has reduced it to the area between D and P_t to accomplish the maintenance of groundwater in stock for the future through less consumption at present.

Block water rates are one approach to influencing water use in practice, described in Exhibit 12.7. In Exhibit 12.7a, increasing block rates are shown for a hypothetical situation. Q_S units can be purchased for price P_S, $(Q_M–Q_S)$ units can be purchased for price P_M, and $(Q_L–Q_M)$ units can be purchased for price P_L. A purchase can be made for less than the entire block of units, but the price for the block of units still applies across all units in that block. S_{LT} is the groundwater producer's long-term supply curve, in this case. In Exhibit 12.7a, medium use is priced to be about 3 times that of small use. Large users are charged two times the price of medium users at the margin. P_{AVG} is the hypothetical average price across all units consumed for a large user, with the marginal price per unit for large users being above the average price per unit.

Decreasing block rates have an inverse relation to increasing block rates. In Exhibit 12.7b, the marginal price for large usage, $(Q_L–Q_M)$ units and beyond, P_L, is less than the average price, P_{AVG}.

EXHIBIT 12.7 ECONOMICS OF BLOCK RATES ON GROUNDWATER USE



(a) Increasing block rate for water use (b) Decreasing block rate for water use

Note: Do not assume units are equivalent for each graph.

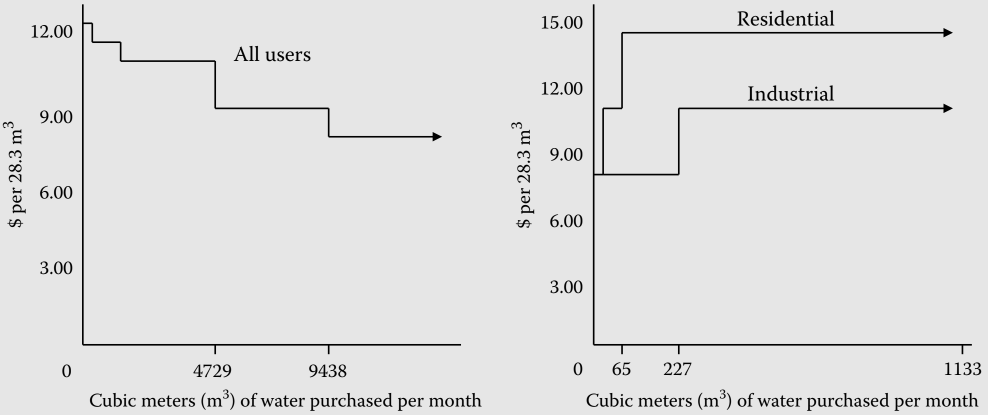
In this example, the large use marginal price, P_{L}, is less than the supply cost given by the long-term supply curve, S_{LT}. This circumstance may not always be true in every case, but does show a situation where a water supplier is using small and medium users' consumption to subsidize the large users.

Increasing and decreasing block rate structures can take many forms. Exhibit 12.8 describes two cities' approaches to implementing these policies. In panel (a), Dayton, Ohio, water rates for 2002 are shown and in panel (b), those for Lincoln, Nebraska, are given. A residential water user (assuming a family of four people) consuming 3300 cubic feet monthly would be charged \$40.36 in Dayton and \$37.17 in Lincoln. An industrial user consuming 400,000 cubic feet per month would be charged \$3911.38 in Dayton and \$4336.00 in Lincoln. Comparing these two approaches, large quantity industrial users definitely pay more under the increasing block rate structure in this example, reflecting a higher marginal value placed on the groundwater in Lincoln as compared with Dayton. Block rate structures can have various forms and not all comparisons would necessarily have this same result. Whether the increasing block rate in this example had the expected outcome of water use conservation by larger water users is a subject for further research.

Water Source—Transferable Water Rights

While groundwater as a source of water supply has been identified as a stock-flow, nonexcludable, and rival resource (see Chapter 3), creation of property rights in water that can be captured through ownership or possession and then transferred offers allocation alternatives for a resource that is becoming scarcer. Transferable groundwater rights are already in practice in some locations. In most states of the western United States and in Mexico and Australia, all places where most groundwater is used for irrigation, rights to groundwater can be owned and transferred (NAS, 1997, pp. 112–113;

EXHIBIT 12.8 EXAMPLES OF BLOCK RATES FOR GROUNDWATER-SUPPLIED WATER SYSTEMS



Dayton, Ohio, 2002 monthly water rates
All water users
First 93 m^3: \$12.23/28.3 m^3
Next 850 m^3: \$11.65/28.3 m^3
Next 3766 m^3: \$10.99/28.3 m^3
Next 4729 m^3: \$9.01/28.3 m^3
Over 9438 m^3: \$8.32/28.3 m^3

(a) Dayton, Ohio—decreasing block rate

Lincoln, Nebraska, 2002 monthly water rates

Residential
First 23 m^3: \$0.79/2.83 m^3
Next 42 m^3: \$1.09/2.83 m^3
Over 65 m^3: \$1.45/2.83 m^3

Industrial
First 227 m^3: \$0.79/2.83 m^3
Over 227 m^3: \$1.09/2.83 m^3

(b) Lincoln, Nebraska—increasing block rate

UNFAO, 2006, p. 24; NAS, 2007, p. 13). Reasons for considering a market-based approach to the transfer of groundwater rights include (UNFAO, 2006, p. 21)

- Traditional land-based approaches not adapted to specific climatic conditions
- Traditional land-based approaches not adequate to allocate water
- Accounting for ecosystem balance
- Recognition of the economic value of water
- Socialist economies transforming to market-based economies
- Regional initiatives
- Support for wider economic reforms and other kinds of social reforms
- Promotion of social goals
- Pressure on water resources

Important characteristics of tradable water rights are (UNFAO, 2006, p. 60)

- Definition of the volume of water associated with the right
- Duration of the right
- Number and content of conditions attached to the right
- Guarantees to the security of the right

Examples of transferable water rights occur around the world. In Arizona, cities running out of water have been purchasing the water rights of farmers who irrigate their agricultural fields. In Australia, water trading (assumed for all water—surface and ground) occurred to grow higher-value crops with 51 trades happening between 2000 and 2002 (UNFAO, 2006, p. 83). In Texas, the Edwards Aquifer Authority has processed 1192 partial sales and lease transfers of groundwater withdrawal rights for 270.7 million cubic meters (219,460 acre feet) (UNFAO, 2006, p. 85). Also, see Easter et al. (1998) for further case studies of water markets around the world.

Bidding among potential water purchasers can increase the price of water. In New Mexico, bidding for water rights ranged from \$14,000 to \$25,000 per acre-foot (\$11.35 million to \$20.27 million per million cubic m; alternatively, approximately \$0.04–\$0.08 per US gal or \$0.01–\$0.02 per L) and higher (U.S. Water News Online, 2006). Groundwater rights sale in Washoe County, Nevada, in 2005 was anticipated to generate revenue of \$15,000 per acre-foot (equal to approximately \$0.05 per US gal or \$12 per m^3) for the county (Washoe County Board of Commissioners, 2005), but water prices rose to \$60,000 per acre-foot in the county that year (Darby, 2007). Note that water costing \$0.05 per gal is worth roughly 25 times the average cost of water supplied for domestic use in the United States in 2007, typically considered the highest value use of water.

Several considerations affecting transferable water rights may result in beneficial economic outcomes. First, security of rights with low transaction costs is a significant factor in whether water transfers occur (Easter et al., 1998, p. 20). Factors reducing the efficiency of water trading include transaction costs, uncertainty in the security of the trade and in ecosystem requirements to be met, and rights to return flows. Initial water rights assignments can include recognition of existing users' quantities of water utilized. Second, trading in the agriculture sector can improve productivity and expand rural income. Third, trading from rural to urban uses provides water to high-value uses and income to farmers. Fourth, transferable water rights may provide a more cost-effective water supply in some locations rather than constructing expensive pipelines, diversions, or other engineering solutions. Finally, equity and the needs of disadvantaged people should be considered in setting up transferable water rights. One approach is to include disadvantaged people in the establishment of transferable water rights (UNFAO, 2006). Easter et al. (1998, p. 21) notes that water markets may thrive if trading internalizes external effects. However, the extent to which such external effects might be addressed is not clear (e.g., the inclusion of community or ecosystem effects beyond the site of production or use may not be priced in bidding on groundwater).

Contaminant Control Policy Relying on User Charges, Taxes, and Penalties

Similar to the economic instruments applied to water source use, user charges, taxes, and penalties may be applied to control contaminant releases, ideally, finding an optimal level for release while minimizing their occurrence in the ecosystem shared with other uses. User charges, taxes, and penalties can all have the same potential effect on the decision of the firm concerning production and waste release options. Again, these added payments by users of apparent waste release are to correct the market failure of free disposal in the ecosystem, from which we have observed damages and costs. Exhibit 12.9 portrays the effects of taxes and penalties on waste releases to groundwater. In panel (a), the intersection of the firm's MNPB curve with the CMD curve suggests a negotiated decision of the firm to choose to produce Q_1. In the ideal situation, the tax level, t, would be set to equal the MD acceptable to the community. The hypothetical level of penalties for waste release (*Penalty*) is set too low to have an impact on significantly reducing the MD from the production of computer chips and associated waste releases. Relative to penalties, the firm would only reduce production to Q_P, where the penalty just equals the marginal net profit benefit to the firm for the last unit (Q_P) produced. In this example, the penalty is set too low, since it does not incorporate the balancing of MNPB and MD. At Q_0, the firm has reduced production and waste release, but MD from contaminants in groundwater are still very large (segment Q_0b). Production at Q_1 is the point at which the tax, t, brings about the balance between the firm's interests for more profit (MNPB) and the public's interest to reduce damages, a socially optimal outcome (Turner et al., 1993, p. 169).

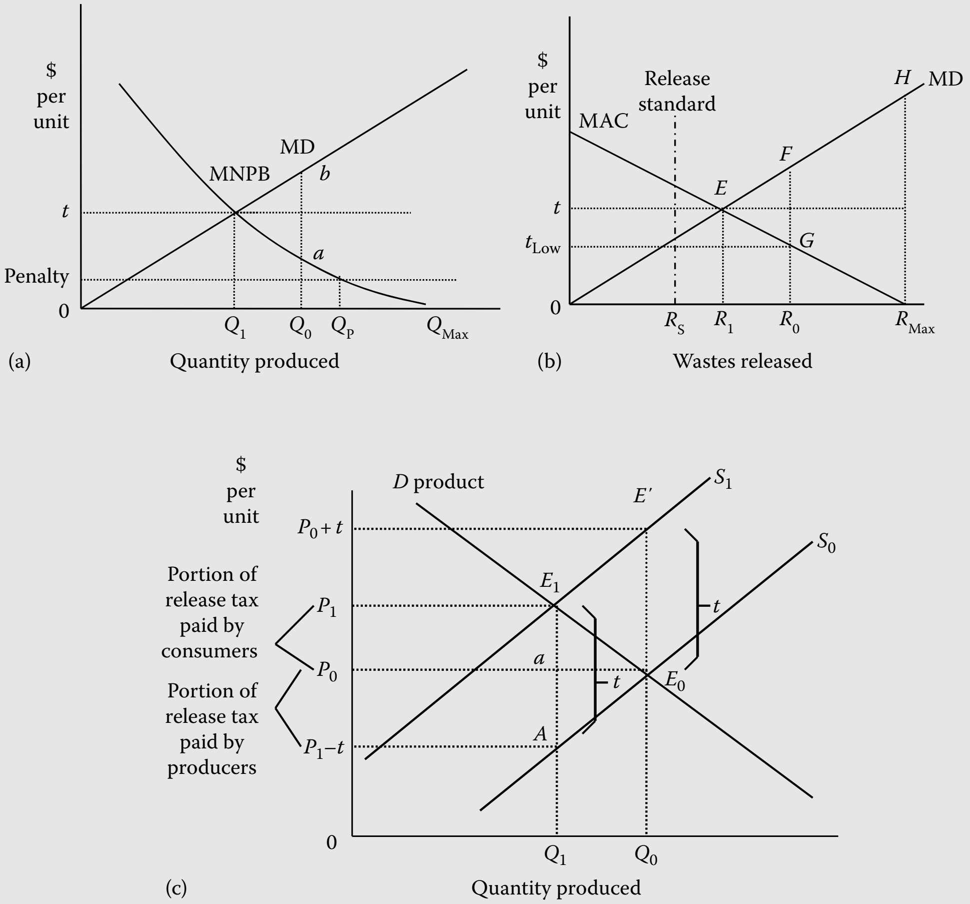
Examining the firm's decisions about abatement controls in panel (b), we see again that the tax guides the firm and community to the point of balancing MAC associated with the waste releases of production decisions with MD. At a tax level of t coinciding with the intersection of MAC and MD in panel (b), waste releases become R_1. Otherwise, the firm may decide to maximize profits and provide less abatement, such as at R_0, or in the extreme case of no waste reduction, R_{Max}. The firm has two kinds of contaminant control costs: (1) abatement and (2) tax. The abatement costs are equal to the area R_1ER_{Max}. Tax outlays are equal to tER_10. If the regulatory agency had decided on a tax rate of t_{Low}, this level would not have incorporated the information to have the MD equal to the MAC. At t_{Low}, the firm would only have had abatement costs equal to the area R_0GR_{Max}, and MD of OFR_0 would have continued. At a production level reflecting R_1, all the damages to the right of R_1 have been avoided.

The governmental regulatory approach should balance private benefit with community damage. If a waste release standard of R_S had been set, MAC would have exceeded MD. These are often the types of costs aggregated across an entire industry and compared with the accumulated damages expected by the public that regulatory agencies attempt to balance. At R_S, an outcome that is not socially optimal would occur: private costs for the last unit produced would exceed any marginal community damage. If the curves of MAC and MD for an entire industry looked similar to those in the graphs, the private benefits (MNPB) at Q_0 in panel (a) and at R_0 in panel (b) would be outweighed by the social damages in a cost–benefit context.

Where concern exists that the taxes collected from firms would far outweigh the MD, the regulating agency could implement a "two-part release tax" (Field, 1994, p. 231). In this situation, no tax would be collected for waste releases up to R_S, for example. The regulatory agency would tax releases greater than R_S at the level of t.

How do the decisions of the firm relate to the results in the marketplace? Panel (c) shows the hypothetical supply and demand relationships. The market equilibrium position, the intersection of the supply and demand curves, is E_0, with Q_0 produced and consumed at price P_0. The supply curve S_0 is the pretax approach for the firm's production. The supply curve shifts upward by the amount of the tax, t, to S_1. Although the supply curve shifts upward, the new equilibrium does not become E', but rather moves to E_1. This new market equilibrium reflects the higher price without any change in the demand curve and corresponds with a new quantity produced and consumed, Q_1, at a new price, P_1. The additional effects of the tax are multifaceted:

EXHIBIT 12.9 EFFECTS OF TAXES AND PENALTIES ON WASTE RELEASES TO GROUNDWATER



(a) Effects of taxes and penalties on a firm's production

Source: Modified from Turner, R.K. et al., *Environmental Economics: An Elementary Introduction*, The Johns Hopkins University Press, Baltimore, MD, 1993, 169. With permission.

(b) Effects of taxes and penalties on a firm's waste releases

Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 230. With permission.

(c) Effects of taxes and penalties on supply and demand

Source: Modified from Turner, R.K. et al., *Environmental Economics: An Elementary Introduction*, The Johns Hopkins University Press, Baltimore, MD, 1993, 172. With permission.

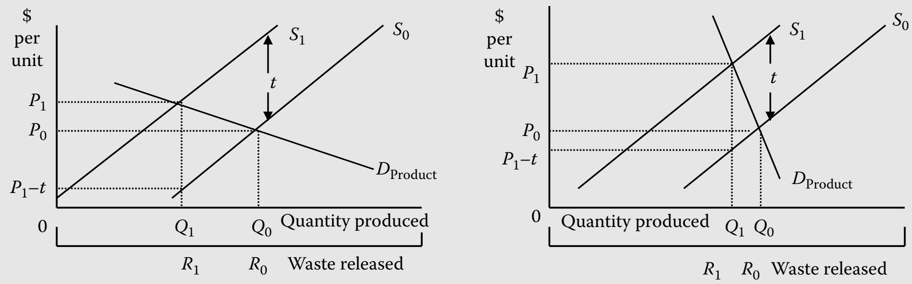
Note: The tax defines the level of production for the firm (panel a) and, thereby, the level of wastes released (panel b), which are reduced because of the tax. The penalty is set too low to influence the operation of the firm (panel a). The tax raises the price to consumers and reduces the quantity demanded by them (panel c). Both consumers and producers pay a portion of the tax (panel c).

1. The consumers pay a portion of the tax equal to the area P_1 P_0 a E_1 and lose consumer surplus of P_1 P_0 E_0 E_1.
2. The producer pays a portion of the tax equal to area P_0 P_1-t A a, while losing producer surplus of P_0 P_1-t A E_0.
3. The tax should be offset by at least equal, or greater, MD avoided, as shown in the other panels.

Additional implications are shown in Exhibits 12.10 through 12.12.

Elasticity of demand for the product produced and offered in the marketplace will affect the change in quantity demanded and the associated waste released. If the demand is more elastic

EXHIBIT 12.10 ELASTICITY OF DEMAND AND EFFECTS OF TAXES

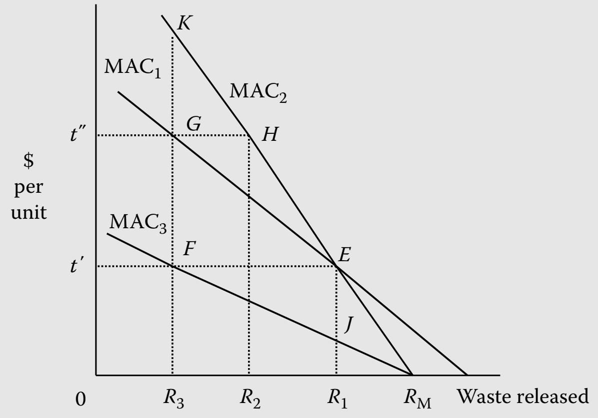


(a) Elastic demand and effects of taxes on a firm's production

(b) Inelastic demand and effects of taxes on a firm's production

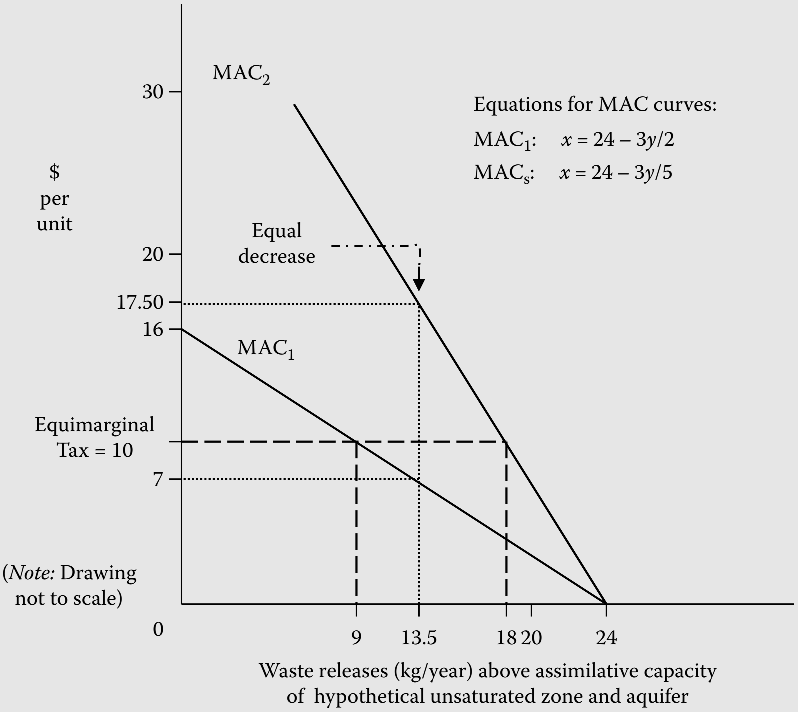
Source: Modified from Turner, R.K. et al., *Environmental Economics*: *An Elementary Introduction*, The Johns Hopkins University Press, Baltimore, MD, 1993, 173. With permission.

EXHIBIT 12.11 UNCERTAINTY, INNOVATION, AND RELEASE TAXES



Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 218, 238, 239, 259.

EXHIBIT 12.12 WASTE RELEASE TAX AND THE EQUIMARGINAL RULE



Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 232.

(the percent change in quantity is more than the percent change in price), response will be as shown in panel 12-10(a). If demand is inelastic (the percent change in quantity is less than the percent change in price), then the effect on the quantity produced and the waste released will be considerably reduced as compared with the more elastic demand situation, as in panel (b). Thus, consideration of the elasticity of demand for production from which the waste was derived is important in evaluating the effect of a tax on reducing contaminants released.

The regulatory agency faces uncertainty in understanding the range of MAC curves of firms releasing a particular waste when a tax approach is applied. This circumstance provides a challenge for both the agency and the firms. Exhibit 12.11 portrays this situation for two firms with two different abatement technologies resulting in MAC$_1$ and MAC$_2$. Ideally, the regulator will set the tax at t', which affects the firms equally and results in waste released of R_1. If the regulator sets the tax too high, such as at t'', Firm 1 modifies its operation to release at R_3, while Firm 2 must reduce releases to R_2. If the tax is set too low (somewhere below t'), more waste will be released than is optimal. Thus, not only does the agency face uncertainty, but the regulated industry must address a range of conditions among the firms affected. Firms with steeper MAC curves will confront a narrower spectrum of outcomes than a firm with a flatter curve, which will have a potentially larger change in releases if the tax is too high or low. Uncertainty for contaminant control technology used by industry drives governmental agencies toward setting standards (Field, 1994, p. 238). Certainly, this has been true for waste releases to groundwater.

A tax on waste releases influences technology innovation for controlling contaminants. Exhibit 12.11 also provides a perspective on decisions firms may make to apply new technology under the scenario of a waste release tax. If the firm has its abatement equipment operating at MAC_2 and a waste release tax is authorized at a tax rate of t' as noted above, it will operate releasing R_1 wastes with contaminant control equal to the area $R_1\ ER_{\mathrm{M}}$ and a waste release tax of $t'ER_1 0$. When the firm decides to reduce its costs by looking into research and development, it may find a new technology that has characteristics of MAC_3. Applying this technology, it now has contaminant control costs of R_3FR_{M} and release taxes of $t'FR_3 0$, with a cost savings of EFR_{M}. Under a tax approach to reducing waste release, the firm has incentive to reduce the combined abatement and tax costs (Field, 1994, p. 239). This circumstance is important in understanding the differences in contaminant control approaches.

The efficiency of a waste release tax is the most compelling point for such a policy. In particular, a waste release tax can be applied to multiple sources without knowing in advance their exact waste disposal levels and affect the discharging sources equally at the margin of their operations. Exhibit 12.12 provides information on two hypothetical sources, 1 and 2, discharging to the subsurface. Discharger 1 employs a technology that has lower MAC, resulting in a flatter (less steep slope) MAC curve. This situation might be similar to applying a newer technology. Discharger 2 uses an older technology with higher MAC. If a tax of \$10 per kilogram of waste released is charged, in-plant compliance costs would be adjusted such that Discharger 1 would reduce its releases from 24 kg per year to 9 kg (a 62.5% reduction), while Discharger 2 would reduce its releases to 18 kg (a 25% reduction). With the same tax applying to all sources, MAC are uniform and the equimarginal principle is satisfied for the purposes of efficiency. Total MAC are \$75 (Discharger 1) plus \$30 (Discharger 2), equaling \$105 with an equimarginal waste release tax.*

How do we know that this is efficient? Exhibit 12.12 shows the total compliance costs for two approaches: (1) "equal decrease," in which both dischargers eliminate the same amount of waste release, and (2) the waste release tax. Both approaches can be set to reduce waste released by the same amount: a total of 21 kilograms per year. Under the equal decrease, both Discharger 1 and Discharger 2 reduce waste releases by 10.5 kg. With the waste release tax of \$10 per kilogram, the result is also 21 kg, resulting in the outcome noted above, i.e., Discharger 1 reduced to 9 kg and Discharger 2 reduced to 18 kg. The exhibit also demonstrates calculation of an equal decrease with each firm reducing waste release by the same amount—perhaps because the regulatory agency believes those results are "fair." Under both approaches, the total compliance cost is the sum of the marginal costs under the MAC curve. Treating both discharging sources the same in terms of volume elimination required under equal decrease, total compliance costs for both sources are \$36.75 (Discharger 1) plus \$91.88 (Discharger 2) equaling \$128.63.† The equimarginal waste release tax compliance costs are \$105. The equiproportionate reduction costs the industry 1.225 times as much as the waste release tax approach and violates the equimarginal principle of efficiency. Furthermore, the waste release tax results are efficient whether or not the regulatory authority understands the MAC of each waste source. Thus, information needs of the regulatory authority are low, but uncertainty may be high relative to volume of waste eliminated. To ensure that wastes do not end up being released to another environmental media, such as the air (as occurs in "air stripping" of contaminants from groundwater contaminated with volatile organic chemicals), the same tax could be applied to all releases of the same waste, avoiding the waste release transfer problem and having an equimarginal result. This assumes that technology (through research) can measure the releases accurately and be responsive to the waste release tax over time.

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* From Exhibit 12.12 for equimarginal waste release tax at Discharger 1, the total compliance costs are (15 waste units × \$10/unit)/2 = \$75, and for Discharger 2, the total compliance costs are (6 waste units × \$10/unit)/2 = \$30. The sum of these costs is \$105.

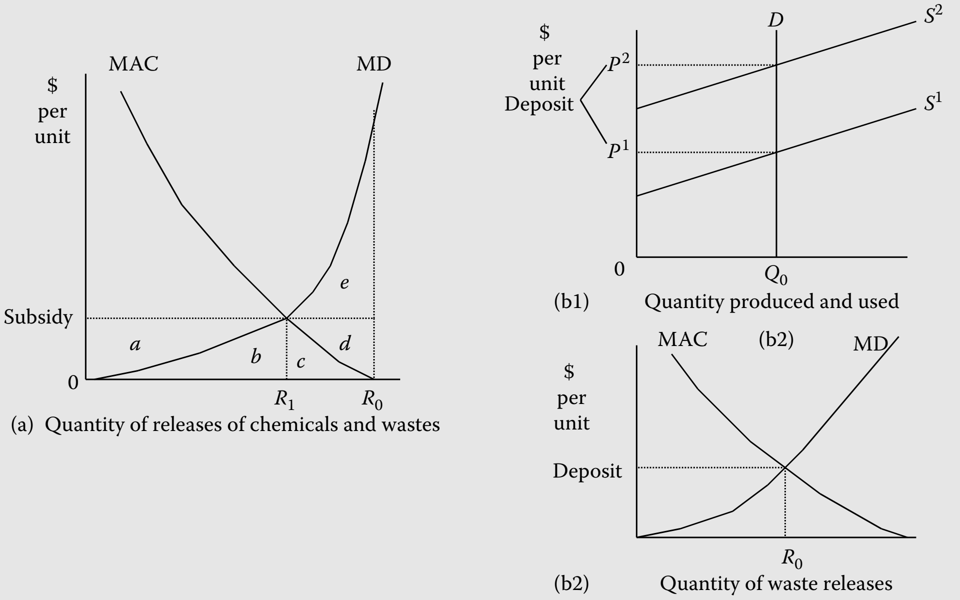
† From Exhibit 12.12 for equal decrease at Source 1, the total compliance costs are (10.5 waste units × \$7/unit)/2 = \$36.75, and for Source 2, the total compliance costs are (10.5 waste units × \$17.50/unit)/2 = \$\$91.88 (rounded). The sum of these costs is \$128.63.

Since groundwater is produced at particular points in the watershed and many sources of contamination may exist upgradient of production wells, consideration of proximity of the source to the wells may also affect how a chemical or waste release tax would be applied. For example, Source A for a chemical in the uplands is 3 miles away and directly upgradient from a city's wellfield and Source B for the same chemical is only 2 miles away. The more distant source will, through dispersion and adsorption, become one-fourth as dilute (assumed for the purposes of this example). The equimarginal rule may still be applied but in zones, based on expected impact to the city's water supply. The damage could be measured in terms of the cost to the city of required treatment and the tax could be used to pay for the treatment. If several sources of contamination exist together in zones upgradient from the wellfield, the sources in the same zone could be taxed the same, but each zone would have a different tax rate based on its impact on the water quality in the wellfield. This is termed "zoned tax" for waste releases and addresses the reality of the contaminant sources spread throughout a watershed and potentially affecting groundwater as well. A similar approach could be taken for releases to a stream (see for example, Field, 1994, pp. 234–236).

Contaminant Control Policy Relying on Subsidies

Subsidies are a payment on a per unit basis to a waste releaser to reduce his waste. If the releaser decides to produce the additional unit of waste, he does not receive the subsidy payment, an opportunity cost of that incremental production. The subsidy works in the same way as a tax, but the firm accounts for it differently. Exhibit 12.13, panel (a), demonstrates the effect of a subsidy that reduces waste release from R_0 to R_1, the objective of the subsidy. Any subsidy approach would require a similar level of monitoring and administration as a tax. In the approach depicted in panel (a), the

EXHIBIT 12.13 SUBSIDIES AND WASTE RELEASES TO GROUNDWATER



Notes: Panel (a) shows how an efficient approach to setting a subsidy might result for a waste release. Panel (b1) indicates the effect of a deposit and return program on the price of a commodity that should be completely recycled (e.g., motor oil). Panel (b2) shows how the deposit might be established. MAC might include consideration of reprocessing and transaction costs to consumers.

EXHIBIT 12.14 A COMPARISON OF SUBSIDIES AND TAXES APPLIED TO WASTE RELEASES TO GROUNDWATER

			Subsidy applied to release		Uniform waste release tax	
Waste releases above AC[a]	(MAC)	Total abatement cost (TAC)	Subsidy at $45/kg	Subsidy subtracting TAC	Taxes at $45/kg	Total (TAC + taxes) costs
(kg per yr)						
100	0	0	0	0	4500	4500
90	50	50	450	400	4050	4100
80	105	155	900	745	3600	3755
70	180	335	1350	995	3150	3485
60	260	595	1800	1205	2700	3295
50	340	935	2250	1315	2250	3185
40	445	1380	2700	1320	1800	3180
30	580	1960	1350	3310	3150	1190
20	700	2660	3600	940	900	3560
10	820	3480	4050	570	450	3930
0	1020	4500	4500	0	0	4500

Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 228, 244.

[a] 65 kilograms (kg) per year is the estimated Assimilative Capacity (AC) for the hypothetical unsaturated zone and aquifer for this example.

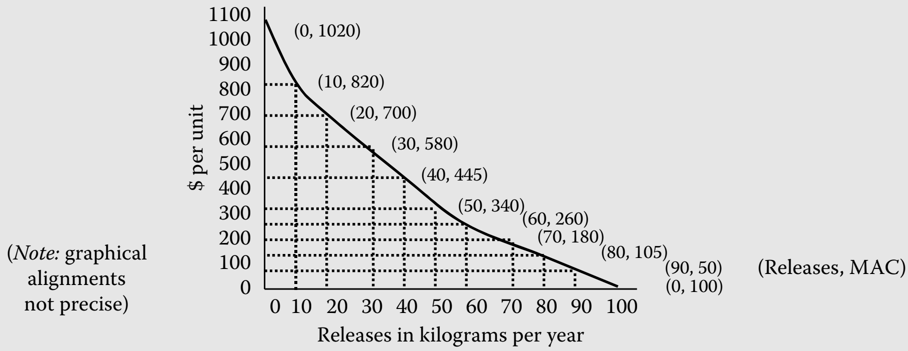
subsidy may be the same monetary amount as a tax, but the subsidy is paid to the supplier of the product only if he or she reduces the waste released. The level of the subsidy is indicated by the line "Subsidy" in panel (a). The amount of the subsidy for reducing the waste release is area ($c + d$). This efficient position assumes that technology is available to enable the firm to have the MAC indicated in panel (a), and the MD are then reduced by ($c + d + e$) under the MD curve.

How do a waste release tax and a subsidy differ in terms of the effect on the decisions of firms in an industry? Exhibit 12.14 shows the comparison of a tax and a subsidy of the same amount ($45 per kilogram of waste) in this circumstance. This example assumes that 65 kg per year is assimilated without damage to human health or the environment. In the case of the tax (right side of the exhibit), the firm would seek to operate at a level that minimizes its total waste release cost, considering both abatement costs and taxes. In this case, total costs are minimized at a waste release of 40 kg per year, resulting in total costs of waste release of $3180 per year (the sum of the MAC up to 40 kg per year). With a subsidy of the same amount ($45 per kilogram of waste), the firm seeks to minimize costs or maximize revenue from the subsidy. In Exhibit 12.14, this position is $1320 (maximum revenue from the subsidy) with the waste release result of 40 kg per year, the same as for the tax approach. For the waste releaser, the subsidy serves as an opportunity cost. If the firm decides to release a volume of waste, it is giving up the subsidy that it could have received had the firm decided not to release the waste (Field, 1994, p. 243).

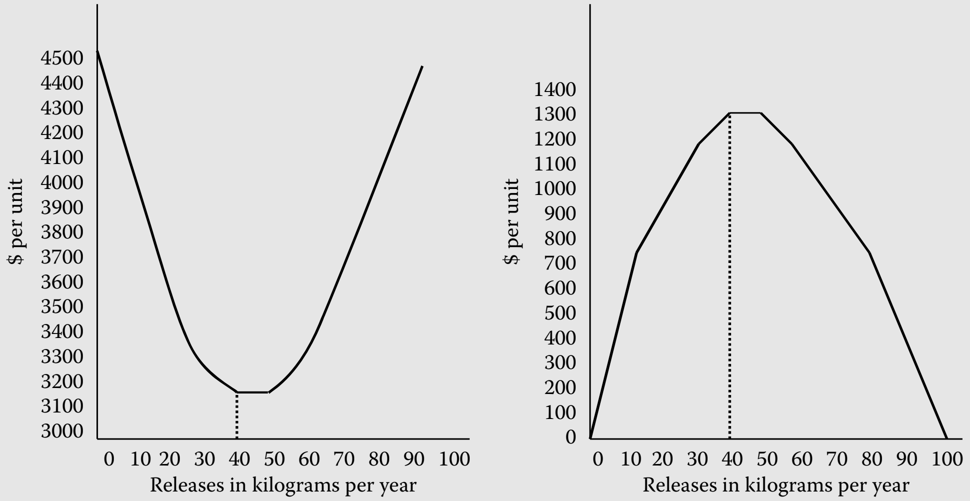
Exhibit 12.15 displays the graphical results for Exhibit 12.14 for MAC, total costs with tax, and total subsidy minus total abatement costs. The point of these graphs is to show how a firm would view its costs relative to a tax versus a subsidy approach, with the resulting operating decision being the same.

Applying the subsidy to an entire industry or set of industries that release the same waste can have the potential perverse effect of increasing the waste released from the intended levels. First, in anticipation of the subsidy, the firm or industry may decide to increase its releases to increase its base waste releases, on which the subsidy determinations might be calculated. Second, because of

EXHIBIT 12.15 GRAPHICAL CONSTRUCTION OF TAXES AND SUBSIDIES FROM EXHIBIT 12.13



(a) MAC curve construction



(b) Total costs with tax

(c) Total subsidy minus total abatement cost

Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 228.

the position that a subsidy puts the firm in relative to maximizing revenue from the subsidy, new firms may be attracted to the industry, increasing total waste releases in the future. More complex subsidy approaches would need to recognize such unwanted outcomes.

The use of deposit and refund is a method for controlling wastes from products that are discarded partially or entirely and reducing impacts on groundwater and other ecosystem resources. The deposit is the tax on the about-to-be-used product and the refund is the subsidy to encourage recycling the used product. Germany placed a deposit refund on lubricating oil that was discharged after use. In this case, the deposit tax went to set up a fund that subsidized collection of the waste oil to reclaim it for future use. The deposit was an incentive to minimize oil contamination. The subsidy program provided incentives for competition among waste oil processors (cited in Field, 1994, p. 245, from Bohm, 1981).

The general economic results of a deposit-refund program are depicted in Exhibit 12.13, panels (b1) and (b2). In (b1), the deposit is reflected in the increase of the price from P^1 to P^2, and the corresponding shift of the supply curve from S^1 to S^2. If this product for which a deposit is required is itself the waste when it is used, such as for oil or other process chemicals, then the efficient level of deposit is shown as "Deposit" in panel (b2). The "Deposit" balances the MAC, convenience transaction costs to users who recycle, and costs of reprocessing, with the MD, such as contaminated groundwater and its affected services to water users.

Contaminant Control Policy Relying on Product Charges

The application of charges to (or fees for use of) products that, once used and disposed, could contaminate groundwater has the same basic economic outcomes as taxes on the product. Exhibit 12.9, panel (c), shows this result. The charge raises the supply curve from S_0 to S_1, and the price to consumers to P_1. Consumers pay a portion of the charge and producers pay the other part, with the net outcome of production being reduced from Q_0 to Q_1 at the higher price.

Contaminant Control Policy Relying on Transferable Release Permits

A common strategy of regulatory authorities to control waste and chemical releases to groundwater is to issue "permits" for a specified amount of waste or chemical discharge to the ecosystem, including groundwater. A number of states in the United States, such as Iowa and New Jersey, have instituted these permits for releases to groundwater. A major assumption relative to public health or ecosystem protection is that the permitting authority knows the correct volume that will be rendered harmless by the time it reaches the first receptor of a permitted contaminant. The permit recipient, also known as the permit holder, is given the right to release a specified volume of waste or chemical. A recent approach to this transaction is not to make the relationship solely between the regulatory authority and the permit holder, but also among permit holders, termed "transferable release permits," which become a property right. The transfer is brought about by the self-interests of the potential waste releasers to optimize their abatement costs at the margin within the regulated aggregate of releases permitted. In the transferable permits case, depending on the MAC of a firm, it may buy or sell permitted release units that the regulatory authority makes available to firms that release the specified regulated contaminants. The regulatory authority may set the initial price, may offer the permits for bid among the potential permit holders, or may establish a minimum price for the permits in perpetuity, which serves as an internal tax on the firms within an industry. The regulatory authority may decide to take a percentage of each transaction per release unit or may charge a uniform amount per transaction to cover its administrative costs. Fundamental to the function of a market for waste and chemical release permits is that knowledge of their prices be commonly known to all potential permit holders. This condition satisfies the equimarginal principle for permits to be exchanged at the market price.

Transferable release permits offer a market approach for a limited amount of waste releases as a more efficient way to control contaminants in the environment. In the United States, the Environmental Protection Agency established a "Water Quality Trading Policy" on January 13, 2003, because "market-based approaches such as water quality trading provide greater flexibility and have potential to achieve water quality and environmental benefits greater than would otherwise be achieved under more traditional regulatory approaches" (USEPA, 2003). Examples cited with this policy for water quality transferable release permits in its "References" do not include releases to groundwater. In a transferable permit market, the government or central authority determines the supply of permits that it desires to manage to reduce waste releases to groundwater within a predefined limit, ideally set based on ecosystem objectives. Industry has a demand for such permits, because it desires the rights to release wastes within the predefined waste limit on which the number of permits is based, or may otherwise not be able to operate its production facility. Typically, some amount of waste release needs to be eliminated because health or environmental standards are not being met, or at least release levels need to be maintained within these standards and not expanded further. This creates a "supply and demand," which may be graphed as the two respective curves intersecting as in Exhibit 1.8. The intersecting supply and demand curves identify the price for the transferable release permits for a quantity of permits to be supplied by the government and demanded by the industry.

Setting the number of permits to be exchanged in the market is the principal challenge of the regulatory authority and a key action that will influence permit price. The authority may set the quantity of permits allowed to be exchanged in the market by understanding the MAC in the industry with the expected units of waste. Other factors affecting price determine who can own permits: only current firms with the target wastes, new firms, or environmental organizations, and then only local firms and organizations, or national ones, as well as the extent of monitoring and enforcement of violations and penalties. Cheating among permit holders reduces the demand for and price of permits. Since groundwater is typically managed as a local resource, unless conjunctively managed with surface water, its future quality is affected by all these factors in a transferable release permit market.

The transferable permits as a property right serve as an inducement to seeking ways to reduce costs of operation in eliminating waste releases. Exhibit 12.11 shows a result from technology innovation that also applies to the response to transferable permits. In the case of transferable permits, assume that t' indicates the transferable permit price with technology that provides current contaminant treatment at MAC_2 and results in R_1 units of waste released. With the ownership of transferable permits affecting the costs of business in the industry, firms engaged in research and development for technology to lower abatement costs can realize reduced operating costs and sell their now "surplus" permits (Field, 1994, p. 258). At R_2, the firm's abatement costs are equal to the area $R_1E\,R_M$. If the firm can deploy technology with marginal costs reflected in MAC_3, waste releases and costs are significantly changed. At permit price t', the firm now will operate with releases of R_3 having abatement costs of $R_3F\,R_M$ with the opportunity to sell its excess permits for $t'(R_1–R_3)$ in revenue, equaling the area R_1R_3FE. The firm's cost and revenue status is $(R_1E\,R_M)–(R_3F\,R_M) + (R_1R_3FE) = (R_MFE)$. This is the same outcome as if the permit market price were a waste release tax, as shown previously in Exhibit 12.11 (Field, 1994, p. 259). So, transferable release permits may be an alternative economic instrument to a waste release tax in certain institutional or political settings.

A transferable release market could work in the ways described above for groundwater, whether controlling chemical applications with resultant residues in agriculture or other subsurface disposal means for point sources of contaminants, or carbon dioxide sequestration in the subsurface. As groundwater demands increase and marginal costs of public health and ecosystem externalities become well understood, transferable permits that allow the market to determine prices for the value of waste-processing services of the subsurface from place to place will be of greater interest and use. These may also promote further innovations that could additionally reduce waste releases.

MARKETS FOR FORMERLY FREE SERVICES

The range of free public services of groundwater and the subsurface environment have been given poor attention. One attempt to categorize these services found that groundwater provided 13 known services as a stock resource and 18 known services as a flow resource (Bergstrom et al., 1996). Other unknown services have obviously not been considered. Most of these services are public and are taken and used as free. For example, corporations that have liquid chemical wastes that cannot be discharged into surface waters for environmental protection or business economic reasons may apply for a permit to inject them deep into the earth under the Underground Injection Control Program in the United States established under the Safe Drinking Water Act. A similar program exists in the European Union and other countries. While the corporations may have to incur the cost of preparing a permit for an injected discharge, treating the liquid waste to a certain level of quality, and injecting it into the subsurface, the value of the subterranean environment as a disposal site is not considered. Technically in underground injection, the deep site is considered to be a "no-migration" zone, meaning that no movement of the waste from the injection zone is expected to occur. To establish a market for such disposal, the government could create "deep disposal zones" controlled by it and auction them off. This action could potentially provide inducement for research to treat these liquid wastes more cost effectively.

Considering climate change and the potential for using the subsurface environment for disposal of carbon dioxide, auctioning tradable permits to inject the unwanted gas into deep geologic formations would provide an exchange value in the market. This bid value would serve as the basis for establishing a *portion* of the measure of value for the subsurface environment as a disposal zone, rather than valuing it at zero, as is the current practice. Transferable release permits for carbon sequestration offer the possibility of further efficiencies in larger carbon dioxide reduction and management that potentially affect groundwater. If transferable release permits for carbon dioxide are not offered for all receiving media (air, water, and underground), carbon dioxide will be released to the media with no or low value, given this framework. Considering the evaluation criteria presented here, bidding to establish a value for the use of the deep subsurface environment as a disposal zone might occur once the state trust obligations are defined by a clear, publicly accepted statement of detailed and measurable objectives for the resource. The maximum bid value would be a minimum economic value since we do not have complete knowledge of the inherent ecosystem purpose and function of this zone. To consider the bid value of the disposal services of the deep subsurface, anything other than a minimum economic value would be similar to mining groundwater in the twentieth century and being oblivious to the possibility of land subsidence and saltwater intrusion, because they were not in the realm of our understanding at the time of initiation of groundwater use in those areas. The value of the upper strata support by groundwater in maintaining a stable ground surface for economic activity was not included in the value of groundwater for the purposes to which it was applied at that time. Our understanding of groundwater, its movement, and quality is considerably greater now, and we are capable of identifying formerly free services—at least a portion of them—that we should take into account.

REMAINING CRITERIA FOR EVALUATING ECONOMIC INSTRUMENTS

Policies for economic instruments provide unique possibilities for conserving and protecting groundwater, which when evaluated through the remaining criteria indicate the following:

Dynamic Incentive

Many of these policies stimulate research and other innovation to respond to increased prices to the consumer. Taxes on excessive groundwater use and waste release promote a demand for research to identify alternatives that can lower the cost of use and waste disposal.

Low Information Requirements

All these policies all require monitoring of groundwater and tracking of the information by a central agency or jurisdiction. Depending on requirements and their implementation, this monitoring may be a substantial expense. This expense could be incorporated as a cost of doing business and would likely raise consumer costs incrementally, but be spread over many units of groundwater storage and production so the effect may be minimal. The "correct" level of taxes and charges requires information, which may be developed through "trial-and-error" approaches to reduce information needs in the longer term. Thus, significant information may be needed to implement economic instruments as a means to conserve or protect groundwater. With the advent of secure electronic data exchange, these requirements may become less costly.

Low Administration Cost

Setting taxes and charges does not require substantial administration; however, ensuring that the expected environmental performance is occurring will be an administrative burden. This is also true for transferable discharge permits and for markets for formerly free services. Product charges can be accommodated by existing administrative systems, but establishing the level of charges that are efficient may require "trial-and-error" approaches or substantially more information. The administering central authority would need to devote resources to examine the monitoring results to ensure compliance and fairness.

AGREEMENT WITH MORAL PRECEPTS

Accomplishing positive environmental results at the least but fair cost is in alignment with good governmental objectives and commonly accepted practices. Ensuring that groundwater services that are used are paid for by the users is fair exchange. The challenge to moral precepts is whether it is acceptable to charge poorer people high rates for water and what little they may need to be disposed. Offering "life line" or subsidized rates to low-income people is one alternative to address this concern and deserves further economic evaluation along with other alternatives for responding to this issue.

ENVIRONMENTAL PERFORMANCE STANDARDS

The most widely used environmental policy is the standard within which water use or contaminant concentrations must be maintained or be out of compliance and in violation of the law or regulation that applies. As previously defined, an environmental performance standard is the maximum or minimum level of performance to be allowed in or with the resource, typically applied to the concentration of contaminants, amount of use of water, technology applied, or process steps followed. Environmental performance standards may include quantity limits; contaminant concentrations in ambient environment, releases or emissions, and content; and specific requirements for technology and best practices.

ECOSYSTEM SCALE

Environmental performance standards may have the greatest applicability to addressing ecosystem scale, in particular, for policies of quantity limits and contaminant concentration controls in groundwater. Typically, such standards are applied to the related activities of an entire jurisdiction, which may be a town, state, or nation. In turn, the standards may be managed at an aquifer or watershed basis for groundwater. The potential to address interests in maintenance of natural capital in the ecosystem for groundwater is expected to be higher for performance standards, because specific targets would be identified for achievement by a groundwater-using or contaminant-conveying activity. The challenge to ensure maintenance of natural capital through environmental performance standards is whether they are directed to specifically do so, or are adopted for other environmental reasons. This latter point is a central aspect of sustainable development further examined in Chapter 14.

POSITIVE ECOSYSTEM RESPONSE

Environmental performance standards are specifically focused on improving the condition of groundwater for both quantity and quality, if they are in place and operative. While these standards are set fairly precisely, they are developed typically through a risk assessment and laboratory-testing process, rather than considering and observing larger ecosystem effects, which may be assumed to occur. Thus, these standards are proxies for expected ecosystem outcomes, representing best judgment based on the capability available to evaluate the ecosystem issue at hand.

Often, environmental performance standards also address human health, such as standards for maximum allowable contaminant concentrations in drinking water. However, removal of some contaminants from water may produce a waste needing disposal. Balancing the costs of achieving health effects with the costs of properly disposing of waste releases is a challenge for health and ecosystem maintenance, and is often addressed through cost–benefit analysis.

EQUITY

Standards appear to be uniform and treat all entities affected in the same way. However, they may be able to be implemented to take into account regional considerations related to groundwater quality and quantity. Certainly, performance standards for groundwater can be implemented at various levels of government, which may each recognize the relevant aspects of groundwater at their respective scales. The result may be a variable standard, depending on the factor being controlled. Standards may be tailored to particular segments of society. For example, health and safety protection standards may apply everywhere but be set at more stringent levels for sensitive or vulnerable populations.

ECONOMIC EFFICIENCY AND EFFECTIVENESS

The standards approach is also referred to as "CAC": the standard is set under law and is expected to be adhered to by all to whom it applies. Environmental performance standards are popular and in wide use because they (Field, 1994, pp. 206–207)

1. Seem simple, typically a number representing a quantity limit or contaminant concentration, such as 10 ppm
2. Specify a target: a particular volume of water or a concentration for a certain contaminant
3. Identify the entity affected directly, usually in terms of a category: water suppliers, landfills, or chemical users
4. Provide a sense of fairness: all entities must respond to the same target
5. Give a clear legal definition of right and wrong: either within the standard or not

In practice, environmental performance standards may be more complex and provide more flexibility in implementation and enforcement than is apparent. The choice of standards best applied to groundwater quantity relative to production or quality considering many potential point and nonpoint sources is not obvious since the subsurface physical processes are difficult to observe (USDA, undated, p. 59).

Water Source Quantity Limits

For quantity limits, the approach may be to attempt to manage around a groundwater production level that conserves water for long-term supply. Exhibit 12.16 provides a look at the economic significance of such a limit for water supply. Typical pricing policy for water might allow shifts in the demand curve as population grows from D_{POP1} to D_{POP2} as in panel (a), while the price remains the same. These demands result in groundwater quantities q_0 and then q_1 being produced from the aquifer. At price $P_{0,1}$, revenues increase as demand has grown and shifted, assuming the same preferences reflected in the shape of the demand curves for water use by the community. However, the marginal cost of the groundwater produced is above the price, and may be nearly vertical as MC approaches q_{safe1}, the safe yield for the aquifer. In fact, at q_1, the aquifer is being depleted, being used at a rate that exceeds the safe yield, resulting in less groundwater being available in the aquifer. If the safe yield limit, q_{safe1}, had been imposed for the situation in panel (a), groundwater production is assumed to have stopped increasing at that point, regardless of new population demands. The added marginal costs may include increased pumping expenditures for producing groundwater from greater depths, land subsidence, and dry streams once supplied by groundwater with baseflow.

In panel (b) of Exhibit 12.16, the expanded population demand, D_{POP2}, has a new demand curve that provides for conservation (perhaps through low-flow showerheads, controls on lawn watering and car washing, and other restrictions) combined with marginal cost pricing through a block rate structure that keeps the demand less than q_{safe2} without a standard. Without a pricing policy of P_2, the expanding population would consume more groundwater, as in panel (a). Such a pricing policy reflects the social costs of supplying more groundwater in a groundwater-limited situation.

EXHIBIT 12.16 ECONOMICS OF SETTING MINIMUM WATER TABLE (SAFE YIELD) REQUIREMENTS

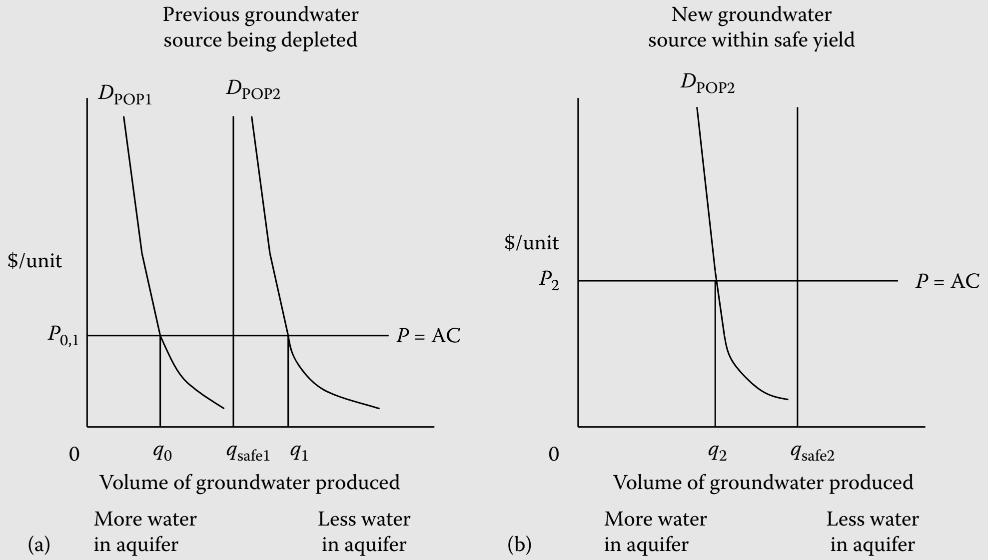
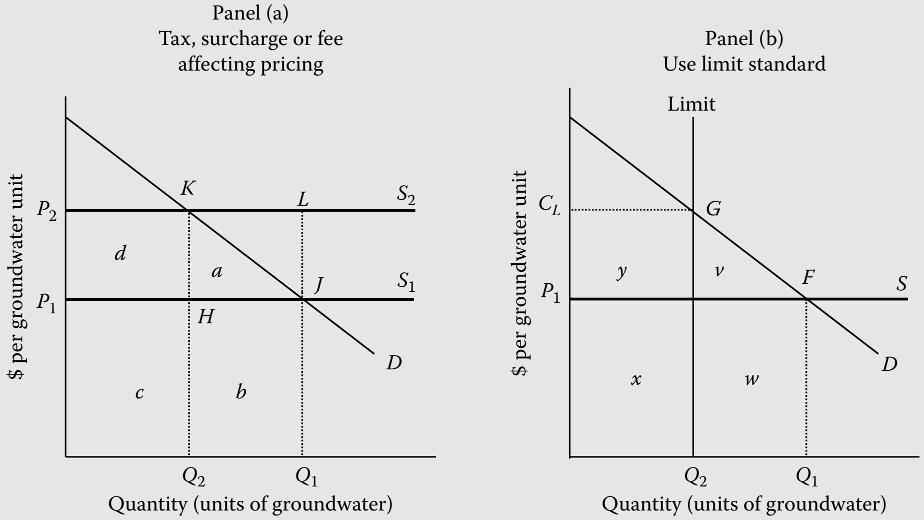


Exhibit 12.17 indicates the difference between a tax or other charge and a groundwater use limit standard. Panel (a) shows that with a tax equivalent to the line segment JL, supply costs rise by that amount from supply curve S_1 to S_2. With this tax and assuming that groundwater in the application being taxed has a demand curve sensitive to price changes, demand declines from Q_1 to Q_2. The cost to consumers

EXHIBIT 12.17 WATER CONSERVATION PRICING VERSUS USE LIMIT STANDARD

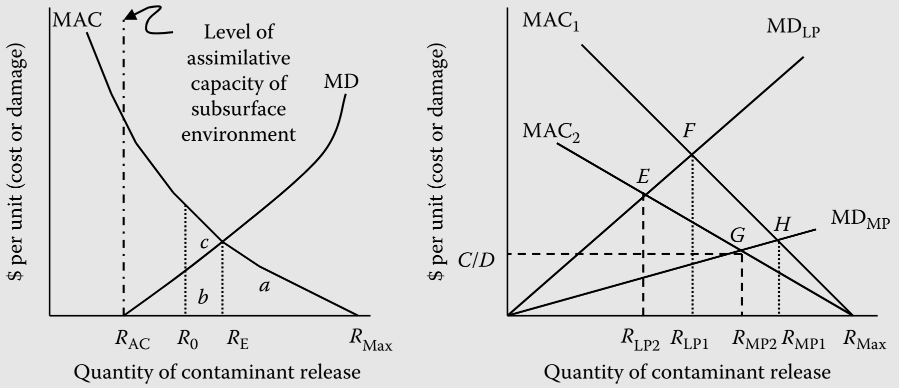


for Q_2 units of groundwater equals $c + d$. With a use limit standard in Panel B, Q_2 is again the resulting output; however, the jurisdiction may not desire to raise raise the price above P_1 but still rely on enforcing the standard to maintain the output level. In this latter case, consumer costs for Q_2 units supplied are x. If the community enforces the use limit standard, it will have costs to do so equaling y. Thus, the total costs of supplying Q_2 are $x + y$ of which x are costs to consumers and y are the enforcement costs of ensuring compliance with Q_2 (C_L–P_1 for each additional unit) to the community (which may be in the form of a surcharge on residents and businesses but not in direct proportion to water use).

Contaminant Concentration Limits in Ambient Environment, Releases/Emissions, and Content

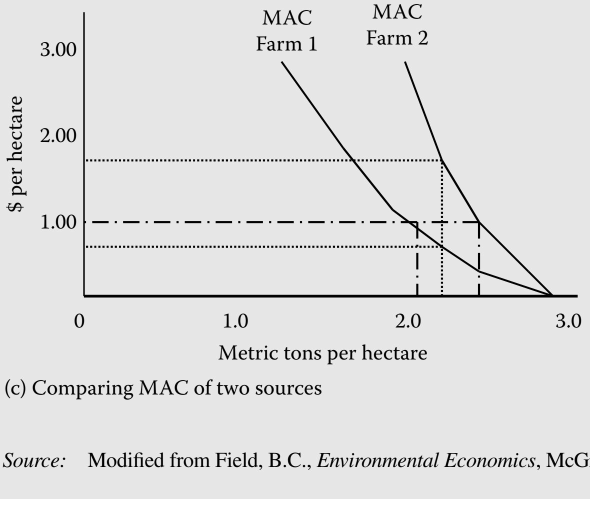
The control of contaminants in the ecosystem through setting of performance standards for their concentrations in the environment, in releases, or in the content of a product is probably the most widely used approach for protecting the ecosystem and public health from contaminants. As noted above, such standards are widely used, because they appear fair and easy to apply. They can be quite complex in their implementation. Exhibit 12.18 describes the general economic effects of contaminant control standards. Panel (a) shows a contaminant release standard of R_E based on negotiation between

EXHIBIT 12.18 ECONOMIC EFFECTS OF STANDARDS TO CONTROL GROUNDWATER QUALITY



(a) Contaminant release standard

(b) Efficient conditions in different locations



Contaminant release (metric tons/ha)	MAC ($ per hectare) Farm 1	Farm 2
3.0	.00	.00
2.9	.05	.16
2.8	.11	.34
2.7	.18	.55
2.6	.26	.76
2.5	.35	1.00
2.4	.45	1.26
2.3	.55	1.54
2.2	.68	1.84
2.1	.81	2.16
2.0	.95	2.50

(c) Comparing MAC of two sources

Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 207, 214, 215.

the firm and the community with an understanding of MAC and marginal social damages. In this example, R_{Max} represents no abatement of the release to groundwater; i.e., all the waste is released to the subsurface, ultimately to affect the quality of groundwater and then the services for which it could be used if its quality is important to those uses. R_{AC} is the assimilative capacity of the subsurface and groundwater for a limited amount of the contaminant to be controlled through the standard. In setting a contaminant concentration standard, R_{E} would represent the efficient outcome. This is the ideal economic position with full information available for both the community and the contaminant releaser. The challenge is that considerable information is needed to arrive at this position: the MAC at each increment of contaminant release of all the dischargers of the contaminant of concern and the MD costs to all the groundwater users for each unit of contaminant released. Research would likely be needed to establish this outcome. To enforce R_{E}, the government would have to establish a process to reliably measure the concentration of the contaminant in the releases of all dischargers. If the local government does not know the ideal position for the most efficient standard, it might establish a standard above the assimilative capacity (R_{AC}) at R_0, closer to R_{AC} than ideally efficient.

Why is R_{E} the economically efficient position? At R_{E}, the MAC to reduce the contaminant concentration just equal the MD: the gainers (those benefiting from using groundwater as a contaminant disposal sink and conveyance away from the location of release) could ideally compensate those damaged by their action. This is so because the abatement costs, represented by the area a below the MAC curve between R_{Max} and R_{E} in panel (a), are substantially less than the damages, the area below the MD curve and to the right of R_{E}. To the left of R_{E}, the MD are significantly less than the MAC. Position R_0 is not efficient in controlling the contaminant since the releaser would pay abatement costs of $a + b + c$ in panel (a), which are more than a at the efficient outcome of R_{E}. Furthermore, the releaser would pay $(b + c)$, which is substantially more than the damages incurred at R_{E}. The challenge is that at any contaminant release point above R_{AC}, community ecosystem damage occurs and the community has to decide whether it is willing to accept the damages at R_{E}. If the community is not willing to accept the damages at that level, it may mean that it undervalued the damages in the negotiation process.

Environmental performance standards relating to controlling contaminants in groundwater and its products generally fall into the categories of (1) ambient standards, (2) release or emission standards, (3) technology standards, and (4) content standards, as described here.

Ambient Standards

Ambient standards are concentrations of contaminants determined to be an acceptable level in the environmental media, groundwater in this case, set under law (usually through interpretive regulation developed through a public input process). For example, in an agricultural area where nitrate fertilizer is applied routinely to increase crop production, the local government may have found through monitoring of the water supply that nitrate in the groundwater is above the health-based standard for drinking water. Because groundwater may be used widely in the area for public and private water supply and nitrate fertilizer is also applied to the ground surface widely, the government may decide that the most cost-effective approach to reduce nitrate in the long term is to enforce a nitrate standard in the groundwater source. This approach would also require monitoring of the water source by sampling wells. In this case, the government's implementation of the standard may require that any farmer whose monitoring well samples have contaminant concentrations that are above the standard must begin to reduce the nitrate applied to his soil until his water samples are below the standard. Another example is the testing of groundwater around the perimeter of a landfill to ensure that ambient concentrations of contaminants disposed in the landfill do not reach a certain level, which can trigger a remedial response. Thus, monitoring and compliance costs would be added to operating costs.

Release or Emission Standards

Release or emission standards are concentrations of contaminants that must not be exceeded in the volume being released or emitted from chemical, biological, or radiological waste generation that is allowed to be placed in or percolate through the subsurface and affect the quality of groundwater.

Typically, under a release standard, a waste releaser would submit an application to the legal administrative organization (a governmental unit) that oversees the standard to receive a permit to emplace the waste in the subsurface. The administrative organization would indicate in the permit the concentration allowable to be released. The administrative organization may take into account the natural assimilation capacity of the subsurface if that is known and if the law allows that consideration. An example is the requirement that liquid wastes injected into the subsurface (called "injectate") through wells must not have concentrations of specified contaminants above the legally established levels before the injectate is pumped down the wells, often under pressure.

A range of types of release standards may include (Field, 1994, p. 209)

- Release rate (e.g., volume per minute)
- Release concentration (e.g., parts per million of nitrate)
- Total quantity of residuals (e.g., rate of release multiplied by contaminant concentration multiplied by length of time of release)
- Residuals per unit of production
- Residuals concentration per unit of input
- Percentage elimination of contaminant

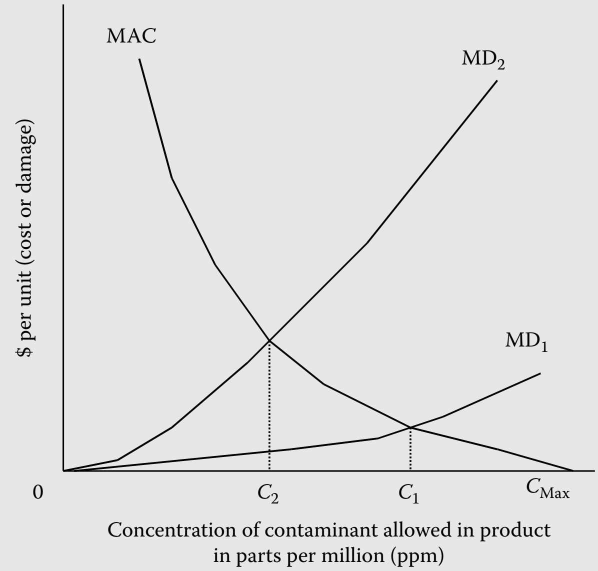
Exhibit 12.18, panel (b), indicates that different locations may have varying efficient outcomes for contaminant release standards, depending on technology deployed and damage response of the communities. In location LP, the MD from a particular contaminant release to groundwater would be $\mathrm{MD}_{\mathrm{LP}}$, while in location MP, the MD would be $\mathrm{MD}_{\mathrm{MP}}$. This variation in MD may be due to the natural assimilative capacity of the subsurface and groundwater in the different places. Additionally, because of surficial, subterranean, and institutional differences, different technologies may be employed more effectively based on these characteristics. If the administrative authority working with the communities and the multiple contaminant releasers in the areas affected can determine the extent of damages from the releases, and if the law allows standards to reflect differences in local conditions, then targeted standards could be developed. In the case of panel (b), this circumstance results in a release standard range of R_{LP1}–R_{LP2} for location LP, reflecting the intersections of MAC_1 and MAC_2 for the firms in the industry and $\mathrm{MD}_{\mathrm{LP}}$. Similarly, R_{MP1} and R_{MP2} give the efficient outcomes for location MP for the two technologies. Notably, community MP and technology MAC_2 have the lowest cost outcome, indicated by intersection G with a cost and damage result of C/D, but not the outcome that has the least amount of waste release, which occurs at intersection E. Such a circumstance might occur when aunderground zone of contamination is closer to the surface affecting the health of people to a greater degree and enabling a less expensive technology to be deployed. Thus, different efficient standards may be based on the location and conditions of the release.

Content Standards

Content standards relate to the concentration of contaminants allowed or accepted in products in use. One of the best examples of content standards for groundwater products is the maximum contaminant levels established for drinking water from groundwater sources. In the case of drinking water, these content standards are established based on health effects research and contaminant risk assessment. Drinking water results from groundwater production and is sold commercially by both public water systems and by water-bottling companies. Economic analysis of content standards is similar to that of contaminant release standards.

Exhibit 12.19 presents an economic analysis of content standards. Ideally, the MD of allowing some level of contaminant in drinking water can be fully evaluated to provide comparison with marginal costs of abating that contaminant. At C_{Max}, no contaminant is removed from the drinking water supplied from groundwater. Under hypothetical circumstances, research may indicate that the current standard, C_1, is not sufficiently protective of public health, and that a much lower level would be a significant health protection improvement. The content standard may change and could

EXHIBIT 12.19 ECONOMICS OF CONTENT STANDARDS



be evaluated in terms of the capability of the treatment technologies available to attain that lower concentration. If the only way to ensure that lower levels can be attained is by instituting greater treatment, then the marginal cost curve (MAC) should be evaluated relative to the now recognized MD to establish the new efficient level in drinking water, in this case C_2.

The United States, European Union, and other countries, which have adopted World Health Organization standards, have content standards for drinking water (for example, see Exhibits 6A.4, 6A.6, and 6A.7). These are based on consideration of damage costs and treatment costs. Whether they are the efficient outcomes for each contaminant needs to be determined, since some of the damages may not be easily evaluated in monetary terms.

Technology Standards

Technology standards are requirements to use certain equipment in specified ways to reduce contaminants in water or other environmental media. For example, requiring certain levels of disinfection for microorganisms in water would be considered a treatment standard. The water would be tested to determine whether the organisms survived and, if so, may require other steps to be taken to ensure safe water. This is the approach taken for many contaminants in drinking water. It would appear in some cases that the difference between technology standards and other standards approaches is not clear (Field, 1994, 209).

Other examples of technology standards to protect groundwater quality are as follows:

- The Underground Injection Control Program implemented in the United States under the Safe Drinking Water Act requires by regulation that deep injection of liquid wastes be done through wells that have both an inner and outer casing with annular space between to capture injected wastes if the inner casing leaks. The mechanical integrity of these wells must be tested regularly. The European Union also has standards for underground injection of wastes.
- The Underground Storage Tank Program in the United States requires double-walled tanks and monitoring of the space between the walls to detect any leak of chemical product so that it can be responded to promptly before further leakage could enter the subsurface and contaminate groundwater.

Exhibit 12.11 previously demonstrated that the cost of current technology is the area R_1ER_M and that of the new technology is area R_3FR_M, so the difference is R_1JR_M. Assuming that t' is a damage function in this case, if R_1R_3FJ is larger than R_MJE, then the new technology is more expensive. However, other benefits of lower releases may be such that this circumstance is acceptable to and valued by the community or society.

Best Practice Standard

Best practice standards are specific steps or gradations of accomplishment directed toward statutorily or regulatorally defined and required objectives for implementing a program. An example of such standards is the requirement to establish a wellhead protection program to protect groundwater sources of drinking water by completing steps of delineating a wellhead protection area for groundwater recharge, identifying potential sources of contamination within the delineated area, and prescribing contaminant management measures as the steps to implement the program. To some analysts, best practices may seem to be technology standards, and while this may be true, generally the outcome from best practices may be less certain, but nevertheless a practical approach that recognizes certain principles, such as groundwater flow rates in different subsurface hydrogeologic settings, contaminant degradation rates in the subterranean environment, and the effects of soil type on the amount of water or contaminant that may percolate below the ground surface (rather than runoff as overland flow) and mix with groundwater. Such a combination of factors may not be as precisely designed into chemical use directions to be able to call them a technology in each case, but still warrant serious consideration in protecting and conserving groundwater.

Exhibit 12.18, panel (c), provides the basis for analyzing best practices through an agricultural example. Two farms, *Farm 1* and *Farm 2*, are located in a watershed that provides considerable recharge to the aquifer within and below it. Both farms are of similar size and use herbicide *X* to increase production. However, *Farm 1* is located on soil with a higher clay content, which tends to bind the herbicide to the soil rather than allowing it to be more mobile and percolate to the water table. The state regulatory authority determined that herbicide *X* was in the water supply of the town downgradient from the two farms and decided to institute the state's requirement for best management practices to be employed in the watershed first before requiring treatment at the water plant. The state required that both farmers reduce their use of the herbicide by the same amount. The state agricultural agent working with the state hydrologist estimated that if the upgradient contributions of the pesticide were reduced by a half ton per acre, the water supplier could be back in compliance with the drinking water standard in three years. Without considering the relative costs of implementing the best practices on each farm, each farmer was required to reduce use of the herbicide by a half ton per acre. To do so, the MAC (such as fertilizer reduction combined with other cultivation changes to maintain production levels) on *Farm 1* were \$0.35 per acre, while the costs for *Farm 2* were \$1.00 per acre, giving a combined cost of \$1.35 per acre. The state agricultural economist looked at the situation and talked with the farmers and discovered that based on best practices, their MAC were different. After studying the MAC curves for each farm, he determined the amounts of reduction for each farm that coincided with the same MAC for both and attained the reduction needed. At \$0.55 in MAC on each farm, *Farm 1* would reduce herbicide release by 0.7 tons per acre and *Farm 2* would reduce its release by 0.3 tons per acre, with the total reduction equaling the required average amount of 0.5 ton per acre per farm (0.7 ton/acre + 0.3 ton/acre = 1.0 ton/acre, then divided by two farms equals 0.5 ton/acre). The total cost was \$0.55 multiplied by 2 (counting both farms), equaling \$1.10 per acre, and saving \$0.25 per acre, a more efficient outcome. At the margin, the two farms pay the same to reduce the necessary amount of herbicide coming into the watershed. This example also demonstrates the economic efficiency principle of "equimarginality"—at the margin, the costs among those entities affected by the action (in this case, a standard) are the same and the result is more efficient, because it uses fewer resources to accomplish the same outcome. This circumstance applies to the other standards reviewed above in a similar way.

REMAINING CRITERIA FOR EVALUATING ENVIRONMENTAL PERFORMANCE STANDARDS

Environmental performance standards provide challenges for economic efficiency in conserving and protecting groundwater and can also be evaluated through the remaining criteria.

Dynamic Incentive

This criterion is problematic for standards, since they tend to be fixed. This is particularly true relative to technology advances. Exhibit 12.11 also considers technology standards and their economics under abatement technology advances. The current technology has marginal costs reflected in MAC_2 with a contaminant release level of R_1, which has abatement costs of $R_1E\,R_M$. With a new technology, a new marginal cost curve can be established, MAC_3, with a contaminant release level of R_3 and abatement costs of R_3FR_M. If the requirement to meet the new level R_3 with the current technology (MAC_2) had been instituted, total abatement costs would have been R_3KR_M, clearly a more costly and less efficient outcome.

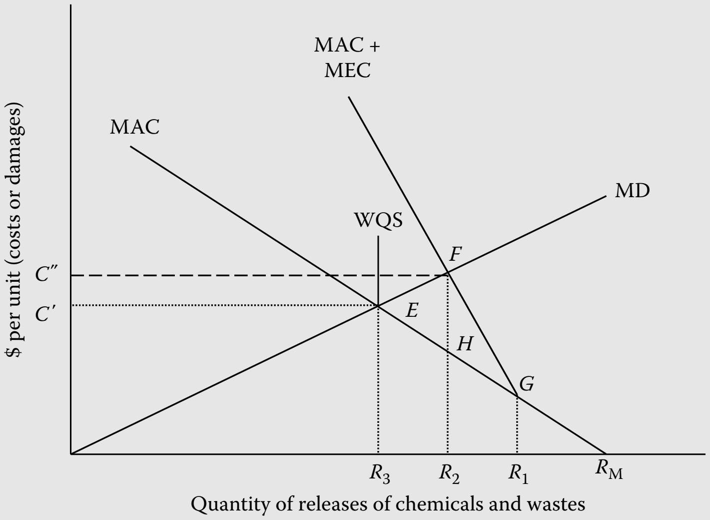
Low Information Requirements

Setting standards usually requires a substantial amount of data to ensure that the standard is as efficient as possible and fair, equitable, and cost effective. To establish a standard may take considerable research by the administrative authority and necessitate surveying the industry or individuals affected. Standards require that monitoring occur regularly to determine whether the regulated entities are achieving them. Legal challenges about whether an activity has caused a standard to be exceeded also require extensive information since the cost of complying may be perceived as high. For groundwater, monitoring may have to be conducted for years, especially in evaluating the results of standards on nonpoint sources of pollution (USDA, undated).

Low Administration Cost

In addition to the costs of obtaining and evaluating information to set standards and ensure compliance, enforcement must also be considered as a significant administrative cost. Exhibit 12.20 addresses the economics of enforcement of groundwater quality standards (WQS). Assume that the central authority was able to obtain information to set an efficient standard at R_3, which has also been adopted as the WQS. If insufficient resources are applied to uphold the standard, then the entities affected by the standard may attempt to avoid the cost of complying with it, because the risk of being prosecuted is perceived to be low, and therefore the cost is low. The costs of enforcement include monitoring wells, testing and laboratory equipment, field personnel and experts, legal processes, and even penalties and fines, if a defendant is found noncompliant. In Exhibit 12.20, the efficient level for the standard is R_3, the point at which the MAC just equal the MD at a waste unit cost level of C'. When the standard is first set, some limited voluntary compliance would be expected, reflected in R_1 at a cost equal to the area of $R_M\,R_1G$ (Field, 1994, p. 221). When the marginal enforcement costs (MEC) are added, a new curve applies to the situation, MAC + MEC, with a reduction in releases from R_1 to R_2. At R_2, the abatement costs incurred are equal to the area $R_M\,R_2H$ with enforcement costs of *FGH.* With active enforcement, potential waste release unit costs to industry are at a higher level at C'' to drive compliance to R_3, the economic response to *E* (the efficient outcome, balancing damages and treatment costs) and the coincidence of *WQS* for public health and ecosystem protection. More stringent enforcement could raise the costs above this level. At an even higher enforcement level, enforcement costs may be so high that the administrators and the judicial system may decide that the economic disorder would be too great and serve as a disincentive to further compliance. The challenge to the administrative authority is to find the right level

EXHIBIT 12.20 ECONOMICS OF GROUNDWATER QUALITY STANDARDS ENFORCEMENT



Source: Modified from Field, B.C., *Environmental Economics*, McGraw-Hill, Inc., New York, 1994, 221.

of cost for enforcement, given the groundwater protection or conservation objectives. Certainly, the extent of compliance may become less as resources for enforcement decrease.

Agreement with Moral Precepts

Environmental performance standards respond to our concerns that unacceptable behavior should be stopped by limiting extreme occurrences of abuse or contamination of groundwater and other environmental media. They also appear to address interests to have equal treatment of what seem to be similar circumstances.

ANOTHER PERSPECTIVE: COMPETITION FOR VERSUS MANAGEMENT OF THE RESOURCE

Economic competition versus management of groundwater is a fundamental consideration in much of the preceding discussion. A significant literature has emerged on this single topic, typically based on hydroeconomic models and evaluations of specific cases. Koundouri reviewed the literature back to 1956 on this topic and presented important observations comparing competition for common property use to management (through property ownership or use controls). For simple (but not realistic) conditions of an unconfined, infinitely conductive aquifer, early research suggested that the economic gain from management versus competition for a common property resource was negligible. However, as considerations of other externalities, drought "buffer" benefits, and intergenerational issues with lower discount rates are incorporated into evaluations, gains from management emerge with implications for resource sustainability. Recent examination has further found that "noninternalized costs of currently observed myopic groundwater extraction are significant. Thus, benefits from optimally managing this resource could be nonnegligible" (Koundouri and Xepapadeas, 2004, p. 7) and may increase welfare significantly (Koundouri, 2004, p. 11).

Exhibit 12.21 summarizes a review of this important aspect of groundwater policy economics. Exhibit 12.22 depicts the condition of pricing for scarcity relative to the marginal production cost and the next technology that could provide comparable water, termed a "backstop" technology, which, in this case, is desalination if there is no other lower cost alternative. As an efficient scarcity price reaches the cost of the backstop technology, then desalination provides the water supply if no other constraints exist.

EXHIBIT 12.21 COMPETITIVE PRICING VERSUS MANAGEMENT OF GROUNDWATER: GISSER–SANCHEZ EFFECT

Background. To reconsider the competitive pricing versus optimal control models for groundwater, Koundouri reviewed the literature reviewed back to 1956, which principally focused on irrigation use of groundwater. In most countries, many farmers are competing for a common property groundwater resource they are depleting. From a neoclassical economics perspective, competitive behavior in the market for water is not the problem but rather the property rights regime of the resource as they affect its price and allocation.

Where groundwater extraction surpasses recharge, farmers pumping the resource will either withdraw it until the aquifer is depleted or the marginal cost of pumping more water will preclude continued production. An efficient allocation of groundwater in this context considers both the cost of extraction plus the opportunity cost of using a unit of water now that will not be available for use in the future, also referred to as the scarcity rent of the resource. The scarcity rent should be a cost to current users of the resource.

The upper end of a shadow price for groundwater would be a water charge that future users would be willing to pay. This willingness to pay may be reflected in the purchase of property rights to the resource or in the development of a backstop technology to provide the water in an expected comparable volume and quality.

Owing to the challenge of defining unqualified property rights for groundwater, scarcity rents are not incorporated in water prices because of complications in their measurement. As a result, groundwater prices undervalue the resource, which in turn is produced in excess of the "socially optimal level." This circumstance is described in Exhibit 12.22.

Gisser–Sanchez Effect (GSE): While groundwater is being depleted around the world, "the social benefits of managing groundwater extraction are numerically insignificant" or otherwise stated, the beneficial economic effect of managing the resource through optimal control management (an institution to control pumping rate) is negligible. This outcome was demonstrated through the application of a hydroeconomic model and solving a series of mathematical relationships for a hypothetical aquifer and pumping strategy.*

Gisser-Sanchez Hydroeconomic Model in Overview

The Gisser-Sanchez hydroeconomic model assumes

- An unconfined aquifer
- Infinite hydraulic conductivity
- Constant return flow (implying a constant rate of water application, constant land use types, independence of surface and groundwater systems, and constant average rainfall)
- Sunk, replacement, and capital costs ignored
- Implied energy costs are constant

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* Citing: Gisser and Sanchez (1980).

EXHIBIT 12.21 (continued) COMPETITIVE PRICING VERSUS MANAGEMENT OF GROUNDWATER: GISSER–SANCHEZ EFFECT

- Implied well pump capacity constraint nonbinding
- Only land over the aquifer is irrigated
- Linear demand and supply curves
- 10% discount rate

For the farmer irrigating in a common property situation, the present value of future income streams is determined by the derived demand for water based on crop values and subtracting the pumping costs.

The optimal control approach to irrigation (not considering other opportunity costs to the ecosystem) is to determine a tax equal to the scarcity value of the resource and maximize the present value of future income streams considering the current water table level and controlling the pumping rate.

A series of equations describe the resource conditions and economic relationships resulting in an outcome that the difference between the competitive and optimal control approaches is negligible: the GSE. As noted previously, the implication of this result has been that there is “little or no role for water policy in the form of pumping limitations.”

Reconsideration of GSE

Reconsideration of GSE, in light of testing its assumptions and research in related subjects and results, highlights several aspects of groundwater use and economics that deserve notice.

1. A tradable permit approach could allow private ownership of shares of the resource and promote efficient allocation. However, property rights to groundwater are not about rights to units of the resource but entitlement to a particular number of units of the resource. The problematic aspects in this approach include pumping externalities and risk externality (arising from the stochastic nature of precipitation, runoff, and recharge and the extent that groundwater can serve as a buffer for surface water drought). Also, time inconsistency affects the initial allocation of permits, since the initial state of the resource is the basis for allocation. Thus, maximizing welfare could be different in the future if the state of the resource is different.
2. Groundwater management should consider the following:

    - Demand and cost curves are not necessarily linear functions—as surface water supplies decrease, groundwater management may provide welfare gains.
    - Property rights offer risk-averse firms opportunity to manage risk to their benefit.
    - Where other researchers evaluated control measures, the increase in value of groundwater may be as much as 10%.*
    - Real economic, hydrologic, and agronomic conditions are not incorporated in GSE, and differences in these factors exist from basin to basin.
    - In the long run, use of new techniques (e.g., dryland farming), input substitution, and a different product mix represent other responses to resource scarcity in the face of the signal of rising resource prices.

(*continued*)

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* Citing: Noel et al. (1980).

EXHIBIT 12.21 (continued) COMPETITIVE PRICING VERSUS MANAGEMENT OF GROUNDWATER: GISSER–SANCHEZ EFFECT (GSE)

- Introduction of a backstop technology for water production (e.g., desalination) reduces the size of management benefits, but the absence of a backstop has resulted in larger welfare gains from management in the face of near depletion.
- GSE may be eliminated in the case of groundwater management where significant externalities are generated from river effects and aquifer depletion.
- The buffer value of groundwater when surface waters are in drought conditions may represent up to 84% of the total resource value—the availability of a unit of groundwater to a firm reduces its income risk in the future and "smooths out" water supply; however, this considers only the private value to the firm and not the socially optimal value.* This buffer value from managing the groundwater in times of drought is often underestimated.
- While water scarcity reduces income, it increases the price of groundwater permits.
- The potential for groundwater management to offer increases in welfare includes situations of "nonlinear extraction costs, heterogeneous land productivity, nonstationary demand, situations of near aquifer depletion, presence of "river effects" and accounting for risk averse extracting agents."
- Quality factors combined with quantity factors raise the optimal steady-state groundwater stock.
- Declining discount rates in sensitivity analyses of GSE generate increased benefits from groundwater preservation for future populations.
- If a groundwater loss is expected to be irreversible, research indicates that groundwater should be extracted at the rate of recharge. This would eliminate GSE when considering the effect of availability for future populations.†

Given these considerations, management of groundwater may have materially positive effects on welfare.

Further reconsideration

Notably, other than "river effects," the research and evaluations cited did not take into account other ecosystem effects and relationships. The marginal costs and externalities on the larger economy are not factored into the analyses and may have wide-ranging implications on other ecological and economic linkages that are poorly understood.

Source: Koundouri, P., *Water Resour. Res.*, 40, 1, 2004, W06S16, doi:10.1029/2003WR002164.

SUMMARY

The range of policies available to address groundwater use and quality degradation range from local relational (including legal rights), risk management, economic instruments, and performance standards that should be evaluated on their efficiency and environmental and social merits to determine the best fit for the situation. The criterion of ecosystem scale is important in understanding whether the policy is so focused on case-by-case market interactions that scale is not a major aspect of the

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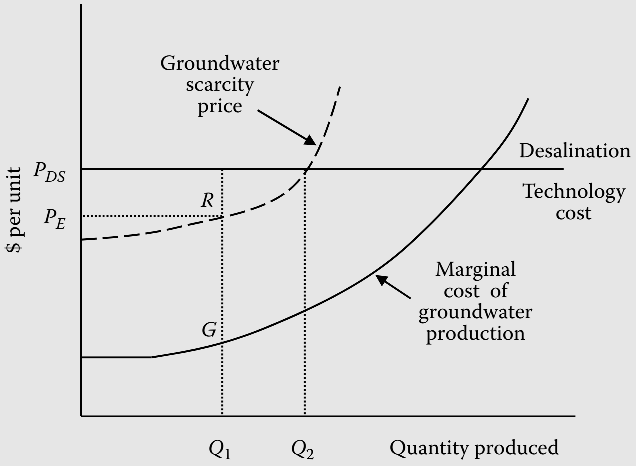
* Citing: Tsur and Graaham-Tomasi (1991).

† Citing: Tsur and Zemel (1995).

EXHIBIT 12.22 GROUNDWATER PRICING CONSIDERING PRODUCTION, SCARCITY, AND TECHNOLOGY



Notes: Pricing for efficient allocation includes the marginal cost of groundwater production and the resource scarcity rent.

The segment Q_1G represents the marginal groundwater production cost. The segment GR is the potential scarcity rent.

The price line P_{DS} is the desalination (backstop technology) cost.

The price P_E is the efficiency price for quantity Q_1, incorporating both the marginal production cost and the scarcity rent.

Should no other lower-cost water source be available to supply Q_1, the backstop technology could supply it at price P_{DS}.

Source: Modified from Koundouri, P., *Water Resour. Res.*, 40, 1, 2004, W06S16, doi:10.1029/2003WR002164.

policy, rather than being a central factor in the policy that it promotes consideration of maintenance of natural capital in groundwater. Likewise, positive ecosystem responsiveness has particular significance for this range of policies because some of them—the economic instruments—can influence ecosystem results of economic decisions, but whether they achieve ecosystem outcomes at the level desired may not be certain. For other policies, such as performance standards, the outcome may be clearly specified (even if not perfectly designated), but the costs may be less certain. The range of policies affects equity variably and need consideration in each case. Efficiency factors count not only benefits (such as avoided damages) compared with costs, but also equimarginality of costs of the policies. Administrative cost and local perception must also be weighed in fashioning the best groundwater management policies. Often, several policy approaches may be considered together to tailor the institutional response to the particular groundwater challenge. Examining open-access competition versus local resource management suggests that management has value in addressing unrecognized externalities that a market approach does not currently include. In all cases, adequate information is essential to make appropriate policy selections.

While these analyses typically are applied at micro-level situations, policy analyses applied to a state or nation will aggregate the effects to the industry or multiple communities and even at the national level. This aggregation provides a macro-level result necessary for policy-making decisions affecting many people or businesses. To some extent then, this additive approach puts these analyses on a continuum from micro to macro level, depending on the circumstances being evaluated.

Taxing outcomes of which society wants less has not been a focus of the U.S. environmental policy. Typically, in the United States, the approach has been to set national standards that raise the cost of activities that impact natural and environmental resources. The European Union members have focused on environmental taxes and charges to discourage unwanted results, many of which reduce impacts to groundwater (Ecotec, 2001). Opportunities may exist for transferable release permits as an economic instrument to better value the waste-processing and disposal capabilities of the subsurface environment affecting groundwater, including disposal of carbon dioxide. It is not evident that any nation has policies that would not allow import of foreign products that are not produced under environmental standards protective of natural capital (such as maintaining groundwater by limiting its use). If that is the outcome desired, then national, state, or local governments must adopt other approaches. Most attention in international agreements that address environmental outcomes has been to focus on standards affecting environmental quality, such as waste minimization and disposal and their associated costs affecting the supply costs of products. Little attention has been given to quantity control, such as limiting groundwater use to maintain long-term supplies. Unlimited use has detrimental effects on future availability and quality. Policies at the macro level that incorporate a vision and objectives to protect essential resources on a sustainable level may then be necessary, depending on societal preferences on the quality of life in the future. This is the subject of Chapter 14, Sustainable Development.

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13 Cost–Benefit Information and Analysis

Many decisions related to the protection and remediation of groundwater in the 1970s and 1980s were not informed by a rigorous or systematic evaluation of costs and benefits. This circumstance existed because of the concern about widespread contamination of groundwater that had occurred and public outcry for a response. Governments wanted to get the sites and the resource cleaned up as quickly as they could, often without a careful study of the options and because of political pressure. Cost–benefit methodology had been applied to surface water supply projects for decades. For groundwater, political and public pressure was largely driving funds to be spent without a disciplined approach to the costs and benefits. Importantly, cost–benefit analysis (CBA) should be viewed as a "process meant to yield information rather to make decisions…" (Lave, 1996, p. 128) One of the first reasonably complete treatments of groundwater with a cost–benefit approach appeared in 1993 (USEPA, 1993). The groundwater supply industry, as a partly regulated sector, makes its investments based on understanding the costs and benefits (returns) of options for supplying water. Clearly, the chemical products industry that has large volumes of liquid waste to dispose of has concluded that underground injection of those wastes, even with permit processing requirements, is often more cost effective than other means of disposal in the existing regulatory environment. These relationships suggest that a cost–benefit framework has application to groundwater resource decision making.

The evaluation of costs and benefits in a structured approach provides significant information to develop policy and assists in making decisions. Typically, it is the completeness or adequacy of including the costs and benefits in these decision processes that presents shortcomings to the use of cost–benefit evaluation approaches. The cost–benefit evaluation method has been institutionalized in government policy development through law and regulation, including application to groundwater-related issues. CBA also has a role in the private sector's decisions affecting groundwater (Hardisty and Özdemiroglu, 2005). A range of evaluation approaches exist, some better suited for particular circumstances than others (Young, 2005, pp. 47–49). The usefulness of these approaches will depend on the goals set forth by the individual or entity requiring the analysis. Certainly, these approaches will present challenges, since, for example, while economists could agree that the nonmarket effects should be included in analyses, they do not have accurate means to do so (Lave, 1996, p. 121). However, these approaches are useful in organizing information for decision making.

Since the advent of CBA, an approach that augments and enhances economic evaluation primarily focused on a microeconomic level of communities and corporations is the "triple bottom line": consideration of economic as well as environmental and social factors in the development and implementation of projects, products, and services. This approach evolved from the work of the International Council for Local Environmental Initiatives (ICLEI) in 1990 that continues to focus on sustainable development at the local level (ICLEI, 2007a,b). This effort recognizes that typical accounting approaches externalize social and environmental costs and do not address natural capital consumption. Measuring and describing human capital and social justice outcomes are significant to this approach. From a groundwater perspective, ensuring a just distribution of the resource to those least able to pay for it would be important. Supplementing this evaluation approach is the calculation of ecological footprints of human consumption: "estimat[ing] the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area" (Rees et al., 1995, p. 7)—basically, calculating the demand on the planet's or nation's natural resources and biological capacity. If a country "overshoots" its natural resource stock and biological capacity, it is "liquidating" its ecological capital rather than living on its annual yield (GFN, 2007), an unsustainable position affecting its long-term economy. The ecological footprint can be calculated at any level depending on the activity being evaluated (for example, a national geothermal program or a water treatment plant). The accounting frameworks of these approaches enable the economist or other analysts to document and compare the costs and benefits of activities and projects or products in other useful units appropriate to the management or organizational entity.

BACKGROUND ON COST–BENEFIT ANALYSIS

CBA is a method of reaching economic decisions by comparing the costs of doing something with its benefits (LBS, 2006). A principal basis of CBA is found in the United States Flood Control Act of 1936, stating an economic criterion of: "the benefits to whomsoever they accrue are in excess of the estimated costs" for projects to improve navigable waters, tributaries, and watersheds. This analysis was further elaborated on in the "Proposed Practices for Economic Analysis of River Basin Projects" (Committee on Water Resources, 1958), and finally addressed by the United States Water Resources Council in its "Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies" (USWRC, 1983). The Organization of Economic Cooperation and Development also issued its "Management of Water Projects" (OECD, 1985). Both of these guides to water project evaluation provide a framework to identify and assess environmental effects in relation to socioeconomic results.

The United States President's Executive Order 12866 brings this technique up to date for public projects and programs. Many texts provide detailed approaches that are abstracted in summary form here. These texts provide various theoretical and practical explanations for procedures and considerations that may be used by the analyst (Andersen and Settle, 1977; Mishan, 1982; OMB, 1992; USEPA, 1993, 2002; Field, 1994; Young, 2005). Importantly, while CBA has received criticism, principally for difficulty in not including nonmonetizable effects, it is a useful way to organize information to inform decisions concerning their potential economic outcomes, and should not be considered solely as a strict decision rule.

In describing CBA, Young (2005, p. 18) indicates that it is

> "the practical application of the welfare economics test for potential Pareto improvement" [see Exhibit 8.7]… "to predict whether a proposed policy initiative would produce beneficial effects in excess of adverse effects, both expressed in commensurate monetary terms. Beneficial effects are those which produce positive utility or remove anything that causes disutility, while costs are reductions in desired things or increases in undesired impacts."

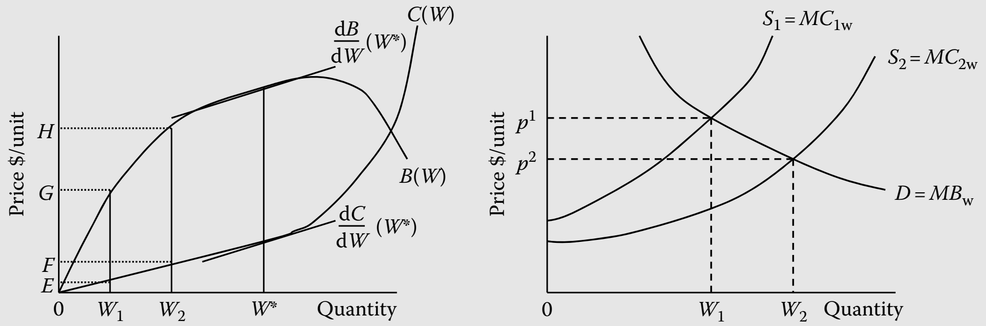
Exhibit 13.1 shows graphically the thought process to move from efficiency for market goods to nonmarket goods, such as groundwater in many circumstances.

The concepts presented in the graphs of Exhibit 13.1 highlight the key relationships important in understanding economic efficiency in a cost–benefit context (abstracted and extended from Young, 2005, pp. 29–35):

Graph *a*:

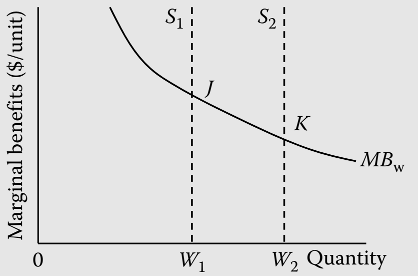
- Shows the aggregate social costs for a water project, $C(W)$, and the aggregate social benefits, $B(W)$, for different quantities of water supplied. The assumption implicit in the graph is that the rate of increase in costs rises with more water supplied, while benefits grow at a declining rate.

EXHIBIT 13.1 GRAPHICAL MEASUREMENT OF EFFICIENCY FOR MARKET AND NONMARKET GOODS



Graph *a*. Comparison of Pareto efficiency and cost–benefit criteria

Graph *b*. Change in economic surplus from shift in supply of marketed commodity



Graph *c*. Change in economic surplus from shift in supply of nonmarketed commodity

Source: Young, R.A., *Determining the Economic Value of Water: Concepts and Methods*, Resources for the Future Press, Washington, DC, 2005, 30–34. With permission.

- Indicates the quantity of water, W^*, at which the net benefits $[B(W) - C(W)]$ are the largest. This greatest difference (maximum vertical distance) between the two curves $[C(W)$ and $B(W)]$ occurs where the marginal benefits (MB) and marginal costs (MC) are equal, that is, where dB/dW equals dC/dW for W^*.
- At W^*, the Pareto efficient solution occurs: no one can be made better off without making someone else worse off. Moving from the left toward W^*, as long as MB > MC, Pareto improvement occurs and, within the budget, any position that is determined to be more acceptable than an existing project or policy could be chosen.
- CBA compares two projects relative to their respective costs and benefits and without knowledge of where the Pareto efficient outcome may occur, which is typical of most proposed activities. Two hypothetical water projects are compared, which would provide different quantities of water, W_1 and W_2. The incremental difference in aggregate costs is represented by the vertical difference between E and F, line segment EF. The line segment GH is the measure of the difference in aggregate benefits. The incremental benefits are larger than the incremental costs, and so a "Pareto Improvement" is determined to occur. If W_1 is the current water supply condition and W_2 is a proposed water project, W_2 would be preferable in a cost–benefit framework, since MB > MC.

Graph *b*:

- For a “marketed” good, such as rights for a specified quantity of groundwater or tanker-supplied water, the curve D (=MB_w) is the demand curve for this water, reflecting consumers’ willingness to pay (WTP) for it at different prices. As the price falls, consumers will demand more water. The falling price level associated with more water indicates that consumers receive less marginal benefit (derive less utility) with each additional unit of water.
- The curve S_1 shows the producer’s first set of MC as water production increases along the curve. If water is less costly to produce at each quantity to be supplied, such as might occur if recharge conditions to an aquifer improve such that the water table rises and reduces energy costs to pump it, then the producer’s (or local water industry’s) supply curve shifts to S_2. Assuming that people’s preferences and incomes have not changed, consumers’ demand for water is still reflected in curve D and the producer offers more water; then the consumers will want more water as the price drops, shown as quantity W_2. In this case, the movement from curve S_1 to curve S_2 is a “nonmarginal shift” in supply (marginal changes in supply are represented by movements along a single supply curve). This circumstance might also occur when water as a productive factor of irrigated agriculture is increased with the addition of a new pump technology, such as with the introduction of the treadle pump in Asia.
- The consumers’ surplus is the area on the graph above the price lines. This surplus is defined as the difference between the price consumers pay (or producers offer) in the market and the maximum that consumers would be willing to pay at each quantity demanded along the D curve, reflecting their marginal benefit, MB_w, as well as their utility for each increment of additional water. The economic surplus is greater for price p^2 than for price p^1.
- The producer’s surplus is the area above the supply curves (S_1 and S_2) up to the corresponding price line. This area represents an economic surplus or profit to the producer above his or her costs to supply water.
- Note that the reverse of the event might occur in the event of a drought that has caused a drop in the water table over an extended period of time. In such a circumstance, W_2 might represent the quantity supplied before the drought. A dramatic lowering of the water table could significantly increase groundwater supply costs, shifting the supply curve to the position represented by W_1. In this case, price p^1 would reflect a new price reflective of increased costs to provide bottled or tanker water and a new consumer demand at that price.
- The extent to which S_1, S_2, and MB_w reflect adjustment for social costs beyond actual production costs or societal benefits in addition to prices offered to consumers, respectively, there may be “shadow prices” that represent these social values (such as monetized costs of less groundwater supplied to stream baseflow or monetized benefits from improved human health from safer water supply), calculated as an estimated value per unit from methods that will be described here.

Graph *c*:

- The MB curve MB_w reflects the demand for a “nonmarketed” commodity such as groundwater as an open access resource; that is, the curve portrays a bound or limit to what consumers might be willing to pay for a nonmarket good. This is also a shadow price. For nonmarketed commodities, this curve is the accumulation of consumers’ demand reflecting the strength of their preferences.
- The supply curve is inelastic. The quantity supplied is not affected by price but rather by the available resource.
- The curve MB_w delineates consumers’ demand and WTP for the nonmarketed commodity. For producers, this curve is their marginal value product (MVP), the increment of return received from employing additional factors of production and a measure of their WTP.

- In CBA, the area under the MB_w curve between W_1 (the present condition) and W_2 (the future condition) is the measure of the economic value of the additional resource to be used. This is the area $W_1JK\ W_2$.
- Examples of this application include the introduction of irrigation using groundwater to areas that have relied on rain-fed agriculture and recognition of the functions of groundwater-maintained wetlands. In both cases, the initial value accorded that the resource might have been at or close to zero, and so the quantity of W_1 would be estimated at or near zero. In a different situation, the aesthetic value of geysers (superheated groundwater forced through fissures in the subsurface to the ground surface as a plume of water rising to the sky) at a national park might expand if additional viewing is possible.
- Notably, opportunity costs are the obverse of MB, that is, they represent benefits lost in a situation in which a resource constrained by quantity or quality limits is to be applied in one alternative rather than another. The graph can then be viewed in reverse. In Graph *c*, foregone benefits would be the result of an action that would cause the quantity to be reduced from W_2 to W_1. This situation might occur when groundwater may become contaminated or when saltwater intrusion is expected to occur and the amount of usable resources may be permanently reduced for some period of time, perhaps even indefinitely. Again, this is the area $W_1JK\ W_2$, counting it as an incremental loss of benefits.

TYPES OF ACTIONS AFFECTING GROUNDWATER

A range of principal actions affecting groundwater can be evaluated using CBA. The range of actions may include

- Production of groundwater—producing—abstracting or withdrawing—groundwater for human and economic purposes
- Conservation of groundwater—managing groundwater to minimize loss, waste, and use
- Protection of groundwater—preventing contamination of groundwater
- Waste disposal in groundwater and the subsurface—using groundwater as a waste sink
- Remediation of contaminated groundwater—removing contaminants from groundwater
- Balancing ecosystem need for groundwater—ensuring sufficient groundwater for flora, fauna, hydrologic cycling, and climatic equilibrium
- Making groundwater available for future use—maintaining and managing groundwater for future uses and generations

Some of these actions may overlap—the significance of each category is its emphasis for economic evaluation. Each type of action will have its own set of costs and benefits, some quantifiable and monetizable, others not so. Exhibit 9.3 highlights how to think about the change in conditions in the aquifer relating to the change in services to people that may be valued in a cost–benefit context for actions affecting groundwater. The concept of the change in services associated with an action—whether it is increasing supply through installation of a well, issuing a local plumbing code to reduce water use, establishing a regulation to prevent or control release of waste to the subsurface, or creating a groundwater reservation to maintain an aquifer for future use—leads to the description of the tangible (and in some cases, less obvious) result that may be valued through economic analysis.

QUESTIONS ADDRESSED

Cost–benefit evaluation seeks to advise the decision maker from an economics perspective in answering the question: “Of the number of investment options addressing a certain objective, given limited funds to invest, which should be chosen?” A subsidiary question that it may also address is "At what level should a particular project or program operate?" (Mishan, 1982). Relative to this examination of groundwater, these questions might address, for example,

In the first case:

1. Should a community invest in a groundwater source or a surface water source for water supply?
2. Should a state or central water authority limit groundwater withdrawals or require installation of water-conserving devices?
3. Should a community treat groundwater of unacceptable quality or develop another water source of adequate quality?

And in the second case:

1. How much water should be withdrawn and still have a long-term groundwater supply?
2. What should be the acceptable level of a contaminant in groundwater sources of drinking water (or of other uses that may be considered)?
3. To what level should groundwater now contaminated be cleaned?
4. Other questions can be derived, and the focus may be on the quantity of groundwater to be managed.

GUIDING PRINCIPLES

Several principles are useful in organizing and conducting CBAs, including

1. *Objective specification.* The resource project or program being considered must have a specific objective to be achieved. The accomplishment of this objective should be observable and measurable. This same objective applies to the evaluation of all alternatives examined in a CBA. If the objectives of the alternatives are different, a comparison of the alternatives' projected outcomes cannot occur.
2. *Societal evaluation.* Obviously, this evaluation operates at the level of a society (city, state, or nation), rather than for an individual. At the societal level, costs and benefits are determined relative to their fulfillment of overall preference for a particular outcome, product, or service. Any action or thing that augments or expands human welfare is a benefit and, conversely, any action or thing that diminishes that welfare is a cost (Turner, et al., 1993, p. 93).
3. *Resource project or program duration or planning horizon.* The time frame over which the resource project or program is expected to incur costs and produce benefits must be established. The accumulation of costs and benefits for a project or program occurs across a specific period of time or planning horizon, which must be defined to allow the comparison of costs and benefits among alternatives evaluated, based on the specified objective. The specification of the duration or the planning horizon is necessary to apply a discount rate to the monetized outcomes of alternatives to evaluate them and account for the value over time of a cost or benefit, as will be explained here.
4. *With and without evaluation.* An evaluation must have a starting point as a reference. For CBA, the starting point is assessing the condition to be changed "without" the action and its attendant effects, both favorable and adverse (USWRC, 1983; Merrett, 1997, p. 86; Young, 2005, p. 35). Projecting the expected changes and resulting effects "with" the development and implementation, an action is the second evaluation point to be compared with the condition "without" the action. The common metric is monetary units. Care should be taken not to include economic results that would have happened whether the

action occurred or not, to preclude expanding and misrepresenting the effects of the action. Exhibit 13.2 describes one approach to establishing a baseline for long-lived resources, like groundwater.

5. *Population and area counted.* The evaluation must have a boundary within which costs and benefits will be accounted, reflecting who benefits from a service or action and who pays the cost (USWRC, 1983; Young, 2005, p. 35; AWWA, 2006, p. 67). The population and area affected will typically be a community, city, state, or nation. However, it could be a river basin; other hydrologic unit, such as the area overlying an aquifer; or a political subdivision, such as a water district. Time and funds available for investigation will constrain the size of the evaluation area, if not otherwise bounded. The population included should be as inclusive as possible to minimize missing major effects (Young, 2005, p. 36). The area and population of interest may also be a habitat of flora and fauna requiring a certain amount (or water table level) and quality of groundwater, such as the Edwards Aquifer in central Texas, and the sustenance of its endangered species.

   The area within which the analysis is to be conducted should be well defined to ensure that factors relevant to the objectives of a project or program are included. A city or county will consider the area within which to account costs and benefits differently than a state or nation. For example, for groundwater conservation, the accounting unit or area may be considered as (a) the water supply utility itself, (b) the utility customers (participants and nonparticipants of a conservation program), or (c) the community as a whole (AWWA, 2006, p. 67). Using smaller areas from which costs or benefits may flow to adjacent areas may significantly change the outcome of an analysis. Additionally, labor rates and inflation may be substantially different from city to city or from city to state or nation. Accounting area definition at the beginning of a project or program to be analyzed is important for these reasons.
6. *Identification of nonmonetary and unquantifiable effects.* Nonmonetary and unquantifiable effects (number of certain species or aesthetic qualities) should be identified, listed, and described in the CBA as additional significant information (USWRC, 1983). Previously, the value of human life was not quantified. Now, in studies of human health effects, a monetary value may be assigned. The CBA may stimulate research, providing information to allow future quantification and monetization of effects not now measured in those ways (Anderson and Settle, 1977, p. 23). Nonmonetary quantification may include the ecological footprint assessment and social equity evaluation relative to ecosystem scale effects and incidence of community impact. Effects that can only be described qualitatively, impacts to receptors—whether human, flora, or fauna—on- and off-site, and, importantly, effects on the ecosystem should be given serious attention with an explanation of their reversibility and magnitude. At the very least, decision makers should have the most complete information organized as potentially favorable and adverse effects to make a determination of an action's value.
7. *Private versus social accounting.* The evaluation of costs and benefits should be clear as to the incidence and application of the effects being considered. Private accounting refers to the effects to firms and individuals of changes in prices. Social accounting considers prices of goods modified for taxes, subsidies, or other political-economic adjustments (Young, 2005, p. 36). The evaluation of groundwater pricing for irrigation has been subject to such accounting considerations, including adjustments for crop, season, and water user category (Tsur et al., 2004, p. 36).
8. *At-source or at-site evaluation.* Consistent evaluation of benefits and costs must focus on the same objectives for alternative projects or programs. The evaluator must determine from the outset whether the analysis will be for products and services at the source of water or at the site of use (Young, 2005, pp. 38–39). The most fundamental difference between

these locations is whether the evaluations will include water distribution and treatment costs. These costs depend on the use of the water, for example, irrigation use will probably not include treatment, whereas municipal use may be further from the source and require treatment.

Another way to consider this factor is to view groundwater use on a continuum of source–pathway–receptor (NRC, 2002, p. 121; Hardisty and Özdemiroglu, 2005, p. 113). Evaluation at the source is as described earlier. The pathway component may include such costs, for example, as those of installing and operating a pipeline for a water supply or of installing and operating interceptor wells if the contamination pathway is well defined and can be intersected for groundwater pumping to allow removal and treatment of contaminants. The receptor is the site of groundwater use or the end point at risk from contamination that may be transported by groundwater—either a human population or a potentially affected fauna or flora habitat.

9. *Short-run versus long-run analysis.* A short-run perspective may consider costs of capital in place as "sunk" (already expended before the analysis) and, therefore, not relevant. In the short run, changes in variable inputs are the focus of analysis. In the long run, all inputs, including capital (plant) costs are variable. Very long-run analyses consider the change in technology as it affects costs (Young, 2005, p. 37).
10. *Life-cycle evaluation.* The anticipated or known duration of a resource project or program may have items or things, such as equipment or structures, that have acquisition or capital costs and operating and maintenance (O&M) costs, and function over a specified period of time to provide benefits to users. These cyclic (repeated) costs and benefits must be included in CBAs over the life of the project or program and not just counted one time.
11. *Decision advisory rule.* The decision advisory rule for the accounting area (society, i.e., city, state, or nation) affected by a decision or project is that the benefits should exceed the costs by an appropriate amount, based on the purpose being addressed (Schiffler, 1998, p. 267; Young, 2005, pp. 11–12).

A formulation of this rule (Young, 2005, p. 13) with a variation having been applied to groundwater projects (Schiffler, 1998, p. 267) is

$$\mathrm{DB} + \mathrm{IB} > \mathrm{DC} + \mathrm{TPC} + \mathrm{CC} + \mathrm{FDB} + \mathrm{FIB}$$

where

DB is the direct benefits of water uses as reflected in WTP
IB is the indirect benefits of water uses
DC is the development costs, including transport costs and any treatment costs
TPC is the transaction and planning costs, including information, contracting, and enforcement costs
CC is the physical conveyance and storage costs
FDB is the forgone direct benefits from reduced production
FIB is the forgone indirect benefits from reduced production, such as loss of livelihoods or a reduction in local/national capability

Direct effects, both benefits and costs, "result from the goods and services that are directly produced by the project… the benefits as measured by WTP for the direct outputs and the costs of producing the direct output measured in terms of foregone production" elsewhere in the economy (Anderson and Settle, 1977, p. 22). An example of a direct benefit is an increase in groundwater production. A direct cost may be for the removal of minerals from water so that it can be used for certain services, such as manufacturing. Indirect benefits and costs are the effects of differences in value of production from activities caused indirectly from the water project or program (Anderson and Settle, 1977, p. 22). An indirect benefit might be increased sales of tractors. An indirect cost could be road improvements to move irrigated crops to market.

Young (2005, p. 13) adds a condition specifying that an activity's costs should be less than the "next best alternative" meeting the same objective:

$$FDB + FIB + TPC + CC < AC \qquad \text{(Ineq. 13.1)}$$

where AC is the cost of the next best alternative.

The next best alternative might be piping water from a distant lake or aquifer, or treating the water at the points of use rather than the location of production, if these are in fact the next least-cost alternatives.

EXHIBIT 13.2 ACCOUNTING FOR THE CONDITION AND VALUE OF GROUNDWATER ASSETS: CREATING A BASELINE FOR COST–BENEFIT ANALYSIS

In the United States, the Government Accounting Standards Board (GASB) has developed an accounting framework for documenting the condition and value of long-lived public infrastructure assets by local, state, and federal governments. This framework is titled "Basic Financial Statements—and Management's Discussion and Analysis—For State and Local Governments" (GASB, 1999). In a broad definition of assets, which includes water facilities, the resource itself—groundwater, in this case—could be accounted for, relative to its condition and value as a natural asset of long-term significance to a community. GASB has provided "Statement 34" (also referred to as "GASB 34") to describe this accounting procedure for public agencies, which establish "funds" to organize information concerning assets and liabilities.

Typically, infrastructure assets are valued using a standard depreciation approach in which a certain percent of the value of the asset is deducted each year because of use and wear. GASB Statement 34 also provides for a "modified approach" that prescribes a framework for asset management through observing and reporting the performance and condition of the asset. Agencies using the modified approach are required to maintain the asset in or exceeding a minimum condition, thereby administering the asset so that its value is not significantly depreciated (Henning, 2002). While this accounting framework would usually apply to water supply systems, such as wells, pipes, and treatment facilities (as well as other public assets, such as dams, roads, bridges, and buildings), it can also be applied to natural assets.

While the GASB Statement 34 does not provide a detailed itemization of the information to be included in a modified approach accounting, the following inputs are generally required (Maze, 2000; Henning, 2002):

- Maintain an up-to-date inventory of infrastructure assets.
- Regularly assess the condition of all infrastructure assets and summarize the results, using a measurement scale.
- Each year, estimate the annual cost required to maintain and preserve the assets at a minimum condition level for the assets' life spans established by the agency. The minimum condition level should be expressed in terms of categories or a condition index (e.g., good, fair, and poor; or, relative to groundwater resources, pristine and available for any use, meeting all drinking water standards, contaminated but usable for drinking, contaminated and unusable for drinking, and maintaining a minimum water table level).

(*continued*)

EXHIBIT 13.2 (continued) ACCOUNTING FOR THE CONDITION AND VALUE OF GROUNDWATER ASSETS: CREATING A BASELINE FOR COST–BENEFIT ANALYSIS

This information on the condition of the groundwater asset could be used for developing a baseline for CBA. Additionally, if a community is implementing a wellhead protection (WHP) program to maintain and protect its groundwater supply, the cost of such a program could also be used as the baseline for analyses focused on changes in the service of groundwater relative to its quality. “The benefit of selecting the modified approach is that it represents a more sound approach to the management of long-lived infrastructure assets” (Maze and Smadi, 2007).

EVALUATION APPROACHES

Several evaluation methods have been used to examine the economic effects of groundwater quality issues: impact analysis, cost-effectiveness evaluation, and cost–benefit evaluation. Cost–benefit evaluation also includes risk–benefit evaluation. Uncertainty considerations affect all these methods. Each general method within the cost–benefit evaluation approach will be described. Many texts focusing on cost–benefit evaluation provide more detail than that given here. The references at the end of the chapter provide a guide for further details on this subject.

IMPACT ANALYSIS

Impact analysis catalogs and describes, through quantification where possible, the range of effects of a proposed action or spectrum of actions affecting a resource or community. Impact analysis may be a part of cost-effectiveness or cost–benefit evaluations (Hardisty and Özdemiroglu, 2005, p. 109). An impact analysis of adding a well to supply a community’s growing population may consider not only the value of the additional water to be supplied and the cost of installing the well, pipes, and treatment, but also the effect on other water users and on the ecosystem receptors for different pumping scenarios in the future. When a local government decides to enact a regulation to control disposal of wastes in its landfill, residents will want to know the economic effect of requiring large and small reductions of waste volumes. Increments of the entire program or even parts of it, such as a special analysis of controlling metal waste disposal, can be evaluated looking at the magnitude of the costs, changes in demands for truck haulage, reductions in landfill space needed, and other affected factors. Analyses could also examine policies at state and national levels. Furthermore, business can look at its internal proposed actions and the incidence of costs throughout its operation in a similar way and determine the impact on its bottom-line profit.

COST-EFFECTIVENESS EVALUATION

Cost-effectiveness evaluation refers to the comparison of the relative expenditure (costs) and outcomes (effects) associated with two or more courses of action (IDC, 2005). Cost effectiveness answers the question: Given an objective, what is the cost, in monetary terms, of different options to address it, and then which is the lowest cost? A town desiring to protect its wellfield from future contamination might evaluate the costs of options, such as changes in zoning, obtaining technical assistance for business, and conducting an education and information campaign. The cost of each option could be compared by dividing each one by the pounds of chemicals expected to be controlled and managed.

Cost-effectiveness evaluation may be one part of a cost–benefit evaluation. Focusing on costs is typical of the government programs at all levels, especially when the benefits may be difficult to quantify and monetize. The critical part of a cost-effectiveness analysis is identifying the full range of costs and who is incurring them: costs to an agency or a business may be obvious; costs to the larger community or to society, the "social costs," may be harder to quantify. These costs might include greater water supply costs from granting development rights or destruction of an important recharge zone for water supply or damages to a fishery from destroying nutrient flux from groundwater through the streambed because of channelization. While these costs should obviously be addressed by any public agency, increasingly private companies have felt the effects on not estimating and incorporating in decisions the social costs of their actions in their accounting. Witness continuing effects of consumer boycotts, market response to poor environmental management, or disrespectful customer handling. The most cost-effective way to manufacture and sell a groundwater pump does not stop at the plant shipping dock. Cost and benefit analytical components based on whether they are incurred privately or by society as a whole are shown in Exhibit 13.3.

EXHIBIT 13.3 PRIVATE AND SOCIETAL COST AND BENEFIT COMPONENTS

Private/Financial Analysis	Social/Economic Analysis
Individual and corporate costs	All costs to society (including external [off-site] and ecosystem costs)
Individual and corporate benefits	All benefits to society (including external [off-site] and ecosystem benefits)
Market prices (including transfer payments)	Shadow prices (market prices without taxes, subsidies, or other transfer payments)
Individual or corporate discount rate	Social discount rate
No equity or distribution effects	Equity and distribution effects

Source: Adapted from Hardisty, P.E. and Özdemiroglu, E., *The Economics of Groundwater Remediation and Protection*, CRC Press, Boca Raton, FL, 2005, 336. With permission.

The results of cost-effectiveness evaluation should also correspond to the "equimarginal principle." With limited resources, and an objective of maximizing output produced or service units provided, allocate total production or provision such that each plant, facility, well, or provider has the same MC; that is, equalize MC among all the sources. Exhibit 13.4 outlines the approaches of "cost assessment" and "cost effectiveness."

EXHIBIT 13.4 STEPS IN COST ASSESSMENT AND COST-EFFECTIVENESS EVALUATION

DEFINING THE ACTION

1. Establish a goal, e.g., ensure all residents of the four-county water supply region have a safe groundwater source through the year 2030, or remediate groundwater to meet local uses in the economy.
2. Set objectives that may be quantified, e.g., supply an additional 1000 cubic meters of water per day meeting safe drinking water standards, or reduce contaminant concentrations in groundwater to 1 milligram per liter.

(*continued*)

EXHIBIT 13.4 (continued) STEPS IN COST ASSESSMENT AND COST-EFFECTIVENESS EVALUATION

3. Establish alternatives (and their specific steps to be implemented) that address the following objectives:
    a. Alternatives for "water supply" may include wellfield near river, wellfield south of community, intake in river, reconditioning and reuse of wastewater, and desalination of deep brackish water (See Chapter 7).
        i Specific implementation steps may include hydrogeologic and engineering investigations, water system design, installation of wells and intakes, pumping water, installing pipes, treating water, testing water, distributing water to users, designing programs to ensure future protection of water sources, and implement source water protection program.
    b. Alternatives for "contaminant remediation" depending on the contaminants may include excavation and removal of contaminated soil and groundwater, *in situ* or *ex situ* chemical treatment, bioremediation, physical separation, air stripping, or containment barrier (See Chapter 7).
        i Specific steps may include hydrogeologic assessment; designing a monitoring network; installing wells; organizing and implementing a sampling plan; testing and reporting results; determining engineering (treatment) and nonengineering approaches; conducting meetings to get public input; identifing the best approach; and designing, installing or implementing (zoning to restrict use as a nonstructural approach), and evaluating the approach through monitoring.
4. Identify effects, both economic and noneconomic, of each option, e.g., degree or extent of potential production or contamination, adverse effects of production or contamination, who and what is directly and indirectly affected by the action, and when the effects of the action occur
5. Define the scope of analysis, e.g., constituency, budget factors, industry or community, and geographic boundaries affected.

ESTABLISHING THE BASELINE

6. Defining the baseline, e.g., cost of doing nothing, such as allowing water quality to deteriorate, resulting in costs of alternate water supply, lost tax revenue, company relocation, changes in health risk; or cost of action in the absence of initiating the proposed program, such as responding to depletion of the aquifer or to its contamination.
7. Specify the timeframe, e.g., the U.S. Office of Management and Budget recommends 30 years for program evaluation.
8. Quantify the baseline: for baseline costs, e.g., treatment costs (costs of remedial measures), replacement costs (costs of providing alternate water supply), and damage costs (costs of health effects, environmental and property damages, economic dislocation, and litigation expense); for baseline effectiveness, e.g., extent or level of depletion or contamination measured in meters or parts per billion, respectively.
9. Consider factors changing baseline estimations: for baseline costs, e.g., extent of depletion or contamination (worst case or range of scenarios), severity of depletion or contamination (higher levels increase costs), and affected parties (sensitive or special populations may require extra steps to protect); for baseline effectiveness, e.g., physical characteristics (geology, and hydrology), extent of existing program (age, expected life, and capital assets), and future trends (population and

EXHIBIT 13.4 (continued) STEPS IN COST ASSESSMENT AND COST-EFFECTIVENESS EVALUATION

industry growth, and chemical use). For conservation programs, the degree of market penetration should be a factor applied based on the extent of expected use of conserving practices (AWWA, 2006, p. 68).

10. Incorporate risk and uncertainty through use of probabilities in baseline calculations and applications of sensitivity analysis: for baseline costs, e.g., estimating the probability of contamination and multiplying it by the cost of contamination gives "expected cost"; for baseline effectiveness, e.g., multiplying the cost of contamination by the baseline effectiveness measure gives an expected baseline effectiveness; for probabilities of risk of contamination, obtain best professional judgments on the percentage of chance that contamination will occur based on use of best practices for and release of hazardous or toxic substances and their possible percolation and migration through the area's geology; and for sensitivity analysis, by changing assumptions in contamination levels or depletion (or other factors) to determine a range of cost effects and effectiveness.

ASSESSING THE COSTS

11. Select and classify the costs:
    a. Direct and indirect costs: Direct costs are incurred by governments, businesses, and persons immediately contributing to or affected by the activity (project or program), e.g., compensation to those organizing and directing the project and cost of equipment to comply or complete construction requirements or, for conservation activities, the incremental cost of implementing a conserving practice or water supply modification (AWWA, 2006, p. 68); indirect costs are those incurred by others affected by the activity but not directly responsible for it or required to respond to it, e.g., a landfill operator must implement more comprehensive monitoring and raise his price of solid waste disposal (an indirect cost) to users of his service.
    b. Program and compliance costs: These are direct costs usually in response to a government activity: Program costs are those of planning and conducting a groundwater program (including construction and public involvement); compliance costs are those which the responding public organizations and industry must incur to implement a regulation (including costs associated with construction and permits).
    c. Public and private costs: Public costs are those incurred by local, state, or federal government and private costs are to businesses and individuals, such as costs to an investor-owned water supplier for installing additional treatment (direct private compliance cost) and to the consumer in the form of higher water prices (indirect private compliance cost).
    d. Primary and secondary effects: Primary effects are those experienced by persons, companies or governments in response to the project or program, e.g., a local public utility implements conservation regulations to avoid expanding its wellfield (the hydrologic, engineering, legal, and administrative expenses are direct public program primary costs); secondary or "spillover" effects are happened on other individuals, businesses, and governments not involved in the activity, e.g., the hopeful pump installer loses a contract with the utility and goes out of business or because of increased pumping, a wetland disappears downstream because of a declining water table, reducing habitat for wildlife and educational opportunities of the local school.

(*continued*)

EXHIBIT 13.4 (continued) STEPS IN COST ASSESSMENT AND COST-EFFECTIVENESS EVALUATION

   e. Monetizable and nonmonetizable costs: Monetizable costs are those to which monetary units (e.g., dollars, pounds, and pesos) can be assigned, e.g., pollution control equipment to be installed valued at $1,550,000 per unit; nonmonetizable costs are those that cannot be assigned a value in monetary units, but may be quantified or not quantified, e.g., wetland habitat of 51 hectares (quantifiable) or elimination of a native species of burrowing animals (nonquantifiable).

12. Select the cost estimation technique:

    Comparative accounting: Specifying the individual activities for the project or program, such as planning, designing, constructing, operating, maintaining, and administering; assigning a value for the costs, based on market prices or professional experience; and summing the costs for a total cost.

    Modeling or systems engineering: Assigning and summing the costs derived from references to the steps in a process or installation and use of required equipment and structures.

    Surveys: Properly designing and conducting a question and answer format for eliciting cost information relevant to the project or activity (a statistically sound survey may be expensive).

    Combination of approaches: Use of comparative accounting for some aspects of the activity, and modeling and surveys for others.

13. Estimate the costs:

    Specify the time period: Usually in years, the time periods for planning, construction, and operation or implementation should be included.

    Incorporate the time value of money: Evaluation should include accounting for the value of money over time, e.g., the cost of an activity this year is higher than if that same cost were incurred next year. Costs can be evaluated in terms of "present value" or "future value" by applying a "discount rate" (see section "Discounting Rate and Time Value of Money" subsequently). Costs can also be compared as undiscounted monetary units to give decision makers a perspective of cost flow over time.

    Evaluate the incremental costs: Calculating the estimated costs above the baseline costs are the "incremental" costs of the project or program (and each option considered within the project or program) that should be applied to the overall cost analysis.

COST-EFFECTIVENESS ANALYSIS:

1. Can be applied to different approaches, varied combinations of approaches, or the same approach at varying degrees of attainment.
2. Should address the same objectives for alternatives evaluated using the same measures of results (e.g., parts per billion, cubic meters, meters of drawdown, person-years affected).
3. Should attempt to control and minimize the influence of other factors (e.g., use defined service area for all alternatives, multiple contaminants, other pathways of contamination) that would complicate evaluation.
4. Should focus on common measurement units for outcomes.

Many good references are available that provide detail on the various aspects of cost and benefit analysis, and are listed at the end of this chapter.

Source: Adapted from USEPA, *A Guide for Cost-Effectiveness and Cost-Benefit Analysis of State and Local Ground Water Protection Programs*, 1993, EPA 813-93-001.

Mathematically, cost-effectiveness analysis can be expressed as

$$C_{\mathrm{LC}} < C_{\mathrm{Ai}} \tag{Ineq. 13.2}$$

where

C_{LC} is the least-cost alternative from among the alternatives (A*i*) identified for analysis
C_{A} is the cost of other individual alternatives (*i*) considered in the analysis

For any particular alternative, A*j*, from among alternatives, A*i*, the costs considered in the analysis are summed and discounted for present value (PV) calculation over time *t* as

$$\mathrm{PV}(C_{\mathrm{A}j})_t = \sum_{t=0}^{t=n} \left[(C_{\mathrm{A}j})_t / (1+r)^t \right] \tag{13.1}$$

where

j is the particular alternative from among alternatives A*i*
r is the discount rate
t is the time period
n is the expected life of the project or program

Life-Cycle Costs

The stream of costs over time may be concentrated in one time period or may be spread out over time. These costs may also be "lumpy" in that capital costs (e.g., for equipment) can occur over several years initially and then may not be necessary for many years (e.g., 5 or 20 or more years). In between capital expenditures, operation and maintenance costs for the equipment may be the annual cost that may vary over time as equipment ages and wears out.

Some actions or projects involving investment in constructed or technology solutions may require replacement or upgrade at a point in the future. These recurring expenditures need to be accounted in calculating the net present value of costs. Even though the nominal costs appear large, when discounted to the present from a distant year, they will become smaller, the higher the interest rate applied to the analysis.

Next, we will consider benefits assessment that provides the basis for comparing the costs of a project or program to the benefits.

BENEFITS ASSESSMENT

To conduct benefits assessment for a CBA, steps analogous to cost assessment should be used. The two analyses should mirror each other in a "fundamental symmetry between benefits and costs as changes in the utilities of individuals" (Freeman, 1993, p. 488). These steps will not be repeated here. The benefits to be assessed derive from welfare improvement or gain.

Important to the assessment of benefits is the recognition of market and nonmarket goods. Market conditions assume competition resulting in one person's or business's private use of groundwater (or some other good) excluding another's use of and benefit from it. Nonmarket public goods have the characteristic of not having exclusionary use and all users benefit. Private goods benefits result from groundwater used in irrigation, industrial, and municipal purposes. Public goods benefits are derived from changes in groundwater quantity or quality affecting water levels, ecosystem sustainability, wildlife habitat, navigation, flood risk reduction, and recreation.

The use of groundwater for the benefits of its services is affected by a range of factors, including

1. Source of production—transmission costs may be involved in getting it to the point of use
2. Point of use—if there are multiple delivery points, distribution costs are involved

3. Quantity available or demanded—this may affect the size of the production, treatment, and distribution facilities
4. Quality available—this may affect the need for treatment or limit the ability to grow certain agricultural products
5. Climate—this may affect the demand for groundwater; arid environments have greater evapotranspiration rates
6. Duration of use—this may affect the type and quality of materials applied to its use and the time period over which benefits are calculated

These and other factors specific to a particular assessment will affect the benefits estimates.

Benefits by Type of Action

Benefits of actions affecting groundwater cover a range of types, including

1. Production—WTP for units of groundwater supplied
2. Conservation—Willingness to accept (WTA) cost savings for reduced groundwater supply to maintain the resource, rather than deplete it, or maintain the infrastructure investment in wells, pipes, and treatment plants, rather than expand or replace it; WTP for long-term water supply while reducing near-term consumption
3. Protection—WTP to avoid risk of contaminating the resource
4. Waste Disposal—WTP to dispose of wastes in the subsurface
5. Remediation—WTP to avoid further contamination of the resource
6. Ecosystem balance—WTP for sustaining the ecosystem and its known, and unknown, services
7. Future use—WTP to hold and manage groundwater for future uses (referred to as "option value") and future generations (referred to as "bequest value")

Benefits of Actions Affecting Groundwater

The benefits of actions affecting groundwater quantity and quality will be calculated differently based on the action (or objective). For "actions taken to produce groundwater" directly, the benefits are calculated using the price of water, without taxes or fees (which are transfer payments), across all services that can be quantified and monetized. Other methods of deriving the value of benefits, if the price of water cannot easily be determined, are described in the subsection titled "Benefit Estimation Methods." Calculating these economic benefits gives a monetary estimate of those services of water from its particular uses and provides the total economic value of water only for uses that can be monetized. Values of "*in situ*" groundwater use still need research (NRC, 1997, p. 53). Units of water multiplied by the prevailing local price are a quantified, monetized measure of benefit of groundwater production as a commodity value. Nonmonetized benefits can be listed and weighted as they relate to the decision to produce groundwater. The net present worth of an aquifer as a commodity may be given by (Hardisty and Özdemiroglu, 2005, p. 128; NRC, 1997, p. 64)

$$\mathrm{NPW}_{\mathrm{aquifer}} = \sum_{i=1}^{s} \sum_{t=1}^{L} [\mathrm{VW}_{it}/(1+r)^t] \tag{13.2}$$

where

$\mathrm{NPW}_{\mathrm{aquifer}}$ is the net present worth of the aquifer
i is the ith use of the aquifer, 1 through s
t is the time period, 1 through L, over which the ith use occurs
VW_i is the value of water in the ith use for time period t
r is the interest rate

The worth of each use of the aquifer is summed over the time period of that use and then all the uses are added together, providing one measure of the total economic value of the aquifer. Exhibit 13.5 shows the estimated economic value for one year of the groundwater in the three aquifers that had the largest total domestic and industrial use. These values could be inserted into the equation above for a specified planning horizon (e.g., 20 years) to calculate the net present value of the aquifers. Alternative water supplies from sources capable of providing water of comparable quantity, quality, and reliability could also have been used to determine the value of these aquifers (Hardisty and Özdemiroglu, 2005, p. 80).

EXHIBIT 13.5 ECONOMIC VALUE OF THE THREE AQUIFERS WITH THE LARGEST GROUNDWATER USE IN NEW ZEALAND

Aquifer	Domestic Allocation (m³/week)	Economic Value of Domestic Use ($NZ million/yr)	Industrial Allocation (m³/week)	Economic Value of Industrial Use ($NZ million/yr)
Christchurch-West Melton	3,374,255	60	4,102,439	2328.1
Heretaunga Plains	1,100,792	20	2,126,258	1078.7
Hutt	963,011	17	1,064,797	564.5

Source: NZMED, *New Zealand Water Bodies of National Importance for Domestic Use and Industrial Use*, 2004, URL: http://www.med.govt.nz/templates/MultipageDocumentTOC_12521.aspx (accessed June 29, 2007).

Note: $NZ = $US 0.658801, January 2, 2004.

For "actions taken to conserve, protect, or remediate," benefits arise from avoiding the need to supplement the water supply over conservation levels, for treatment or for alternatives to replace a contaminated resource. As noted in Hardisty and Özdemiroglu (2005) and Crocker et al. (1991), Raucher (1983) lays out a foundational framework to measure these benefits for the case of groundwater quality protection. This framework can be extended to groundwater quantity, in the case of depletion or groundwater mining. Typically, groundwater protection is implemented at a local level or site of potential or actual overuse or contamination. An aggregate measure can be developed for a program affecting many localities or sites. The expected net benefits from actions to protect groundwater may be given by

$$E(\mathrm{NB}_i) = E(B_i) - X_i \tag{13.3}$$

where

$E(\mathrm{NB}_i)$ is the expected net benefits of protection strategy i
$E(B_i)$ is the expected social benefits of protection strategy i
X_i is the social costs of conducting protection strategy i

Monetary outlays to implement a protection activity are often specified in public documents or business accounts and readily understood. Social benefits are, on the other hand, not often clearly specified or easy to understand. "The benefits of groundwater protection [or conservation] are defined by the change in the expected damage associated with contamination" (Raucher, 1983, p. 320) or depletion—worsening quality or lessening quantity. The expected damages—or, in the case of conservation, reduced-water-consumption-related expenses—E(D) are defined as

$$E(D) = p[qC_r + (1-q)C_u] \tag{13.4}$$

where

p is the probability (in the absence of policy i) that contamination [or depletion] will occur ($0 \leq p \leq 1$)

q is the probability that contamination [or depletion] would be detected before tainted water was used [or lower water table was observed] ($0 \leq p \leq 1$)

C_r is the expense of the most economically efficient response to the contamination incident [or depletion occurrence] ($C_r \geq 0$)

C_u is the cost incurred if contaminated water were used in the same manner as prior to the incident [or if the amount of water used was the same as prior to the water table being observed as lower] ($C_u \geq C_r$)

This is a projection or an estimate of these costs and may be further specified as

$$C_u = I_C + M_C + P_C + E_C \tag{13.5}$$

where

I_C is the illness cost (in the case of remediation or protection)

M_C is the mortality cost (in the case of remediation or protection)

P_C is the production or manufacturing cost in the case of remediation or protection, from adjusting processes to water of lesser quality or the change in production expenses in the case of conservation, from reduced water consumption resulting in lower production expenses

E_C is the losses to the ecosystem such as from unusable groundwater, lost or damaged habitat, or other lost or damaged ecosystem services that can be quantified and monetized

Key features of this framework highlight its application to actual situations. The incorporation of probabilities overtly indicates that uncertainty pertains to this evaluation, relating to the complexities of the subsurface environment and their implications on groundwater flow and contaminant transport (Hardisty and Özdemiroglu, 2005, p. 126). Groundwater elevation and contaminant data and modeling are important aspects of the analysis. The greater the time involved, the greater the number of receptors affected by a contaminant plume or a depleting cone of depression. The receptors may be people or local and regional habitat for flora and fauna.

Hardisty and Özdemiroglu (2005, p. 126) note that

> The endpoints of the argument reveal some interesting assertions. If, in the worst case, contamination [*or depletion*] is certain ($p = 1$) but impossible to detect ($q = 0$), groundwater would continue to be used in the same way and damage would result. The expected damage E(D) = C_u. Alternatively, if contamination [*or depletion*] remained certain ($p = 1$), but there was full certainty of detection ($q = 1$), then the least-cost remedial [*or conservation*] solution would be implemented, and so E(D) = C_r. Hence, for a monitoring policy that improved q, the expected net benefit would be $C_u - C_r$.

Least-cost response assumes full information and rational decision making and may not address uncertainty of the response's performance.

Additionally, time plays a critical role in the evaluation of benefits from groundwater protection (Raucher, 1983, pp. 322–323).

An expanding contaminant plume could affect more people or other life forms. Similarly, a growing cone of depression from groundwater production could affect many more users. Extended periods of time will result in greater damages and benefits to be included in evaluation.

The formulation does not include option value (WTP for the possibility of future use) for the affected groundwater. The framework could be constructed to recognize this value. Future values could also be accounted by having an infinite evaluation period or applying a zero discount rate.

Mathematically, the benefits of conservation, protection, and remediation can be expressed as follows (modified from Hardisty and Özdemiroglu, 2005, p. 130):

- For the conservation case:

$$B_{CE} = \sum_{t=0}^{T} D_{Ct} + D_{Et} \tag{13.6}$$

where

D_{Ct} is the projected future water production expense assuming no change in water use that would be averted from changed water use practices to reduce water demand beginning in time t

D_{Et} is the projected future water production expense assuming no change in water use that would be averted from engineered or physical water system or water appliance changes to reduce water demand beginning in time t

Note that where one of the approaches, D_C or D_E, precedes the other, one or the other of the subscripts may be $t + 1$ or $t + 2$ or some other numeral indicating the difference in the period, in which the practice or system change occurred beyond the other practice or system change. Thus, if the engineered system or water appliance change occurred three years after the water use practices changed, the equation might read

$$B_{CEt} = \sum_{t=0}^{T} D_{Ct} + D_{Et+3} \tag{13.7}$$

Expense-saving benefits from reduced water production include (AWWA, 2006, p. 70)

- Reduced water purchases from wholesale water agencies
- Reduced operation and maintenance costs (energy from pumping [production, treatment, and distribution] and lower chemical use)
- Reduced or deferred treatment plant capital expansion costs
- Reduced water storage costs
- Reduced wastewater processing costs (once the water is used)

The following equation can be used to estimate water savings (AWWA, 2006, p. 71):

$$E = R \times C \times V \tag{13.8}$$

where

E is the estimated reduction in water use from the conservation measure in units (liters or cubic meters per year) for the period (year) of interest

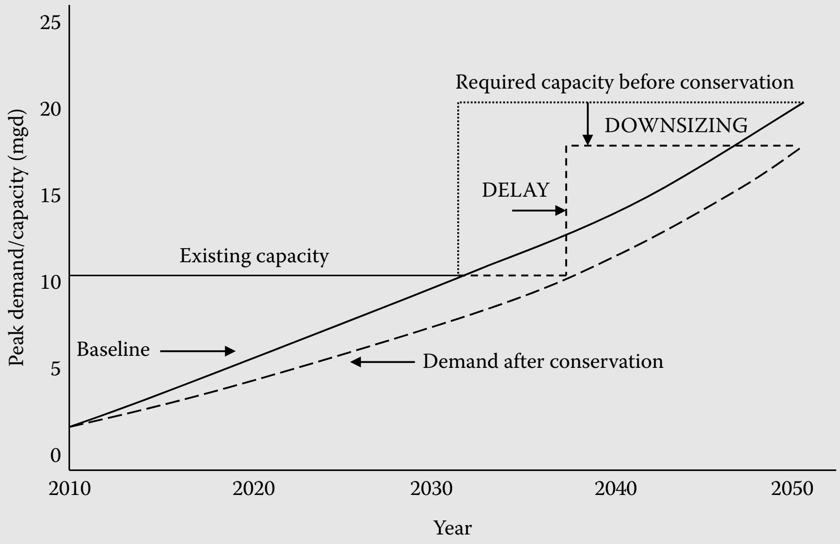
R is the percentage reduction in water use from the conservation measure, assuming all customers practice or install the measure for the period of interest

C is the percentage of coverage of the measure for the group of water users (market penetration) for the period of interest

V is the volume of water use without the water-conservation measure in units (liters or cubic meters per year) for the period of interest

To the estimated reduction in water use, E can then be applied to the annual unit cost of purchasing water from a wholesaler, the annual unit cost of operation and maintenance (principally for energy and chemicals, if treatment is needed), and the cost savings from delayed, downsized, or eliminated capital facilities, which would have been necessary to supply that volume of water annual. Planning for facilities usually accounts for peak demands above average daily demand. Conservation may mean delaying construction by several years with an associated monetary savings from capital expenditures and its debt service. If wastewater is treated centrally, these conservation measures may also translate into deferred wastewater treatment plant construction with similar savings (AWWA, 2006, pp. 73–82). Exhibit 13.6 shows the potential savings from delaying or downsizing capital facilities owing to conservation.

EXHIBIT 13.6 EXAMPLE OF DELAYING AND DOWNSIZING A CAPITAL FACILITY



Source: AWWA, *Water Conservation Programs—A Planning Manual*, *Manual of Water Supply Practices M52*, AWWA, Denver, CO, 2006, 75. With permission.

A similar relation would apply to the protection and remediation cases

- For the protection and remediation cases:

$$B_{ARt} = \sum_{t=0}^{T} D_{At} + D_{Rt} \tag{13.9}$$

where

D_A is the projected future damages and losses assuming no change in water use that would be averted from steps taken to avoid using contaminated water beginning in time t

D_{Rt} is the projected future damages and losses assuming no change in water use that would be averted from physical or engineered protection and remedial measures taken to prevent groundwater contamination or eliminate or reduce the volume of contaminated water beginning in time t

Note that the damage or loss that occurred in a time period before time t_0 (such as t_{-1} or t_{-2}) cannot be counted in this calculation but can be used to estimate or model the damage or loss in future time.

Exhibit 13.7 describes graphically the benefits from damages and losses averted. This description applies to both the "conservation case" as well as the "protection and remediation case."

The amount of benefit from preventing groundwater contamination may be understated if only exogenous risk mitigation is considered, such as actions taken by communities or responsible parties (Crocker et al., 1991). Collectively or individually, people may take actions to prevent their exposure because of their perception of the contamination and their exposure (or potential exposure) to it. The benefit of the avoided cost of these potential actions may not be trivial and could include finding alternative regional groundwater sources of water or moving from the affected area to another source of groundwater, if they would have the means to do so, as well as other preventive actions. The benefits derived from these actions, reflecting the individuals' WTP for them, should be included in the net benefit calculation where they can be identified. Another view of this matter is to consider the avoided cost of central action at the community level as a "floor" of the benefits of averting damages from contamination. Similarly, people, individually or as a group, may act to avoid perceived damage from loss of groundwater supply and implement their own actions to avert this possibility and ensure themselves of a long-term supply. Exhibit 13.7 describes the conceptual approach to consider damage and avoid the loss.

EXHIBIT 13.7 BENEFITS FROM DAMAGES AND LOSSES AVERTED FROM CONSERVATION, PROTECTION OR REMEDIATION

Graph 1

Area *a* represents damage or loss that occurred before action was taken in time t_0

Area *b* is the damage or loss projected to occur after action takes place in time t_0 continuing through the planning horizon t_2 from changes in practices

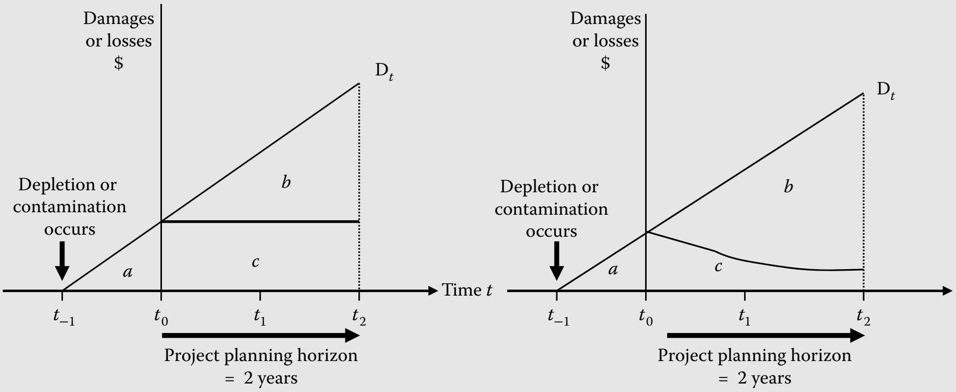
Area *c* represents the damage or loss projected to occur over the planning horizon from structural changes to reduce or eliminate the depletion or contamination

Graph 2

Areas *a*. *b*, and *c* represent damage or loss as in Graph 1. The differences are that

In Area *b*, damage may be greater because more people are affected

In Area *c*, damage is projected to become less over time because the contaminant concentration in the plume becomes less or the cone of depression slows its expansion



In Graph 1, damage or loss in the period prior to t_0 cannot be considered in benefit calculation since this was prior to the conservation, protection, or remedial action. If practices to avert damage or loss and structural changes are assumed to be totally successful (an ideal outcome that may not be achieved in practice), then total damages avoided include the areas represented by $b + c$.

In Graph 2, some factor has caused the cost of remediation to drop over time, perhaps natural attenuation. While the population has increased to make area *b* larger, the structural action contributes less to the overall damage.

Source: Modified from Hardisty, P.E. and Özdemiroglu, E., *The Economics of Groundwater Remediation and Protection*, CRC Press, Boca Raton, FL, 2005, 132–133. With permission.

In calculating benefits, neoclassical microeconomics indicates that they should be discounted to reflect the time value of money. In the cases described for conservation, and protection and remediation, the discounting equations are

- For the conservation case:

$$\text{NPVB}_{CEt} = \sum_{t=0}^{T} [(D_{Ct} + DEt)/(1+r)^t] \tag{13.10}$$

where NPVB_{CEt} is the net present value of conservation benefits

- For the protection and remediation case:

$$\text{NPVB}_{ARt} = \sum_{t=0}^{T} [(D_{At} + D_{Rt})/(1+r)^t] \tag{13.11}$$

where NPVB_{ARt} is the net present value of protection and remediation benefits

Similar equations may be developed for application to ecosystem balance and future use of groundwater. Relative to both ecosystem balance and future use of groundwater, actions may be taken to reduce future demand on the ecosystem and the existing stock of groundwater (similar to water conservation and any scale including a national or global level, such as reaching international agreement on water efficiency requirements for all water using appliances), improve ecosystem balance and water available for future use (such as improving recharge features in watersheds with large areas of human-constructed impermeable zones and pathways), and damage the ecosystem or future groundwater availability (e.g., destruction of vegetative cover and active soil zone that provides for infiltration of precipitation and cycling of water and nutrients). This aspect of benefits estimation needs further research to facilitate quantification and monetization. Issues of scale will be addressed in Chapters 13 and 14.

Note that in both the contaminant remediation and protection cases, the actual time of travel (for the remediation case) and the projected time of travel (for both cases) are important in calculating the discounted costs and avoided damages. In Exhibit 13.8, cost-effective placement of groundwater contaminant removal facilities must take into account the movement of the contaminant plume and the potential receptors, as well as the timing of the installation and initiation of removal operations. In the example, installation (and subsequent operation) of removal facilities near (and possibly somewhere to the left of) Receptor B prior to 2½ years following the contaminant release may not be effective, so the discounted costs should not be included before or in the second year. Thus, costs will be staged and incurred at (or projected to be incurred at) different times based on the hydrogeologic and contaminant migration evaluations.

Additionally, as the plume migrates, the contaminant concentration becomes less over time because of several subsurface processes (such as diffusion, dilution, and degradation). Thus, the projected health effects avoided of human receptors may be less (assuming prompt and effective action is taken in this case) depending on contaminant concentration "zone" in which they consume groundwater. The avoided costs per person would then be less. The receptors could also be important ecosystem factors related to groundwater, such as wetlands habitat or endangered subsurface species.

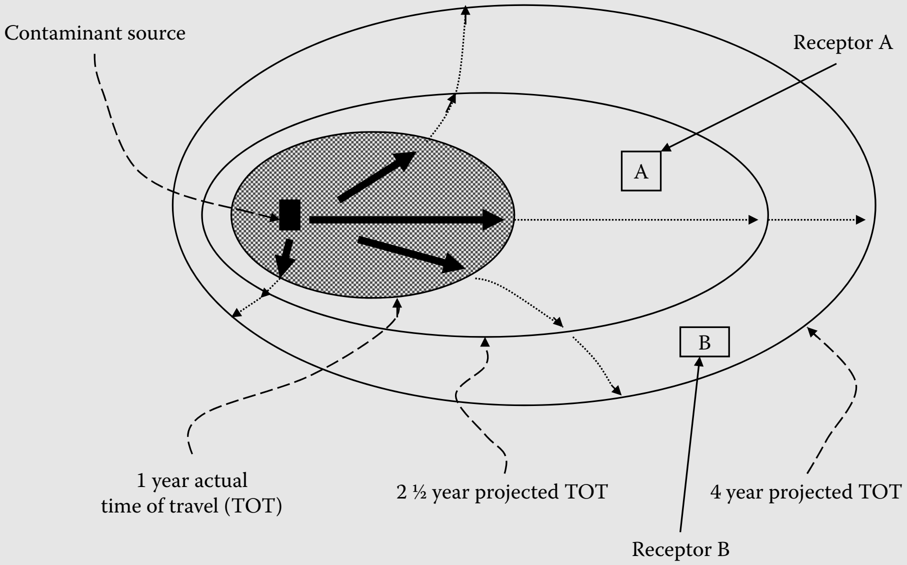
The value of benefits for balancing ecosystem requirements or future use may be calculated in a similar fashion to producing groundwater for current and nearer-term use.

- For the ecosystem balance or future use case:

$$\text{NPW}_{\text{aquifer}} = \sum_{t=1}^{L} [\text{VW}_{it}/(1+r)^t] \tag{13.12}$$

EXHIBIT 13.8 CONTAMINANT TIME OF TRAVEL AND PROJECT PLANNING

For contaminant remediation and protection projects, taking into account time of travel is important to placement of contaminant removal facilities relative to the source and the actual or potential receptors and then discounting associated costs and benefits.



where

$\mathrm{NPW}_{\mathrm{aquifer}}$ is the net present worth of the aquifer
t is the time period, 1 through L, over which the ith use occurs
VW_t is the value of water in time period t
r is the interest rate

In the ecosystem balancing or future use cases, any current price of water may not be applicable. In that regard, other methods for determining value may be appropriate. Some of the principal methods for doing that calculation are presented in the next subsection. Groundwater services, including some ecosystem services, are identified in Exhibits 3.17 and 3.19.

BENEFIT ESTIMATION METHODS

A range of methods have evolved to estimate benefits to people resulting from programs and policies directed at the environment and public health endpoints, including groundwater resources. These methods are summarized here. References that further elaborate on specific methods are provided at the end of this chapter. Young has prepared a particularly useful description and evaluation of methods to value water (2005). As noted previously, these methods have as their theoretical underpinning welfare economics, which indicates that changes in people's well-being can be evaluated by understanding the relationship between prices paid for quantities of goods and services in the market. Young divides methods into deductive and inductive methods (2005, pp. 47–49). He notes that if water is a variable factor of production, methods relying on the theory of producers' demand are appropriate (such as, if water is a fixed factor, then the analyst should use the theory of economic rents). The methods cover stated (direct) and revealed (indirect) preference measurement techniques.

A more detailed description of some methods that have received wider use are presented subsequently and are a summarization of Young (2005, selected portions of Chapters 3 and 4, which have more detailed descriptions and discussions of the methods):

1. *Market price/demand function (inductive)*: Direct observations of transactions for water can provide price and quantity information for short-term use or long-term acquisition of water rights, based on WTP (Young, 2005, p. 47); however, in most parts of the world purchase of water rights is uncommon (Young, 2005, 108). This approach gives a "commodity value" to the groundwater. From this information, the analyst can construct demand functions based on neoclassical economic concepts of supply and demand (Inductive, stated preference). In a competitive market, where the supply of inputs and the demand for output are not affected by participants entering or leaving the input or output markets, the value of water from projects that affect the quantity of water as an input or output can be calculated at the margin. In this case, Price = MC for water, then price multiplied by quantity provides the calculation of commodity value. For long-term transactions of water rights, asset valuation applies since these purchases reflect the preconceived present value of future net benefits (Young, 2005, p. 109). Asset valuation is discussed later in this chapter.
2. *Producers' residual income-input deduction (deductive)*: This method relies on the ability to calculate the income remaining to the producer after all inputs are priced and subtracted from it (Young, 2005, pp. 53–61, provides a detailed explanation of the theory summarized here) (Deductive). The remainder is an estimate of the value of water for that use. Assumptions include perfectly elastic supplies of inputs and a perfectly elastic demand for output. The procedure draws on the model of the firm and derives from developing a production function, such as

$$Y = Y(X, W, K) \tag{13.13}$$

where
Y is the output
X is the inputs other than water
W is the water
K is the capital

Introducing prices at the margin (a change in production from adding one more unit of input), the value marginal product (VMP) of input X_j is

$$P_y\ \partial Y(X, W, K)/\partial X_j$$

where
P_y is the price of Y
∂Y is an additional amount of product Y
$P_y \partial Y$ is the change in the producers' income
∂X_j is one more unit of input X_j
j is the jth input of 1 through j inputs

For a profit-maximizing firm, VMP for each input is that input's price. At the margin of production, variable costs must be covered to continue to produce output, dropping K from the relationship. Since the price of Y includes the producers' payment of the price of inputs, X_j, the producers' surplus is $P_y Y - P_x X$. If water is the variable input of interest, then $P_y\ \partial Y(X, W, K)/\partial W$ is the VMP for a marginal addition of water to the production process and stands as a proper quantification of the producers' benefit or WTP for increments of input used (Young, 2005, p. 56).

Extending this further, the calculation of the (residual) value of water as a factor input price is imputed by (Young, 2005, p. 61)

$$(Y \cdot P_Y) - [(P_M \cdot X_M) + (P_H \cdot X_H) + (P_K \cdot X_K) + (P_L \cdot X_L)] \qquad (13.14)^*$$

where
P_W is the imputed price of water as an input to production
P_M is the price of materials and equipment as inputs
P_H is the price of labor (human input)
P_K is the price of capital
P_L is the price of land
$X_{M,H,K,L}$ is the amount of input derived from materials and equipment, labor, capital, and land, respectively
X_w is the amount of water as an input

This method has greater applicability to industrial processes using water as a variable input.

3. *Producers' residual income-rent deduction (deductive)*: This approach is based on the concept of economic rents, which are monetary outlays greater than the price necessary to induce the use of a resource or the earnings a factor would receive elsewhere in the economy (Young, 2005, p. 62). British economist David Ricardo (1772–1823) published his theory on profits including "rents" in 1815 (NSSR, 2006) noting that more productive land received income greater than the cost of farm production and not due to any extra effort by the farm owner. He termed this increment of additional income "rent." Another British economist Alfred Marshall (1842–1924) developed the concept of "quasi-rents" to respond to the circumstance when resources may temporarily be in short supply and command higher returns to be put to use. Since water is a fixed input to agriculture and areas of limited (scarce) water resources draw on water for irrigation, groundwater use in those areas might attract additional income, such as in spot markets during times of drought (Tsur et al., 2004, p. 39). Current definition for "quasi-rents" then equates to compensation to fixed inputs. Neoclassical economics indicates that firms face perfectly elastic supply curves to obtain variable inputs at a stable price. In the market place, their output does not affect selling price and the price of their good is likewise stable. In this case, Total revenue (TR) = output (Y) multiplied by the price of Y in the market (P_Y), or TR = $Y \cdot P_Y$. Profit-maximizing firms will operate where Price = MC.

In Exhibit 13.9, the MC curve crosses the curves for average total cost (ATC, total cost divided by output) and average variable cost (AVC, variable cost divided by output) at their lowest point on the graph, as expected. Price P_Y corresponds to output Y_0 in the market. In this case, water is assumed to be scarce. Fixed costs, the difference between total and variable costs in the short run, cover the cost of the production facility or building and equipment. Variable costs must be paid to operate the facility for production to occur. In Exhibit 13.9, the area *c* is the rent to water (R_w) that a producer would receive in locations of water scarcity. Other rents (R_{nw}) not related to water (e.g., land, management, and other natural resources) and quasi-rents (QR) to the production facility and its other features including management and land are represented in area *b*.

The equation for total revenue that reflects rents and quasi-rents is

$$\text{TR} = \text{TVC} + \text{QR} + R_w + R_{nw} \qquad (13.15)^\dagger$$

and solving this equation for rents to water gives

$$R_w = \text{TR} - [\text{TVC} + \text{QR} + R_{nw}] \qquad (13.16)^\ddagger$$

(Young, 2005, p. 68).

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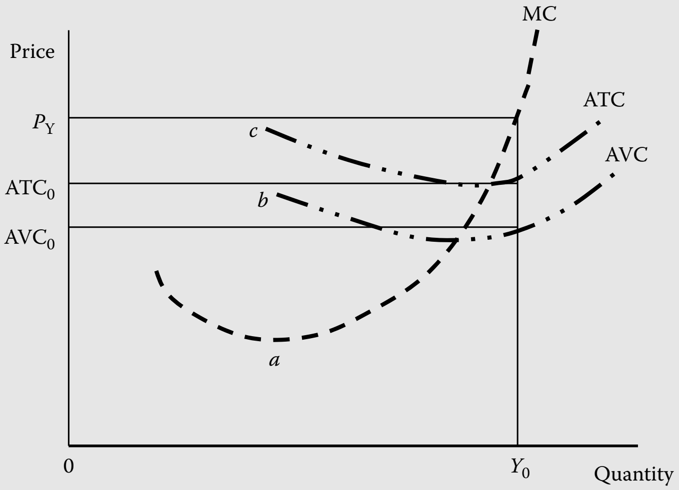
[*] See Young (2005).

[†] See Young (2005).

[‡] See Young (2005)

Rents are a measure of a change in welfare because of increased prices or decreased quantities available. Exhibit 13.9 presents this method in graphical form.

EXHIBIT 13.9 BENEFITS ACCRUING TO PRODUCERS AS RENT



Notes:
$a+b+c = Y_0$ multiplied by P_Y = Total revenue (TR)
b = Quasi-rents (QR) and any other nonwater rents
c = Water-related rent

Source: Young, R.A., *Determining the Economic Value of Water: Concepts and Methods*, Resources for the Future Press, Washington, DC, 2005, 66. With permission.

4. *Change in net rents (deductive)*: When prices and quantities of other inputs change in production moving from an existing condition to a new condition (without and with a project or program), the change in net income can be evaluated. This situation could exist for irrigated agriculture or other industrial production. This approach utilizes information of production functions in both conditions and approximates the product price as well as prices and opportunity costs of other factors (Young, 2005, p. 84).

   In this procedure, the net income or rent (Z) is the result of total revenue (quantity multiplied by price, $Y \cdot P_y$) from which the sum of all of input costs is subtracted (the amount of each input multiplied by its respective price, $X_j \cdot P_{xj}$), or

$$Z = (Y \cdot P_y) - \sum_{j=1}^{n} (X_j \cdot P_{xj}) \tag{13.17*}$$

   Assigning values $j = 0$ for the condition without the project or program and $j = 1$ with the project or program to allow comparison of the change in conditions (increased food production from expanded irrigated agriculture) resulting from implementing the activity ($\Delta Z = Z_1 - Z_0$, the change in net rent) and dividing by the change in the quantity of water input used (ΔW) results in the following equation:

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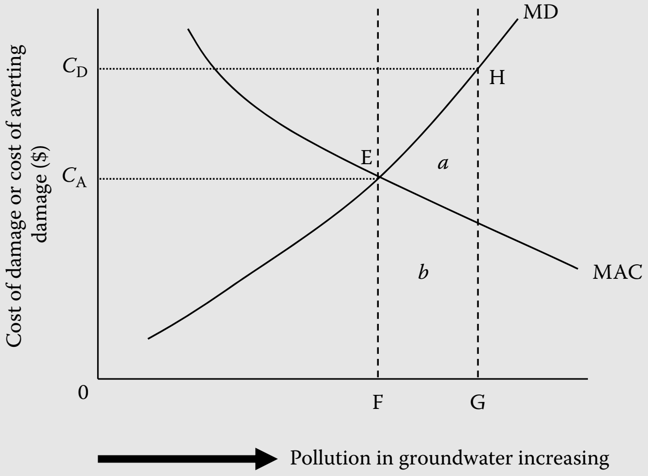
* See Young (2005).

$$\frac{\Delta Z}{\Delta W} = \frac{\left[(Y_1 \cdot P_y) - \sum_{j=1}^{n} (X_{j1} \cdot P_{xj}) \right] - \left[(Y_0 - P_y) - \sum_{j=1}^{n} (X_{j0} \cdot P_{xj}) \right]}{\Delta W} \qquad (13.18)^*$$

The net rent changes by the amount calculated for each unit of water used.

5. *Averting behavior and avoided damages (inductive)*: This method relies on establishing a relationship between pollution levels and expected health or environmental damages. This method incorporates knowledge of actual or expected damage associated with increasing contaminant concentrations, such as increasing cancer rates with higher concentrations of natural arsenic in groundwater (ATSDR, 2005). Costs could be measured for steps taken to avoid exposures at different levels of contamination, reflecting groundwater of different qualities. These costs for taking averting actions reflect a WTP to avoid potential health or other damages from expected pollution in groundwater. Therefore, these averting costs represent a measure of benefit if the costs can also be avoided. In the neoclassical model, the efficient outcome is one in which the marginal averting costs (MAC) to avoid potentially degraded groundwater quality just equal the marginal damages (MD) that would be incurred (Field, 1994, p. 95). Exhibit 13.10 portrays this result. The model implied by the graph suggests that a person would incur costs to avert (C_A) or avoid a damage as long as the damage cost (C_D) is greater than the averting cost for the level of pollution (Young, 2005, p. 133). If the pollution expected is at *G* and the acceptable level is F, the benefit received is area *a* plus area *b*, as long as the averting costs are likely to be incurred to get to the intersection point E from H. Area *a* + *b* is the net benefit of avoiding potentially degraded groundwater quality extrapolated for health protection from taking averting actions that, if not taken, would have resulted in higher pollutant levels expected at G.

EXHIBIT 13.10 GRAPHICAL PORTRAYAL OF AVERTING BEHAVIOR AND AVOIDED DAMAGES



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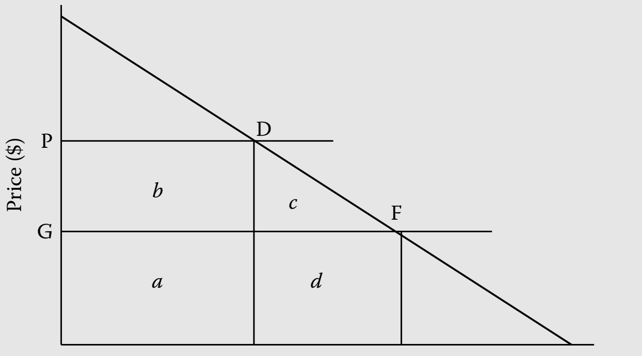
* See Young (2005).

6. *Alternative cost saving (deductive)*: This method compares two viable alternatives addressing the same objective and assigns a benefit to the least costly alternative equal to the difference in their costs. Young (2005, p. 102) notes that this method applies only in the few situations, in which a less costly project of predetermined output is compared with the next likely project that could accomplish the same objective, counting as a gross benefit the cost of the next likely project. Verification must occur that the next likely alternative project would have been developed if the less costly project was not constructed. This evaluation method again is constructed around the knowledge of production functions for the output of interest from two alternatives. The net benefit is the difference in the cost of the alternatives. The production functions lead to the specification of input costs. The less costly alternative may have resulted from a new technology or other circumstances, such as a public alternative that takes advantage of economies of organizational scale or a different technology that generated its consideration. A sufficient study of the alternatives should demonstrate that the demand for the outcome is adequate to be addressed, especially by public funds. For groundwater projects, this analysis may be between a private development project as compared with that of public development. The objective is to produce the output at least cost. This approach may be useful in evaluating water transfers from one sector to another (such as from agriculture to municipal). Caution should be used to ensure that the alternatives are each economically practical. Exhibit 13.11 describes this method. Production level *E* is expected from the project alternatives regardless of which is implemented (a common objective for the alternatives). Areas *a* + *b* represent the "gross benefit or WTP." The net benefit for producing at level *E* is *b*.

A different case with an expected total output of *W* can be defined with the assumptions of no specified scale, no perfectly inelastic demand for this good or its service (i.e., more would be demanded at a lower price), and a private alternative and a public alternative with one providing more highly priced water. The benefit attributable to the lower-priced alternative is the combined area of *b* + *c* because the alternative produces at level *W* with price *G* responding to greater demand for water at less cost.

EXHIBIT 13.11 EVALUATION OF ALTERNATIVES' COSTS



Source: Young, R.A., *Determining the Economic Value of Water: Concepts and Methods*, Resources for the Future Press, Washington, DC, 2005, 103. With permission.

7. *Travel cost (inductive)*: The travel cost method is the original revealed preference method that can be used to quantify the nonmarket value of ecosystem assets, and was developed by economist Harold Hotelling. It was first applied to estimating the value to visitors of parks in the United States, which had no entrance fees at the time (mid-1950s), by collecting and aggregating data on visitors' expenses for travel, lodging, and equipment in experiencing the parks' ambience and attraction (Hanemann, 2005, p. 9). Even though the parks had no market price for entrance, these expenses (reflecting market prices for those goods and services) are taken to be an estimate of the parks' values to those visitors and, more broadly, of benefits from water-based environmental settings (Schiffler, 1998, p. 41).
8. *Hedonic property value (inductive)*: This method relies on revealed preferences of purchasers of properties that have environmental characteristics, including water availability and quality features, which affect their price. The objective is to determine the value attributable to a particular environmental characteristic. Property prices in the area of interest are compared with property prices in a control area, assumed not to be affected by the characteristics being examined. The data are collected in the areas and applied to multiple regression analyses to calculate an expected price for the properties in each group and estimate the difference and contribution of the value of explanatory variables, which include the characteristic of interest, to the price of the properties (Merrett, 1997, p. 168). For groundwater, environmental characteristics might be depth to the water table, natural (ambient) water quality, or contamination.
9. *Contingent value (inductive)*: The contingent valuation method (CVM) also is based on revealed preferences of people for particular outcomes affecting nonmarket public goods. The simplest form of this method asks a representative group of people directly about the monetary value they have—or the greatest payment they would be willing to make—if a hypothetical change in a good or service derived from the ecosystem occurred if a market existed for that good or service (Freeman, 1993, p. 165; Field, 1994, p. 149; Merrett, 1997, p. 169). Assuming the responses are honest, they are considered actual statements of the value for ecosystem goods and services (Freeman, 1994, p. 165). The basic steps in a contingent value evaluation are (Field, 1994, p. 149)
   a. Identify and describe the ecosystem or human health characteristic to be examined
   b. Identify participants to respond to survey questions, including the statistical processes to select the participants
   c. Develop and conduct a questionnaire to survey participants by in-person, telephone, or mailed interviews
   d. Analyze responses to the questionnaire to estimate the monetary value for the participant group of the change in the characteristic evaluated

After a detailed review of the use of CVM relative to the environmental damages from a major oil spill, an expert panel in the United States issued guidelines for CVM surveys (Young, 2005, p. 141):

a. "Discrete choice" format of questions resulting in "yes" and "no" answers should be employed, similar to decisions people make in buying goods or voting on public issues.
b. In-person interviews are more desirable than telephone contact and mailed surveys.
c. A clear description of the environmental condition to be affected by a program or policy.
d. Notices in surveys concerning responses should indicate that WTP for or avoid environmental changes would decrease moneys for other economic exchanges.
e. Messages in surveys about "substitutes" for environmental changes (such as alternative water sources).
f. Supplemental questions should solicit participants to indicate an understanding of the potential effect of their responses and the rationale of their answers.

10. *Choice modeling (inductive)*: Derived from psychologists, attention to consumers' choosing among goods with varying features in the market, such as groundwater of different qualities, choice modeling considers the utility people hold for different characteristics of a good or service when selecting from multiple possibilities (Young, 2005, p. 148). In this survey approach, respondents are presented with alternatives having different features, including cost of the alternative, and are asked to rank the alternatives, expressing preference in their ranking. The alternatives include a "status quo" to set a baseline. The difference in the cost of the alternatives compared is evaluated as the marginal WTP for changes in a nonmarket situation (Freeman, 1993, p. 327).

Additional methods for estimating the monetary value of benefits for CBA are provided in Exhibit 13.12. Reviews and critiques of these methods can be found in texts by Young (2005) and Merrett (1997) and provide the basis for the disadvantages listed in the exhibit. Young (2005) provides an extensive explanation of the methods, their theoretical underpinnings, and their applications.

Two methods are not included in the list of Exhibit 13.12 because of issues of overestimation and misspecification of benefits, input–output modeling and regional multipliers, while useful planning tools may overestimate WTP for transactions involving water. The "value-added" approach that is incorporated in them counts certain economic transactions, such as payment of taxes or use fees, as benefits, but in CBA, these would be considered as a variable production cost. A detailed discussion of this issue appears in Young (2005, pp. 88–98).

Further note on regional benefits estimation. Hanemann (2005, pp. 28–29) reviewed macroregional (subnational-level) estimates of economic development benefits from water projects in the United States and found no significant relationship between water development and population or economic growth. This may suggest a transfer from one set of economic activities to another within a region or among regions. At the microlevel, however, a relationship can be shown between water availability and employment. Hanemann further argues that water availability may be neither a necessary nor sufficient condition for economic development, even though it is essential to life and certain production processes. Economic development is the result of a complex set of linkages among factors, producers, and consumers. Depending on the circumstances, water may or may not be a critical factor for economic development.

BENEFITS TRANSFER

Extending the understanding of the benefits associated with groundwater and its protection is important to individual, industrial, local, state, or national policy for its best use. An additional step in this process is the procedure of "benefits transfer." Benefits transfer allows an evaluator to use the results of previously completed studies of benefits in other situations and circumstances. The procedure of benefits transfer, summarized in Exhibit 13.13, describes the conditions that should be considered to make the most use of these other primary results in similar cases. A major focus of the benefits transfer method is to obtain estimates of benefits that will be reliable to the user. An advantage to benefits transfer is that it potentially reduces the cost of quantifying benefits by not having to conduct another field survey, thereby drawing on the productive efforts of others.

The procedure of benefits transfer allows the benefits estimator to extract the evaluation outcomes of other studies and reconcile them to the case(s) now examined. Best professional judgment in extending such outcomes is paramount to a successful application of this technique, which is widely used in establishing the resource values for many purposes, including policy and regulation development. A cautionary note to the wide application of this method is that if highly accurate estimates are the project objective, then a well-formulated evaluation of benefits through a field project should be conducted. The assumptions and other differences in the use of others' studies will necessarily introduce variability in the benefits transfer results and should be clearly documented.

EXHIBIT 13.12 SUMMARY OF METHODS FOR BENEFIT ANALYSES

Method Name	Brief Description	Applications	Advantages	Disadvantages
Deductive Methods				
Producers’ residual income	Measure of the difference in the VMP of final production and the VMP of inputs based on the models of the producers’ net income or rents, assuming prices of market outputs and other inputs remain the same	Private goods: Applies to production and treatment of groundwater and other resources at-source for producers or at-site for consumers; widely used for irrigation projects and programs	Provides a close approximation of benefits	Assumptions that market prices for outputs and inputs remain unchanged are restrictive; requires considerable and reliable estimates of input prices; difficult in estimating cost of owned inputs (e.g., equity capital, entrepreneurship, management, and land)
Producers’ change in net rents	Measure of the value of the change in factor inputs to production based on models of producers’ net income or rents, assuming prices of market outputs and other inputs remain the same	Private goods: Applies to production and treatment of groundwater and other resources at-source for producers or at-site for consumers	Provides a close approximation of benefits	Assumptions that market prices for outputs and inputs remain unchanged are restrictive; requires considerable and reliable estimates of input prices; difficult in estimating cost of owned inputs
Producers’ supply or cost function	Computation of the area underneath the supply curves after a change in service flow	Private goods: Applies to production and treatment of groundwater and other resources at site	Computation not difficult if supply curves are available	Data intensive
Alternative cost savings	Measure of the difference in cost between the two best alternative projects addressing the same objective	Private goods: Applies at-source or at-site for water as an intermediate good for agriculture and industry and for household consumption	Useful to evaluate projects, programs, and water transfers among using sectors	Data intensive; assumptions of future costs for long-lived projects and programs may be problematic
Inductive Methods				
Market price/ demand function	Direct measure of exchange value for a commodity/graphical relationship between price and quantity demanded	Private goods: Applies to all commodities offered for sale in the market, including groundwater and its substitutes, providing WTP at-source or at-site	Provides the most direct measure of commodity value	Does not incorporate passive (nonuse) or intrinsic values

(*continued*)

EXHIBIT 13.12 (continued) SUMMARY OF METHODS FOR BENEFIT ANALYSES

Method Name	Brief Description	Applications	Advantages	Disadvantages
Inductive Methods				
Consumer/producer cost savings	Measure of the value of the decrease in factor inputs to production, assuming prices of market outputs and other inputs remain the same	Private goods: Applies to production and treatment of groundwater and other resources at-site	Provides a close approximation of benefits	Assumptions that market prices for outputs and inputs remain unchanged are restrictive
Supply or cost function	Computation of the area underneath the supply curves after a change in service flow	Private goods: Applies to production and treatment of groundwater and other resources at-site	Computation not difficult if supply curves are available	Data intensive
Contingent valuation	Expressed preference done through survey of a representative sample of relevant population to obtain stated preference for good or service contingent on scenario describing a hypothetical but realistic market event to derive population's WTP for the event	Public goods: Used for a wide variety of changes at-source or at-site, including water quality, water level, aesthetic and ecological; also applied to passive (nonuse) values; could incorporate mortality risk reduction values (see subsequent text)	Provides direct expression of value for situations identified; adaptable to a range of policy applications	Subject to more criticism if used for total use value; hard to distinguish use and passive (nonuse) values; caution needed in conducting these surveys to obtain reliable results; challenges to method: people not forced to pay may not fully comprehend the situation described, "anchor" price, and information presented can influence outcome
Choice modeling	Expressed preference involves relating survey responses of interviewees who rate or rank outcomes of scenarios or equivalent sets of alternatives to observed prices for similar outcomes, deriving WTP	Public goods: Applied to a range of amenities, such as water quality and recreation	Provides direct measure of interviewees' preferences	Relatively complex in presentation
Risk–risk trade-off	Asks interviewees to compare places by cost of living, risk of a particular disease, and risk of a widely practiced and insured activity that could result in death	Public goods: Applied to the avoidance of disease; could incorporate mortality risk reduction values (see subsequent text)	Provides direct measure of interviewees' preferences	Limited trade-offs considered

Wage-risk studies	Evaluates relative risk through worker acceptance of higher wages for greater occupational risks	Public goods: Widely used to provide figures for reducing the risk of death (mortality)	May give most defensible estimates of reducing mortality risk	Workers voluntarily take risk on the job, whereas environmental risk (such as exposure to chemicals in the air) is involuntary; interviewees may not be the affected population
Averting behavior studies	Revealed preference estimates of WTP through evaluating measures that individuals take to reduce risk	Public goods: Applied at-site to avoid drinking water contamination and other contaminant avoidance (e.g., use of bottled water, home treatment of tap water, and water softening)	Provides direct measurable steps that the individuals may take to reduce risk	May understate WTP by only relying on actions taken; may be difficult to examine specific motive for action (e.g., use of bottled water)
Avoided cost studies	Revealed preference using comparison of expenditures before and after regulation or action, with the difference being a benefit estimate	Public goods: At-site valuation of water distribution system corrosion control; groundwater remediation; aesthetic qualities of water; damages to materials	Expenditures may be readily available; method easy to apply; provides useful input to policy development	May not be a true measure of benefits if effects on consumers are not accounted for
Cost-of-illness Studies	Evaluates medical costs and lost wages (or other monetary losses) of ill persons	Public goods: Widely used to evaluate morbidity costs (nonfatal health effects)	Method well developed and easy to understand; types of costs readily measured; many studies already exist	Does not provide WTP estimates; economic theory does not provide much support for method; may overstate WTP where insurance encourages people to seek treatment they would not pay for; does not incorporate WTP for risk aversion
Mortality risk reduction valuation	Uses empirically determined estimates of the value of a statistical life (VSL), derived by adding each person's risk reduction for an affected group; a variant is value of statistical life-year (VSLY)	Public goods: Used for evaluating the benefits of health-risk reduction for all types of environmental media	Can be applied through contingent valuation and other methods	VSLY is not sensitive to factors such as current age, latency of effect, life years remaining, and social valuation of different risk reductions

(*continued*)

EXHIBIT 13.12 (continued) SUMMARY OF METHODS FOR BENEFIT ANALYSES

Method Name	Brief Description	Applications	Advantages	Disadvantages
Inductive Methods				
Morbidity risk reduction valuation	Cost-of-illness studies are sometimes used; WTP studies are more appropriate	Public goods: Used for evaluating the benefits of health-risk reduction for all types of environmental media	Incorporates illness in benefits estimates where necessary	Available literature does not address many illnesses; benefit transfer techniques may not fit all applications; sources of bias should be identified and discussed
Hedonic price/ property value	Revealed preference through statistical evaluation of property price incorporating value (implicit price) of the amenity	Private or public goods: Used for at-source evaluation of water availability and impact of contamination of water sources	Data is readily available	Extent of incorporating value of amenity into property price not clear
Travel cost	Revealed preference measure of travel distance and cost of travel to recreation site or water level/quality change for sample visitors to derive a demand curve	Public goods: Used for at-source evaluation of water level or quality change and recreational activities	Gathering data is time intensive	Relies on travel distance and cost of travel as a proxy for price of visit
Benefits transfer (see text and exhibit subsequently)	Use of information from other studies of similar circumstances	Private or public goods: Used for the range of environmental media	Reduce time and resources needed to conduct study	Dependent on the quality of original studies and similarity of circumstances of project details to original studies

Sources:

1. Abstracted from USEPA, Assessing the benefits of drinking water regulations, Washington, DC, 80, 2002.
2. Bergstrom, J.C. et al., *J. Am. Water. Resour. Assoc.*, 32, 2, 279, 1996.
3. Young, R.A., *Determining the Economic Value of Water: Concepts and Methods,* Resources for the Future Press, Washington, DC, 2005, 47.

EXHIBIT 13.13 BENEFITS TRANSFER PROCEDURE

A concise statement of a five-step benefits transfer procedure is

1. *Specify the baseline effects.* Document the specific resource, health, population, amenity, legal, and other effects that may be associated with the action (project, regulation, etc.), the changes resulting from these effects, and any uncertainties in the body of knowledge of these effects.
    a. For groundwater, the full range of effects may include changes in the resource, health outcomes, property rights, and aesthetic amenities.
    b. The specific changes may address resource conditions (e.g., quality, quantity, water table and wetland fluctuations, and ground and surface water interactions), ecological impacts (flora and fauna), personal physical signs (e.g., in thyroid disease, loss of energy, weight loss, inability to work, and depression), population effects (e.g., age categories, previous conditions changed, and size and nature of sensitive subpopulations), legal and other transaction costs (e.g., access lost, alternate water supply, water treatment requirements, and legal documentation and permits), landscape appreciation (e.g., vegetation changes and loss of pristine condition), and temporal aspects (e.g., frequency and length).
2. *Find related results.* Conduct a literature search for studies with the corresponding or comparable objectives, outcomes, and effects expressed in economics terms.
3. *Examine reported results for "quality and applicability."* Relative to "quality," ascertain that "accepted best practices for the methods used" (including statistical design and peer review) produced the results. Evaluate "applicability" relative to (1) "the similarity of the effects"; (2) the correspondence of physical conditions, human effects, and legal aspects; and (3) "the ability to adjust for differences between the study [baseline] scenario and the policy [proposed action] scenario."
4. *Convey the estimates.* Use the results of the other studies in the description of benefit estimates for the proposed action for the applicable effects. These estimates may derive from a single-point estimate from one study, an equation obtained from econometric analyses, or subsuming the results of many studies through statistical methods (Atkinson et al., 1992; Boyle et al., 1994).
5. *Analyze and communicate uncertainty.* Describe the implications of uncertainty on the new estimates for the proposed action. Typically, each step of the benefits transfer will also have uncertainty associated with it. The studies' scenarios (physical condition, illness, population characteristics, property rights relationships) will not be in exact fits with the proposed action. Sensitive analyses and qualitative description of differences will be useful in portraying uncertainty.

Sources: Abstracted and modified from EPA, Assessing the benefits of drinking water regulations. Washington, DC, 80, 2002.

COST–BENEFIT ANALYSIS

CBA is firmly established as the economic basis for public decisions affecting natural resources and the environment. CBA can also be applied to the financial analysis that an individual or corporation may do for private transactions taking into account the factors outlined in Exhibit 13.3. CBA can be applied to decisions about water production from wells by both public and private sector interests. From an environmental regulatory standpoint, the United States Environmental Protection Agency has issued its "Guidelines for Preparing Economic Analysis" (USEPA, 2000a), which provide the basis for evaluating the cost of pollution control regulations compared with damages reduced or avoided. For groundwater-related actions, these guidelines can be applied to regulations for underground injection control (UIC), underground storage tanks (UST), Resource Conservation and Recovery Act (RCRA) (for hazardous waste facilities), Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA or "Superfund") (for abandoned hazardous waste sites), Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), and the Toxic Substances Control Act (TSCA). However, different issues remain in its application, not the least of which is the problem of identifying, quantifying, and monetizing benefits, such as the value of human life. Other issues surround the topic of the appropriate discount rate to apply to future benefits and costs, the principal one being whether future benefits relating to irreversible resource or environmental situations should be discounted or, if so, at what rate.

CBA typically is applied to public sector projects and sources to determine whether these public activities have a positive net benefit. This analysis examines public projects from a societal standpoint, not just obvious benefits and costs, but also benefits and costs of less than obvious receptors. Receptors of costs or benefits might even be in jurisdictions not accounted for in the original CBA. This would occur in a public project in which costs and benefits were only reported for the immediate locality, rather than for an entire watershed and its hydrologic cycle, considering the transitory and interlocal (or interstate or international) effects. Thus, care must be taken in using assumptions for CBA, since this method could be used to derive almost any outcome. Special caution should be exercised in circumstances for which a cost or benefit is derived but no market price exists or if an externality is involved in the result of a decision, the market price does not adequately incorporate it (LBS, 2006).

The types of public actions to which CBA is typically applied relative to groundwater are

1. Site-specific activities or projects, such as establishing a new wellfield to supply water to a community, construction of a sludge disposal landfill, or purchase of land around a wellfield to prevent potentially contaminating activities from locating over community groundwater supplies
2. Statutory or regulatory programs, such as statewide or national implementation of wellhead protection (a voluntary program) or monitoring standards for hazardous waste disposal facilities

To summarize, the fundamental steps of CBA are as follows:

1. Clearly specify the objectives of the activity, project, or program
2. Specify the alternatives that address the objectives
3. Determine the timeframe or planning horizon
4. Specify the evaluation area affected by the activity, project, or program
5. Identify the full range of effects that might be anticipated
6. Determine the baseline conditions of the resource (e.g., concentration of chemical or biological parameters) and other factors and inputs (e.g., current number and production capability of wells)
7. Quantify the inputs and outputs related to accomplishing the objectives within the evaluation area
8. Identify the social costs and benefits of the inputs and outputs
9. Monetize, where possible, and otherwise quantify the social costs and benefits
10. Specify and apply the discount rate or range of rates to future benefits and costs
11. Document all assumptions made in the analysis
12. Determine the net benefits or costs

The economist can then inform the decision makers of the method, steps, assumptions, and results of the CBA as factors in the decision process.

NET BENEFITS CALCULATION

The net benefits calculation requires the expected costs to be subtracted from the expected benefits. Both the benefits and costs are affected by the geologic matrix containing the aquifer as well as the nature of the human and ecosystem receptors. The net benefit calculations are as follows:

- For the groundwater production case:

  In this case, the commodity value (or benefits) of groundwater is discounted and reduced by the discounted costs to produce it. This calculation can also be used to compare the value of groundwater to costs of conservation, protection, and remediation, as one measure of the net benefits of these activities as compared with other alternatives, such as expanded groundwater production for a similar amount of groundwater to be supplied. The calculation for monetized activities of the project or program when considering groundwater production is

  $$\sum B-\sum C=\left\{\sum_{i=1}^{s}\sum_{t=1}^{T}\left[\mathrm{VW}_{it}/(1+r)^{t}\right]-\left[\left(C_{P1}+C_{St}+C_{Et}\right)/(1+r)^{t}\right]\right\} \tag{13.19}$$

  where

  i is the ith use of the aquifer, 1 through s

  t is the time period, 0 through T, over which the ith use occurs

  VW_{it} is the commodity value of water in the ith use for time period t

  r is the interest rate

  C_{Pt} is the expense to produce (or conserve, protect, or remediate, depending on the activity being evaluated and the economic comparison being made) the groundwater in time period t

  C_{St} is the social cost to produce (or conserve, protect, or remediate) the groundwater in time period t

  C_{Et} is the ecosystem cost to produce (or conserve, protect, or remediate) the groundwater in time period t, which some economists consider to be part of social costs but is explicitly recognized in this equation

  This equation says that the net benefit of producing groundwater is equal to the discounted value of the groundwater produced from the aquifer for its range of uses subtracting the costs to produce the groundwater and the costs to society and the ecosystem on which it depends.

- For the conservation case:

  The conservation case focuses on changed water demand and its associated reduced and therefore avoided production expense as compared with the costs of implementing a conservation program:

  $$\sum B-\sum C=\sum_{t=0}^{T}\left\{\left[D_{Ct}+D_{Et}-C_{Ct}-C_{Et}\right]/(1+r)^{t}\right\} \tag{13.20}$$

  where

  t is the time period, 0 through T

  D_{Ct} is the projected future water production expense assuming no change in water use that would be averted from changed water use practices to reduce water demand beginning in time t

  D_{Et} is the projected future water production expense assuming no change in water use that would be averted from engineered or physical water system or water appliance changes to reduce water demand beginning in time t

  C_{Ct} is the expense to conserve the groundwater in time period t

C_{St} is the social cost to conserve the groundwater in time period t

C_{Et} is the ecosystem cost to conserve the groundwater in time period t, which could also be considered a part of social cost

This equation says that the net benefit of conserving groundwater is equal to the discounted value of the projected future reductions in groundwater demand to the community, state, or nation and the ecosystem subtracting the expected costs to conserve the groundwater and the associated costs to society and the ecosystem on which it depends.

- For the protection and remediation case:

  The protection and remediation case compares avoided contaminated groundwater-related damages to the costs of protection or remediation:

$$\sum B - \sum C = \sum_{t=0}^{T} \left\{ \left[D_{At} + D_{Rt} - C_{ARt} - C_{St} - C_{Et} \right] / (1+r)^t \right\} \tag{13.21}$$

where

t is the time period, 0 through T

D_{At} is the projected future damages and losses assuming no change in water use that would be averted from steps taken to avoid using contaminated water beginning in time t

D_{Rt} is the projected future damages and losses assuming no change in water use that would be averted from physical or engineered protection and remedial measures taken to prevent groundwater contamination or eliminate or reduce the volume of contaminated water beginning in time t

C_{ARt} is the expense to avoid or remediate groundwater contamination in time period t

C_{St} is the social cost to avoid or remediate groundwater contamination in time period t

C_{Et} is the ecosystem cost to avoid or remediate groundwater contamination in time period t, which could also be considered a part of social cost

This equation says that the net benefit of avoiding or remediating groundwater contamination is equal to the discounted value of the projected future damages and losses to the community, state, or nation and the ecosystem subtracting the expected costs to avoid or remediate groundwater contamination and the associated costs to society and the ecosystem on which it depends.

Other authors have indicated that other benefits, such as social benefits including option value and ecosystem value, if monetizable, can be added to the benefits in the equations mentioned earlier using the appropriate methods identified previously (for example, see Bergstrom et al., 1996; NRC, 1997).

The presentation of net benefits may occur in a descriptive or a tabular format for ease in comparison. Exhibit 13.14 provides an example of a net benefits analysis of groundwater protection for community water supply. It shows that the net benefits are significant for protecting groundwater from contamination. Further, it indicates benefits from avoided costs of contamination of groundwater may be substantially understated in the case examined. Exhibit 13.15 provides one tabular format to present net benefits.

QUANTIFIABLE NONMONETIZABLE AND NONQUANTIFIABLE COSTS AND BENEFITS

Quantifiable but nonmonetizable and nonquantifiable costs and benefits may be significant to decisions about water projects and programs (USWRC, 1983; Hardisty and Özdemiroglu, 2005). Several approaches exist to describe these costs and benefits (USWRC, 1983; OMB, 2003; Hardisty and Özdemiroglu, 2005). The approach outlined here uses an assessment of likelihood for prospective results of action affecting groundwater based on technical evaluation:

EXHIBIT 13.14 A BRIEF EXAMPLE OF NET BENEFITS ANALYSIS: GROUNDWATER PROTECTION IN LANCASTER COUNTY

This brief example considers the actions of a group of communities in the United States making decisions resulting in the incurrence of the costs for protecting their wells and groundwater supply from contamination through a process of "wellhead protection." Wellhead protection (WHP) in the United States typically consists of (1) forming a community planning team, (2) defining the land area to be protected for the community's groundwater supply, (3) identifying and locating potential contaminants affecting that area, (4) managing the protection area for safe groundwater supply, and (5) planning for the future (USEPA, 1991). This example employs the net benefit steps identified in the preceding text.

The setting in 1994: Four small communities in eastern Lancaster County, Pennsylvania with a combined population of approximately 19,000 desired to implement a wellhead protection program to protect their groundwater, which was the source of their water supply. The geology underlying the communities is Terre Hill—conglomerates, sandstone, and shales of the Hammer Creek Formation; New Holland and Earl and East Earl Townships—dolomite. Eastern Lancaster County's bedrock is highly fractured. Groundwater quality is generally good, although nitrate levels are a concern for most of the wells. New Holland has observed elevated TCE levels in some wells. The combined number of wells serving these communities is eleven.

Approximately 112.7 km to the west of Lancaster County, the town of Gettysburg, Pennsylvania, experienced a major groundwater contamination situation from leaks and spills of commercial operations. This contamination included tetrachloroethylene (also referred to as perchloroethylene or PCE), trichloroethylene (TCE), 1,2-dichloroethylene (1,2-DCE), benzene, and vinyl chloride, which threatened the municipal wells. The contaminant plume had organic chemical concentrations ranging from 210 parts per billion (ppb) to 36,300 ppb. The geology is principally shale and sandstone with some limestone.

1. *Specify objectives*: Minimize contamination of the communities' groundwater supply.
2. *Specify alternatives*: (1) Do nothing; (2) establish a wellhead protection program; or (3) establish a WHP program and implement groundwater monitoring.
3. *Determine planning horizon*: 10 years.
4. *Specify evaluation area affected*: Terre Hill, New Holland and Earl and East Earl Townships, Pennsylvania.
5. *Identify effects anticipated*: If no action is taken, groundwater supply could become contaminated, resulting in the treatment of groundwater for public supply; New Holland had elevated levels of TCE most likely from industrial activity. If action is taken to implement wellhead protection, contamination potential is significantly reduced in all the communities.
6. *Determine baseline conditions of the resource*: These conditions are described earlier in the setting; other factors include depths of wells ranging from 73.8 to 188.9 m. Withdrawal production ranges from 163.5 cubic meters/day for the community (New Holland) with the deepest well to 3,785 cubic meters/day for the community (East Earl) with the shallowest well.
7. *Quantify inputs and outputs related to accomplishing objectives within area* (all 1994$US):

(*continued*)

EXHIBIT 13.14 (continued) A BRIEF EXAMPLE OF NET BENEFITS ANALYSIS: GROUNDWATER PROTECTION IN LANCASTER COUNTY

Alternative 1 (do nothing):

- a. Inputs:
    - i. Possible contamination of all or some of 11 wells in eastern Lancaster County with a similar result to the nearby community of Gettysburg
    - ii. Contamination "likely" as evidenced by nitrate and TCE contamination of groundwater observed
    - iii. Jeopardizing health of 19,000 residents
- b. Outputs:
    - i. Closed wells
    - ii. Water supply reduced and water not withdrawn
    - iii. Health effects if unhealthful water quality results observed
    - iv. Potential for need to obtain alternate or treated water supply
    - v. Groundwater remedial treatment

Alternative 2 (implement WHP program)

- a. Inputs:
    - i. Community WHP steps including protection area delineation, contaminant source identification, management plan, contaminant source inspection, and permitted facility inspection
- b. Outputs:
    - i. Protected groundwater supply (volume of water potentially affected by contamination; from Gettysburg case: 40,880,350 cubic meters)
    - ii. Health effects avoided

Alternative 3 (implement WHP program with monitoring of groundwater source)

- a. Inputs:
    - i. Similar to Alternative 2
    - ii. Installation of monitoring wells and conduct of regular sampling and testing of groundwater quality
    - iii. Maintenance of early contaminant response plan and response capabilities
- b. Outputs:
    - i. Similar to Alternative 2
    - ii. Advance notice of actual changes in the quality of the groundwater source
    - iii. Community protection from advance notice of groundwater quality changes

8. *Identify social costs and benefits of inputs and outputs*:

Alternative 1 (do nothing)

- a. Inputs
    - i. Social costs—risks to residents unknown
- b. Outputs
    - i. Social benefits—none

EXHIBIT 13.14 (continued) A BRIEF EXAMPLE OF NET BENEFITS ANALYSIS: GROUNDWATER PROTECTION IN LANCASTER COUNTY

Alternative 2 (implement WHP program)

a. Inputs
   i. Social costs—program implementation costs; individual awareness of residents for contaminant sources; individual steps to avoid use of contaminated water; zoning may preclude use of certain land for particular types of development, thereby reducing its value, while other land may rise in value

b. Outputs
   i. Social benefits—protected groundwater source; avoided health costs; avoided community water treatment and water emergency costs; potential for attracting business to community seeking location with protected water source; reduced operating, water treatment, and emergency response costs of business; land values may be maintained or increased because of groundwater protection

Alternative 3 (implement WHP program with monitoring)

a. Inputs
   i. Social costs—similar to Alternative 2; also includes costs for well installation and maintenance; early response plan readiness maintenance

b. Outputs
   i. Social benefits—similar to Alternative 3; greater confidence of residents and business of protected groundwater supply; unnecessary protection steps of individuals avoided

9. *Monetize where possible, otherwise quantify the social costs and benefits:*

Alternative 1 (do nothing)

a. Social costs
   i. Potential for need to obtain alternate or treated water supply: from Gettysburg example = $406,927 (includes discounted costs to 2005)
   ii. Groundwater remedial treatment costs: from Gettysburg example = $3,608,424 (includes discounted costs to 2005)

b. Social benefits—none identified

Alternative 2 (implement WHP program)

a. Social costs
   i. Protection area delineation and contaminant source identification = $52,380 (includes opportunity cost of volunteers' time to identify contaminant sources in communities = $6600)
   ii. Management plan = $20,400
   iii. Contaminant source inspection = $175,590 (includes discounted costs to 2005 for regular inspections)
   iv. Permitted facility inspection = $175,589 (includes discounted costs to 2005 for regular inspections)
   v. Total WHP program cost = $423,959 (includes discounted costs to 2005)

(*continued*)

EXHIBIT 13.14 (continued) A BRIEF EXAMPLE OF NET BENEFITS ANALYSIS: GROUNDWATER PROTECTION IN LANCASTER COUNTY

- b. Social benefits
  - i. Avoided cost of contamination remediation of similar contaminants of concern (from nearby Gettysburg case) = $4,015,351 (includes costs to 2005 discounted to 1994)
  - ii. Commodity value of water potentially affected by contamination; from Gettysburg case: 40,880,350 cubic meters priced at $0.758/cubic meter = $30,994,000

Alternative 3 (implement WHP program with monitoring)

- a. Social costs
  - i. Similar to Alternative 2 but must include monitoring costs approximately $250,000 (includes discounted costs to 2005 back to 1994 for monitoring each year) (see USEPA, 1996b, p. 34, for comparable costs for monitoring program around wellfields of 13 wells in two different communities) equaling $673,959
- b. Social benefits
  - i. Similar to Alternative 2; avoided cost of contamination remediation = $4,015,351 (costs to 2005 discounted to 1994)
  - ii. Commodity value of water potentially affected by contamination; from Gettysburg case = $30,994,000

10. *Specify and apply the discount rate* = 7% for costs and benefits from 1994 to 2005, the timeframe of the analysis (already applied to costs and benefits in previous step)
11. *Document all assumptions*:
    - a. Wellhead protection is fully effective (i.e., no groundwater contamination after implementation of WHP program)
    - b. Potential remediation costs would be similar for locations 112.7 km apart
    - c. Only potential contamination is from contaminants previously monitored and from sources identified at the time of assessment
    - d. Groundwater monitoring will be effective in observing all contaminants of concern
12. *Determine the net benefits or costs*:

Alternative 1 (do nothing): Net Cost = $4,015,351 for contamination remediation [no costs included for (1) other contaminants for in situ treatment or at the community water system treatment plant or (2) health effects]

Alternative 2 (implement WHP program): Net Benefit = $4,015,351 (avoided remediation costs) subtracting $423,959 (WHP program costs) = $3,591,392 [no costs included for (1) other contaminants for in situ treatment or at the community water system treatment plant or (2) potential health effects avoided as an additional benefit]

Alternative 3 (implement WHP program with monitoring): Net Benefit = $4,015,351 (avoided remediation costs) subtracting $423,959 (WHP program costs) and $250,000 (monitoring costs) = $3,341,392 (costs and benefits not included in Alternative 2 also apply to Alternative 3)

Benefit to Cost Ratios:

Alternative 1: $0/$4,015,351 = indeterminate
Alternative 2: $4,015,351/$423,959 = 9.47: 1
Alternative 3: $4,015,351/$673,959 = 5.96: 1

Economic conclusion: Alternative 2 has higher net benefits but assumes that no other sources of contaminants will occur in the protection area resulting in no monitoring for future contaminants

EXHIBIT 13.14 (continued) A BRIEF EXAMPLE OF NET BENEFITS ANALYSIS: GROUNDWATER PROTECTION IN LANCASTER COUNTY

in the groundwater resource supplying the wells of the communities' water systems. Avoided cost benefits may be significantly underestimated because health effects avoided are not included. Contamination remediation costs may be underestimated because more time may be needed to clean up the groundwater to an acceptable level of safety. Other avoided costs from averting groundwater receipt of other contaminants are not included, which may understate benefits still further. Averting costs taken by individuals to avoid contaminated groundwater are also not counted.

Source: U.S. Environmental Protection Agency (USEPA), *Benefits and Costs of Prevention: Case Studies of Community Wellhead Protection*, Volumes 1 and 2, EPA 813-B-95–005 and EPA-813-B-95–006. Washington, DC, 1996b, 63, 189.

U.S. Environmental Protection Agency (USEPA), *Protecting Local Ground-Water Supplies Through Wellhead Protection*, EPA 570/9-91-007. Washington, DC, 1991, 12, URL: http://www.epa.gov/r10earth/offices/water/whpgprnt.pdf (accessed August 16, 2007).

EXHIBIT 13.15 NET BENEFITS EXAMPLE SUMMARY TABLE: GROUNDWATER PROTECTION IN LANCASTER COUNTY

	Present Value Benefit	**Present Value Cost**	**Net Present Value Benefit**	**Benefit: Cost Ratio**
1. Monetized value	$4,015,351	$423,959	$3,591,392	9.47: 1
a. Range	Not calculated	Not calculated		
b. PV year	1994	1994		
c. Planning horizon	10 years	10 years		
d. Discount rate	7%	7%		
e. Value reference	USEPA, 1996b	USEPA, 1996b		
f. Assumptions	Remediation costs similar nearby; contamination only from sources monitored; monitoring effective for all contaminants	Wellhead protection fully effective		
2. Quantified/ nonmonetized values		Protected water source and avoided health damages for 19,000 people		
a. Value reference		USEPA, 1996b		
b. Assumptions		WHP fully effective in protecting water source		

Sources:

1. Adapted from Hardisty, P.E. and Özdemiroglu, E., *The Economics of Groundwater Remediation and Protection*, CRC Press. Boca Raton, FL, 2005, 336. With permission.
2. Adapted from U.S. Office of Management and Budget (USOMB), *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs*. Washington, DC, 1992, 5526. With permission.
3. Adapted from U.S. Environmental Protection Agency (USEPA), Guidelines for preparing economic analysis. Washington, DC, 180, 2000a.
4. Adapted from U.S. Environmental Protection Agency (USEPA), Assessing the benefits of drinking water regulations Washington, DC, 80, 2002.

Note: Each alternative or option should be expressed in the same format—this one, or other formats—to compare across the alternatives. The relationship between present value benefits and costs can also be expressed as a ratio of benefits to costs (present value of benefits divided by present value of costs), referred to as the benefit–cost ratio (BCR), as shown in the last column of the table.

Highly likely—The result will, with near certainty, happen or apply to the situation and is given great weight in ranking or scoring methods.

Likely—The result is expected in many circumstances and is weighted as occurring, but not as heavily as if it were highly likely.

Unlikely—The result is possible but probably will be considered as not happening in ranking or scoring methods.

As a second order of effect from a nonmonetizable and nonquantifiable result, this approach includes "significance." A result may be highly likely to occur but may be found to have a small impact or area of occurrence. In such a case, its significance would be categorized as "small," rather than "large" or "medium." In some circumstances, significance may be qualified as to whether it is determined to be "irreversible." In this case, for example, loss of a species of aquatic life found only in a particular aquifer may have strong biodiversity considerations associated with it based on the law protecting the species and reflecting its value to ecosystem and society. The results may then be expressed in a table or matrix supporting the CBA, such as in Exhibit 13.16.

COSTS AND BENEFITS CONSIDERING GROUNDWATER IN A HYDROLOGIC CYCLE CONTEXT

Addressing projects involving groundwater in the context of the hydrologic cycle may improve the results of those activities. Including the watershed and its hydrology might provide opportunities for positive outcomes not otherwise considered. See the example of Exhibit 13.17 for such an outcome. An evaluation that recognizes that groundwater exists as a stock resource when its

EXHIBIT 13.16 NONQUANTIFIABLE AND NONMONETIZABLE EFFECTS EXAMPLE SUMMARY TABLE: GROUNDWATER PROTECTION IN LANCASTER COUNTY

Nonquantifiable/Nonmonetizable (Noted If Documented Elsewhere)

Receptor Categories	Quantified (Documented Elsewhere)	Monetized (Documented Elsewhere)	Likelihood (Highly Likely [H], Likely [L], Unlikely [U])	Significance (Large [G], Moderate [M], Small [S], Irreversible [I])	Comment (Noted If Documented Elsewhere)
Public Health Effects					
1. Adults and children					
a. Avoided health effects	✓		H	G	More research needed
Community Effects					
2. Avoided community water treatment and water emergency costs			H	G	More research needed (USEPA, 1996a)
3. Reduced operating, water treatment, and emergency response costs of business			L	M	More research needed (USEPA, 1996a)

EXHIBIT 13.16 (continued) NONQUANTIFIABLE AND NONMONETIZABLE EFFECTS EXAMPLE SUMMARY TABLE: GROUNDWATER PROTECTION IN LANCASTER COUNTY

Nonquantifiable/Nonmonetizable (Noted If Documented Elsewhere)

Receptor Categories	Quantified (Documented Elsewhere)	Monetized (Documented Elsewhere)	Likelihood (Highly Likely [H], Likely [L], Unlikely [U])	Significance (Large [G], Moderate [M], Small [S], Irreversible [I])	Comment (Noted If Documented Elsewhere)
Ecosystem Effects					
1. Habitat maintenance			L	G	More research needed
2. Biodiversity maintenance			L	G	More research needed
3. Water cycling maintenance			L	M	

Sources:

1. Adapted from Hardisty, P.E. and Özdemiroglu, E., *The Economics of Groundwater Remediation and Protection*, CRC Press, Boca Raton, FL, 2005, 181. With permission.
2. Adapted from U.S. Environmental Protection Agency (USEPA), *Economic Analysis Resource Document,* 1999, Ch. 9, URL: http://www.epa.gov/ttn/ecas/econdata/Rmanual2/0.0.html (accessed July 22, 2007).
3. Adapted from U.S. Environmental Protection Agency (USEPA), Business benefits of wellhead protection—Case studies, EPA-813-B-95-004, Washington, DC, 1996a.

subsurface movement is very slow and as a flow resource when it is naturally or artificially more easily recharged and flowing at relatively greater velocities will be able to incorporate positive and negative externalities beyond the project site. This approach applies whether the project is directed at groundwater specifically or at a surface water (stream, lake, or wetland with standing water) with recharge or discharge relationships with an aquifer.

EXHIBIT 13.17 INCORPORATING THE HYDROLOGIC CYCLE IN INTERLOCAL AND TEMPORAL FACTORS IN COST–BENEFIT ANALYSIS

This simplified example incorporates the hydrologic cycle in the comparison of approaches for an idealized erosion control and sport fishery project. The comprehensive approach of considering groundwater in the hydrologic cycle from a watershed standpoint is illustrated by contrasting it with a single-purpose, limited-scope project.

Approach 1—Single-purpose, limited-scope project. Consider, for example, that a state agricultural water quality program working with the town of County Seat sought to reduce erosion and sedimentation to a stream to improve sport fishing in the middle Aguaflujo watershed. Over the planning timeframe of 10 years, the estimated value of the sport fishery would increase each year, leveling off in years 9 and 10. The program office had an objective of reducing sedimentation by 400 tons per year and spent $2000 in the first year, gradually convincing farmers on management practices to hold water on the land longer. The farmer education program continued for two more years at lower cost. An additional benefit would be greater infiltration and percolation and groundwater recharge, helping stabilize the variable groundwater supply of County Seat.

(*continued*)

EXHIBIT 13.17 (continued) INCORPORATING THE HYDROLOGIC CYCLE IN INTERLOCAL AND TEMPORAL FACTORS IN COST–BENEFIT ANALYSIS

After fully implementing the erosion and sedimentation control project in year 3, it was immediately found that the reduced sedimentation also reduced the drinking water treatment costs to the downstream Aquaflujo watershed utility, which used the river for its source of water, by $500 annually. After the program had been implemented for 5 years, County Seat's wells, which were down gradient from the agricultural portion of the watershed tested positive for pesticides and higher levels of nitrate that had never been previously observed. The State drinking water agency ordered County Seat to supply bottled water to all residents until the problem was addressed or appropriate treatment was installed. Bottled water cost the town $2000 over two years and eventually adding treatment cost of $4000 in the first year (completed seven years after the sediment reduction project) and $1700 per year afterward for labor, maintenance, and treatment media disposal. An investigation of the groundwater flow and quality found that the management practices in the farm land upgradient of County Seat's wellfield had caused the problem by holding water on the land longer and allowing it to infiltrate with the pesticides and nitrate. Once pesticide and nitrate response and treatment were in place, health benefits would begin accruing. These costs and benefits, undiscounted, may have been reported as follows:

INITIAL SEDIMENT REDUCTION–SPORT FISHERY PROJECT COUNTY SEAT

Timing and Surrounding Community Effects

	Costs	Benefits
Year 1	$1000—Farmer education	$0—Increase in value of sport fishing
Year 2	$800—Farmer education	$100—Increase in value of sport fishing
Year 3	$700—Farmer education	$200—Increase in value of sport fishing
Year 4	(none)	$400—Increase in value of sport fishing
Year 5	(none)	$800—Increase in value of sport fishing

PESTICIDE AND NITRATE TREATMENT PROJECT INITIATED

Year 6	$1000—Bottled water	$1200—Increase in value of sport fishing $200—Health protection
Year 7	$1000—Bottled water $2000—Treatment project	$1400—Increase in value of sport fishing $400—Health protection
Year 8	$500—Treatment operation/ maintenance	$1500—Increase in value of sport fishing $500—Health protection
Year 9	$500—Treatment O&M	$1500—Increase in value of sport fishing $600—Health protection
Year 10	$500—Treatment O&M	$1500—Increase in value of sport fishing $700—Health protection

EXHIBIT 13.17 (continued) INCORPORATING THE HYDROLOGIC CYCLE IN INTERLOCAL AND TEMPORAL FACTORS IN COST–BENEFIT ANALYSIS

COST–BENEFIT ANALYSIS

Initial sediment reduction—sport fishery project

- Costs of $3900 compared with benefits of $8600 over the ten-year planning timeframe seemed too good to be true to County Seat residents who would not have to provide any funding, but simply be a signatory sponsor.
- Costs:Benefits = 1: 3.4

Pesticide and nitrate treatment project addition

- Additional costs of $9500 were incurred because County Seat and the State agricultural program did not consider environmental externalities of its actions. Near-term health benefits of $2300 would accrue and grow into the future.
- Costs:Benefits = 4.1: 1

Total costs and benefits

- Ten-year costs = $13,400
- Ten-year benefits = $10,900
- Costs:Benefits = 1.2: 1

Consideration of effects on the outside community

- While perhaps not obvious on first look at a sport fishery improvement project, the economic external benefit to the outside community could have been identified by looking at the more complete hydrologic effects of the project in the Aguaflujo watershed.
- Since these effects were beyond the evaluation area for the improvement, they could have been described "qualitatively."
- These effects were quantified in the example; however, while they are benefits of the project, they were ignored.
- If the downstream community did not participate, the benefits could have been added either as "secondary cost reductions," subtracting them from the costs by the State, or adding them as "secondary cost savings" and summing them in the total benefits.
- If the downstream community decided to share the costs of the project, then its costs would directly be added to the total costs and its treatment cost savings would directly be added to benefits to reflect its cost–benefit perspective in the project.

Approach 2—Watershed approach considering groundwater in the hydrologic cycle. Could this combination of hypothetical events have turned out differently in economics terms if the watershed hydrology had been considered? If the agency had sufficient capability to understand the watershed characteristics of erosion and sedimentation on the sport fishery of the Aquaflujo River, it may have the knowledge or access to the knowledge to address the chemical features of the pesticides and nitrates, as they would interact with the hydrogeology of the larger region. The farmer support needed for reducing pesticide and nitrate

(*continued*)

EXHIBIT 13.17 (continued) INCORPORATING THE HYDROLOGIC CYCLE IN INTERLOCAL AND TEMPORAL FACTORS IN COST–BENEFIT ANALYSIS

concentrations could have been negotiated earlier by the state and County Seat since they were deriving commercial value from the initial project. This support would cost County Seat $100 per year to compensate farmers for lost income related to reduced use of pesticides and nitrate fertilizers beginning in year 4. At that point, the cost of the treatment and the operation and maintenance may have been avoided, as well as the purchase of bottled water. Health protection benefits would begin accruing two years earlier. In this case, the costs would have been $3200 (regardless if the downstream town participated) and the benefits would have totaled $12,700 (from sport fishing and avoided treatment of pesticides and nitrates at the water plant because of "treating" them in the watershed through the farmer agreements). If the downstream city participated, then another $3500 in benefits might be included.

- Costs over the 10-year planning horizon: $3200
- Benefits over the 10-year planning horizon: $14,100 (benefits attributable to the fishery, avoided water plant addition and downstream treatment savings)
- Costs:Benefits = 1: 4.4

Note: Considerable knowledge of watershed hydrology is necessary to conduct such an analysis in a real situation. Much about watersheds and their hydrogeology have been learned since the 1970s that can be applied to circumstances similar to those described earlier.

A conclusion from this example is that short-term, narrow solutions ignore costs and benefits to others. The best science, considering all the major components of the hydrologic cycle in this case, could be applied in concert with a comprehensive economic analysis to define the result that will best fit the long-term circumstances.

Caution: Care must be taken during analysis of a hydrologic systems approach that ecosystem effects and costs are not shifted from one media to another, such as from groundwater to surface water, or groundwater to air (the atmosphere). Shifting effects and costs from one media to another, if ignored, are actually costs that must be counted in the analysis; otherwise, they may be treated incorrectly as benefits simply because they do not occur in the media that is the object of the analysis. If the shifting of effects is the basis for the benefits, then the analyst should raise this point of information to the decision maker and indicate this result. At the same time, the analyst may be able to show that options exist for real benefits, but this may entail a change in the project or program. The change may be in demonstrating a real reduction in certain outputs, such as less chemical use from improved management practices resulting in a smaller amount of residuals needing disposal, or from more efficient water use practices to reduce the volume of water consumed in a project or program.

DISTRIBUTION EFFECTS AND EQUITY

While efficiency as reflected in cost–benefit and cost-effectiveness analyses is important in utilizing resources in a manner that reflects public trust and stewardship, the distribution effects of groundwater allocation decisions become significant, especially if shifts in water availability and its cost impact the health and well being of people who are economically disadvantaged. Distribution is the process and result of the allocation and sharing of goods and services among individuals in the economy (Bannock et al., 1979, p. 134). This consideration also embraces the needs of future generations in having resources available to them for their sustenance (Daly and Farley, 2004, p. 12) and is part of social justice factors of the "triple bottom line" evaluation emerging in business management. Public projects are often evaluated for distributional equity, as this may be a specific requirement (for example, OMB, 1992, p. 7). Private sector projects typically do not incorporate distributional equity (Hardisty and Özdemiroglu, 2005, p. 106), although they may affect the distribution of income and wealth of the local population, thereby affecting its well being. The effects of the resulting allocation of resources and income impacts flowing from them are referred to as distributional equity.

While neoclassical economics focuses almost exclusively on efficient allocation, attention to distribution effects of resource decisions addresses the needs of people who may be most affected by the lack of consideration for access to increasingly scarce and essential goods, such as groundwater and other ecosystem factors on which all people rely for life's sustenance. The basis, then, for considering distributional equity focuses principally on two directions:

1. Disproportionate impact on a segment of the population that has few resources to bear the effects of the allocation or is disadvantaged because of low income, limited social or institutional access to resources or the results of the allocation, or compromised health or limiting physical factors.
2. Targeting a population to benefit from a project because of the considerations of low income, limited access, or health and physical constraints.

In case (1), the information on the disproportionate impact can be used to modify the project or program or its implementation to offset or compensate that segment of the population. Thus, those who gain from the project or program would compensate those who do not gain (OMB, 1992, p. 7) or are impacted by less water availability or lower quality or by pollution or other negative effects of the activity because of its concentrated effects on them.

At the outset of project or program planning and development of objectives and alternatives, the economic analyst can incorporate distributional equity in the activity by (USEPA, 2000b, p. 142)

1. Identifying prospective consequential economic impacts and their array of equity effects
2. Performing a preliminary assessment of these impacts and effects
3. Developing options and conducting more in-depth analyses of the distributional economic and equity effects

EFFECTS ON COMMUNITIES AND GOVERNMENT ENTITIES

Distribution effects include a range of categories to be evaluated that apply to communities or governmental jurisdictions and compared with the overall population or area of the country, or political or hydrologic subdivision. The water company or utility itself must understand the effects of changes in groundwater quantity or quality on its own operation. Other agencies may be similarly affected. Issues that these agencies may consider cover (USEPA, 2000b, p. 156), but are not limited to

1. People affected at and below the poverty line
2. Cost of water relative to income
3. Gender
4. Number of children per family
5. Number of elderly residents (who frequently have fixed incomes)
6. Ethnicity (percent of ethnic group of entire population)
7. Unemployment rate
8. Revenue amounts by source
9. Credit or bond rating of the community
10. Overall net debt as percent of full market value of taxable property

11. Health-sensitive subpopulations
12. Industry sector
13. Small business
14. Skills/education level

An evaluation of distribution effects would address whether these categories of effects are disproportionately borne by people, typically as a group in the area of a water project or program, that may be deemed disadvantaged socially or economically. If people are disproportionately affected, then the project, as formulated or implemented, would be determined to have negative distribution effects and be inequitable. The project can be reformulated to adjust for this outcome and become more distributionally equitable. Some example indicators of distributional equity effects on communities and governmental jurisdictions that might be quantified are given in Exhibit 13.18.

Considering a community's cost of water from a distributional equity perspective, countries have set or have considered guides on water supply affordability. In the United States, the Environmental Protection Agency (2006) has set a benchmark of 2.5% of median household income as the measure of affordable water supply for small communities serving 10,000 or fewer people. The European Union (2006) set an affordable "tariff level" for households paying for water derived from investment in water supply and sanitation facilities constructed in Africa, and Carribean, and Pacific locations at 5% of household income. An evaluation of a water services tariff level for China indicated that the combined bill for water supply and wastewater should be less than 5% of household income with the average-income household (with monthly water use of 14 m^3) paying 1.5%–2.9% of income, while the low-income household (with monthly water use of 9 m^3) would pay 2.2%–3.6% (Clark et al., 2006, p. 3).

EXHIBIT 13.18 EXAMPLE INDICATORS OF ECONOMIC AND FINANCIAL WELL BEING OF COMMUNITIES AND GOVERNMENT ENTITIES

		Possible (Example) Benchmark Values in the United States		
Indicator	**Definition**	**Weak**	**Mid-Range**	**Strong**
Bond rating	Ability of the community to absorb additional debt (to pay for any capital requirements of the rule) and the general financial condition of the community as measured by a community's credit capacity and thus reflects the current financial conditions of the governmental body	Below BBB (S&P) Below Baa (Moody's)	BBB (S&P) Baa (Moody's)	Above BBB (S&P) Above Baa (Moody's)
Overall net debt as percent of full market value of taxable property	Ability of the community to absorb additional debt (to pay for any capital requirements of the rule) and the general financial condition of the community as measured by the ratio of overall net debt (the debt to be repaid by property taxes) to the full market value of taxable property in the community for households and businesses	Above 5%	2%–5%	Below 2%

EXHIBIT 13.18 (continued) EXAMPLE INDICATORS OF ECONOMIC AND FINANCIAL WELL-BEING OF COMMUNITIES AND GOVERNMENT ENTITIES

		Possible (Example) Benchmark Values in the United States		
Indicator	**Definition**	**Weak**	**Mid-Range**	**Strong**
Unemployment rate	The ratio of involuntary unemployed persons to all people in the workforce	More than 1% point above national average	Within 1% point of national average	More than 1% point below national average
Median household income	One-half of the households fall above the median and one-half fall below the median of income as measured by the flow of money to household members 15 years old and over	More than 10% below the state median	Within 10% of the state median	More than 10% above the state median
Property tax as percent of full market value of taxable property	The general financial health of a community as an entity considering the burden property taxes on a community as measured by the ratio of property tax revenues to full market value of taxable property	Above 4%	2%–4%	Below 2%
Property tax collection rate	The general financial health of the community as an entity as measured by the efficiency with which the community's finances are managed relative to its capacity to generate revenue through axes on real estate and other property	Less than 94%	94%–98%	More than 98%

Source: Adapted from USEPA, Guidelines for Preparing Economic Analyses, EPA # 240-R-00-003, Washington, DC, 2000b, 159, URL: http://yosemite1.epa.gov/ee/epa/eerm.nsf/vwSER/DEC917DAEB820A25852569C40078105B?OpenDocument (accessed July 31, 2007).

EFFECTS ON BUSINESSES

A project or program affecting groundwater services and products may also have disproportionate impacts on industry and particularly on small business in the area under evaluation. Questions that may be addressed include (USEPA, 2000b, pp. 151–156)

1. Can the business within its competitive industry pass on increased production costs to consumers? Inability to pass along increased costs may make a business unviable.
2. Will price increases because of higher production costs result in reductions in output from lower operating rates at existing plants and farms, closure of some plants and farms, or reduced future growth in production relative to what would have occurred in the baseline? Supply elasticities may be used to forecast changes in output and prices. Financial analyses of specific firms in the area of evaluation may point to businesses most affected, including analyses of revenues, costs, income statements, and balance sheets from which financial testing can examine the probability of financial problems. Tests may address negative discounted after-tax cash flows, profitability, and ability to finance operations and pay obligations (for example, interest coverage ratio [cash operating income divided by

interest expense], times-interest-earned [earnings before interest and taxes divided by interest expense], and the current ratio [current assets divided by current liabilities]) (USEPA, 2000b, p. 154). If some firms or farms are uncompetitive, shifts in employment to firms that are "more efficient competitors" may occur and be of interest to local governments, which may lose these workers from their jurisdictions.

3. How will employment and income change in related industries and businesses? An evaluation of linkages to the affected sector and community is important. Shifts in water availability and prices will have effects on other industrial sectors that rely on water as a critical factor in production or are dependent on its availability (for example, see Young, 2005, p. 223).
4. Will market entry for businesses be facilitated or obstructed? The amount capital cost associated with responding to change in groundwater availability or quality may be a significant factor in business' abilities to address opportunities resulting from a project or compliance requirements of a program. Capability to obtain debt or equity financing for capital costs may be important for businesses if those costs are high.

ENVIRONMENTAL MANAGEMENT EFFECTS

The third component of the "triple bottom line" of current government and business management is the consideration of the environmental costs and benefits of an action, good, or service. In the organization of this text, from an ecological economics perspective, this is actually the first consideration that affects the other components. If resources are not available or in such a degraded condition so that they cannot be used in a sustainable manner, industry and government that provide the economic order for business to occur have been short-sighted and focused narrowly on near-term gain to the exclusion of long-term viability. An approach to managing the environmental effects of government and business actions has emerged in the form of "environmental management systems"—EMS. The concept is that by implementing EMS, adverse or negative environmental effects will be reduced from what they would have been, expressed mathematically as

$$\mathrm{AEE}_{\mathrm{Without\ EMS}} > \mathrm{AEE}_{\mathrm{With\ EMS}}$$

where AEE denotes adverse environmental effects.

At the local level, government and business leaders have recognized that protecting groundwater is an important and necessary cost of doing business. First, groundwater conservation and protection potentially reduces the investment needed to treat water, keeping costs to government and business for water supply lower than they would have otherwise been. Second, a stable quantity and quality of groundwater available to business enables companies that use it as a reliable factor of production to better manage manufacturing processes and control costs, rather than having to reinvest in new equipment or change production steps to accommodate variations in availability or characteristics of water (USEPA, 1996a). The International Standards Organization (ISO) has developed approaches for business and industry to organize and guide implementation of activities to support environmental protection and conservation. Key elements of the ISO EMS are described in Exhibit 13.19. Importantly, these elements allow the evaluator to capture environmental benefits of an activity, product, or service that may not be easily quantified or monetized. However, from a sustainability perspective, these elements can be critical to long-term business and ecosystem viability.

Government and corporate actions to prevent pollution of groundwater serve to convey an increased value for the resource in the economy, as more resources are focused on maintaining and protecting it. Such action by the private sector signals a willingness to account for a more complete cost of doing business to provide products and services. This voluntary response potentially serves to defer government consideration of environmental standards or tax policies that could raise prices

EXHIBIT 13.19 ISO 14001—ENVIRONMENTAL MANAGEMENT SYSTEMS (EMS)

1. Key elements of ISO 14001

Key elements of ISO 14001 EMS that a corporation or community can adopt in its business practices to prevent groundwater and environmental pollution through a comprehensive approach are

ENVIRONMENTAL POLICY

The environmental policy and the requirements to pursue this policy via objectives, targets, and environmental programs

PLANNING

The analysis of the environmental aspects of the organization (including its processes, products, and services as well as the goods and services used by the organization)

IMPLEMENTATION AND OPERATION

Implementation and organization of processes to control and improve operational activities that are critical from an environmental perspective (including both products and services of an organization)

CHECKING AND CORRECTIVE ACTION

Checking and corrective action including the monitoring, measurement, and recording of the characteristics and activities that can have a significant impact on the environment

MANAGEMENT REVIEW

Review of the EMS by the organization’s top management to ensure its continuing suitability, adequacy, and effectiveness

CONTINUAL IMPROVEMENT

The concept of continual improvement is a key component of the environmental management system; it completes the cyclic process of plan, implement, check, review, and continually improve.

(“This material is reproduced with permission of the American National Standards Institute (ANSI) on behalf of the International Organization of Standardization (ISO). Copies of ISO 14001 and all ISO standards can be purchased from ANSI at http://webstore.ansi.org/; info@ansi.org”.)

2. Potential benefits to governments and businesses implementing ISO 14001

Categories of Government and Business Benefit	Benefit to Groundwater Resource
Materials savings from more complete processing, substitution, re use or recycling of product inputs increases in process yields	Less residual to be disposed
Less downtime through more careful monitoring and maintenance	Residuals tracked
Improved utilization of by-products	Less residual to be disposed
Conversion of waste into commercially valuable forms	Less residual to be disposed

(continued)

EXHIBIT 13.19 (continued) ISO 14001—ENVIRONMENTAL MANAGEMENT SYSTEMS (EMS)

Categories of Government and Business Benefit	Benefit to Groundwater Resource
Reduced energy consumption	
Reduced material storage and handling costs	Less contaminant potential stored
Savings from safer workplace conditions	Fewer accidental releases
Reduction of costs associated with emissions, discharges, waste handling, transport, and disposal	
Improvements in the product as a result of process changes	Less consumer product disposal
Higher quality, more consistent products	Less consumer product disposal
Lower product costs (e.g., from material substitution)	
Reduced packaging costs	Less consumer waste disposal
Reduced packaging costs	
More efficient resource use	Groundwater quantity preserved
Safer products	Less consumer waste disposal
Lower net costs of product disposal to customers	
Higher product resale and scrap value	Less consumer waste disposal

Source: Adapted from Goodman, S.L. and Veritas, D.N., 1998, Is ISO 14001 an important element in business survival? ISO Information Center March 6, 2004, URL: http://ems-hsms.com/Docs/ISOBusSurvival.pdf (accessed February 16, 2008).

3. Additional economic benefits from implementing EMS on corporate and community levels

Corporate Benefits	Community Benefits
1. Improved view of company by financial analysts and stockholders, increasing stock prices	1. Improved view of community, improving financial ratings and lowering borrowing costs
2. Improved view of company's products, increasing market share	2. Improved view of desirability of community's living environment
3. Improved view of company's social responsibility, improving recruitment ability	3. Improved view of community's cultural ethic
4. Free advertising through positive media coverage	4. Free community promotion to attract environmentally responsible businesses
5. Identification of new business opportunities through materials recycling	5. Expansion of jobs in environmentally responsible businesses
6. Reduced probability of future civil and criminal prosecutions and reduced levels of fines and penalties from noncompliance	6. Reduced environmental litigation costs
7. Reduced worker health and safety problems and costs	7. A healthy and safer community to live in
8. Improved view of company thereby facilitating acquisitions, mergers, and foreign activities	8. Improved business environment with more jobs
9. More productive research and development generating more significant innovations, such as new processes and products	9. More business activity creating more jobs and products with less impact on the ecosystem

Source: Adapted from Sullivan, T.F.P., (ed.), *The Greening of American Business*, Government Institutes, Inc., Rockville, MD, 1992, 147.

Sources:

1. International Standards Organization (ISO), Technical Committee 207 on Environmental Management, (through the American National Standards Institute) Environmental management systems—Requirements with guidance for use, 2004, URL: http://www.iso.org/iso/iso_catalogue/management_standards.htm (accessed February 16, 2008). With permission.

to consumers to address the imperfection in the market that could not value groundwater appropriately. Since standards or tax policies can change, this circumstance could introduce uncertainty in accounting for resource costs and the extent to which they are effective in managing groundwater for the greatest social benefit. A pollution tax may still be necessary in situations where significant distortion in the economy undervalues, and, therefore, underprices, the services of the subsurface and groundwater and results in contamination that is unacceptable to other users of those underground resources.

EFFICIENCY RECHARACTERIZED—ALTERNATIVE ACCOUNTING

With the recognition that global ecological systems are under stress on a number of fronts (for example, "greenhouse gas" emissions, acidification of oceans, climate change, reduction in biodiversity, and mining of large aquifers), ecological economists, scientists, and other professionals from related disciplines have initiated different calculations that provide ecological and economic comparisons. These approaches represent alternative accounting frameworks. Building on the environmental management systems concept is the tracking of consumption of ecological capacity, assessing the ecological footprint of an activity, project, or product. One approach is to evaluate, document, and record in appropriate units the use of natural capital and its services. This method allows the economist or analyst to consider the impact of a groundwater-related project on the ecosystem and provides the decision maker an understanding of the limits of the resource being used. Exhibit 13.20 indicates factors that could be considered and added to, as more information is available. Once a baseline footprint of consumption or waste generation is established, the regular calculation of future consumption and waste can be used to target and guide responses to reduce them to more sustainable levels. Mathematically, this relationship may be expressed as

$$\mathrm{C}_T > \mathrm{C}_{T+N} > \rightarrow \mathrm{C}_S \qquad \text{(Ineq. 13.3)}$$

where, for any particular economic activity, project, or product,

C_T = consumption (or waste generated) footprint in time T

C_{T+N} = reduced consumption footprint in time $T + N$, an intermediate target date N year(s) in the future

$\rightarrow$ = "approaching"

C_S = consumption to a sustainable level in a future target year

This relationship applied to groundwater would indicate that current consumption of the resource is reduced over time through measures (water saving appliance use, reduced water waste, etc.) based on circumstances (geology, climate, population, infrastructure technology, etc.) to a sustainable yield for an aquifer.

Daly and Farley (2004) have proposed a "comprehensive efficiency identity." This efficiency measure is a ratio in nonmonetary units of services gained from manmade capital stock (MMK) to the services sacrificed from natural capital stock (NK). This relationship recognizes that the purpose of economics is to facilitate the provision of services and not to create or generate the most product or

EXHIBIT 13.20 CALCULATING THE ECOLOGICAL FOOTPRINT OF AN ACTIVITY OR PROJECT

The Global Footprint Standards are a guide to calculating resource use and waste release and converting them into equivalent land area units for comparative purposes. Selected types of resource uses and waste releases that may be considered in this accounting framework are provided here (ICLEI, 2006, p. 36). The standards are described in reference GFN (2006). This accounting approach may be applied to groundwater-related activities and projects. The particular table here is for an initial rapid ecological footprint assessment.

Resources	**Quantity**	**Conversion Factor**	**Total Area of Land (ha)**
Energy consumption			
Electricity			
Gas			
Liquid fuels			
Renewable energy			
Solid fuels			
CO_2 emissions generated from fossil fuels			
Materials			
Production			
Consumption			
Stock creation			
Timber			
Metals			
Chemicals			
Other raw materials			
Food: Consumption by food type			
Waste: Materials discarded by			
Households			
Commercial undertakings			
Industry			
Construction sector			
Transport: Passenger km and CO_2 emissions by			
Car			
Bus			
Rail			
Air			
Other modes of movement			
Water:			
Consumption by sector			
Leakage			

EXHIBIT 13.20 (continued) CALCULATING THE ECOLOGICAL FOOTPRINT OF AN ACTIVITY OR PROJECT

Volume of aquifer depleted/ contaminated

Land use: A breakdown of land used within the [area]

Total

Source: International Council for Local Environmental Initiatives (ICLEI), Liveable cities: The benefits of urban environmental planning, 2007a. With permission.

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output (Daly and Farley, 2004, p. 422). Nonmonetary units are important in this calculation since technical efficiency can increase resource consumption by lowering the unit price of inputs, making them more attractive to use relative to other inputs. Furthermore, the total cost of the finished product may be lower creating more demand, which may be problematic for a resource being depleted. The ratio [MMK services gained]: [NK services sacrificed] takes into account technical, allocation, and distribution efficiencies; manmade capital maintenance; and growth in natural capital for sustainability purposes. This identity and its calculation are described in more detail in Chapter 14, Sustainable Development.

COST AND BENEFIT ESTIMATE ISSUES

Beyond the principles identified earlier and the correct specification of quantifiable and monetizable benefits and costs, a range of other factors affect the presentation of these evaluations. These factors include inflation, discounting, risk trade-offs, regional variability, accounting area, and double counting. Addressing these factors in any analysis will help ensure that it is more defensible and useful. These factors affect the magnitude of the benefits and costs for groundwater resource evaluations.

INFLATION

Inflation is the general increase in prices faced by consumers in an economy, reducing their purchasing power as measured in nominal monetary terms (Bannock et al., 1979, p.235). Inflation is usually determined by the central government through surveys of the prices for “bundles” of goods and services at specified points in time (e.g., monthly). Inflation is typically expressed as a rate on a monthly or annual basis, such as 0.1% per month, or 1.2% per year. The bundles of goods and services can be broad for the entire economy or can be developed by regions of the country or by an industry, such as construction or water supply. The significance of this for groundwater analyses is that focusing on the water sector and regions of the country may show that, for example, inflation in the water industry is less than that for the economy as a whole. Inflation may be greater in New York City than in Kansas City, Kansas, or Bangalore, India. This circumstance is certainly true in comparing inflation among different countries, for example, in 2002, Mexico had an inflation rate of 6.4%, whereas Spain’s inflation rate was 3%.

Inflation is reported with reference to a base year. Typically, the base year is the most recent year for which information is available. Information on inflation rates is routinely reported in the United States in the “Economic Report of the President” published each year (USEOP, 2002) and in the European Union in the monthly “Statistics in Focus, Economy and Finance, Harmonized Indices of Consumer Prices” (EU, 2008). For example, the 2002 US Report indicates that the consumer price index (CPI), the principal inflation indicator used in the United States, was 177.1 in 2001 and 160.5 in 1997. The difference in the CPI between those two years equals 10.3% of the 1997 index, and can be interpreted to indicate that inflation rose by that percentage between those years. The average annual rate of inflation from 1997 to 2001 was about 2.5%, while the specific rates for those years ranged from 1.6% in 1998 up to 3.4% in 2000. To adjust a nominal price (a price that is not adjusted for inflation) of $1.30 for a commodity in 1997 to 2001 prices (adjusting for inflation), $1.30 is multiplied by 1.103 (1 plus the adjustment factor of 10.3%), equaling $1.43 US dollars in 2000:

1997 Price	Multiplied by	Adjustment Factor	Equals	2001 Price
$1.30	×	1.103	=	$1.43

This type of calculation is referred to as “real dollar (or other monetary unit) adjustment” but does not indicate real changes in value over time, referred to as “discounting.” Care must be taken not to combine nominal and real values in the same analysis, but use one or the other approach and clearly document which is being used.

To account for inflation in the future, in the United States, for example, the Office of Management and Budget recommends using the “rate of increase in the Gross Domestic Product deflator from the Administration’s economic assumptions for the period of analysis.” For longer-term projections, the inflation rate of the sixth year of the budget forecast can be used (OMB, 1992, p. 5). Approaches will vary by country and the guidance or directives of each nation’s central economic policy office should be consulted for the appropriate technique.

DISCOUNTING AND THE TIME VALUE OF MONEY

Discounting allows calculation of “real time” value of money. The purpose of discounting (the act of applying a discount rate to future monetized costs and benefits) is to efficiently allocate scarce resources over time, reflecting temporal preferences for money. Discounting is used typically to calculate current year values for different payment or income streams in the future for alternate investments or uses of money, also called “opportunity costs,” with a further description in Exhibit 13.21. In practical terms, a unit of money (e.g., $100) is worth more to have today than one year from now, because it can be invested now and earn a return (or interest) in the future (Bannock et al., 1979, 131). Calculating investments made in the future in terms of current year value requires using a projected “discount” rate, typically presented as an annual rate. Applying the rate to the investment or receipt of money over time results in calculating the “net present value” (NPV) of the flow of funds to current year values.

Choice of the appropriate discount rate for projects and actions affecting societies is a controversial topic. The selection of the discount rate relative to a government decision or action may be the single more important factor in describing the economic results for decision-making purposes (Daly and Farley, 2004, p. 273). The United States Office of Management and Budget requires a discount rate of 7% (0.07) to be used on federal actions, for which discounted funds flow analysis is necessary (OMB, 1992, p. 5). This is a “real” discount rate, adjusted to remove anticipated inflation. This rate is considered to be that which “approximates the marginal pretax rate of return on an average investment in the private sector in recent years” (OMB, 1992). The use of a different rate must be

EXHIBIT 13.21 OPPORTUNITY COST

The difference between the return received by a proposed project and that of the best alternative investment of the corresponding risk is called the “opportunity cost” (of the proposed project). Another way to think about it is value foregone when the most favorable option is abandoned in deciding on a course of action (Daly and Farley, 2004, p. 437). It can also be expressed as a rate of return (a percent; e.g., project rate of return [ROR] is 5%; the ROR of the best investment of similar risk is 8%; the opportunity cost ROR is 3%). The United States Office of Management and Budget has established the opportunity cost discount rate of 7% for federal projects and programs after considering alternative investment returns over a recent period of years in the United States economy (OMB, 1992).

Another way to consider opportunity cost: In the context of a response to a contamination incident, from the perspective of economic efficiency, the approach of choice has the lowest overall additional cost to society. That added cost is the cost of the contamination of groundwater (or other resource), which is the opportunity cost to society. Specifically, the opportunity cost is any resulting health or environmental effect plus the cost of treatment, as compared to a baseline condition of “no contamination” (O’Neil, 1990). The society would not have to incur these costs if the contamination had not happened.

Alternative values for water may change depending on time or season of the year. For example, farmers may have a greater value for groundwater during the growing season (Winpenny, 1994, p. 10). Thus, measuring opportunity cost for ground (or surface) water is very challenging, since it will differ depending on location, season, time of day, water quality, variability, and use, as well as other factors particular to the specific occurrence of water (Easter, 1998, p. 35).

substantiated. The United States Environmental Protection Agency allows for concurrent analysis using an alternate rate of 2%–3% (0.02 to 0.03), considering that the federal outlays would be for current use. Any adjustments for inflation or deflation (assuming nominal prices decrease) to future funds flows should be made before applying a discount rate to an analysis. Alternatively, Daly and Farley (2004, p. 273) indicate that the social discount rate should be lower than individual discount rates and equal to the community’s or nation’s overall appraisal of the rate at which value in the future should be transformed to present time.

Time value of money also relates to the time value of objectives. Higher discount rates promote allocation of funds planned to be used nearer to the present time, since more distant expenditures and benefits are more heavily discounted through compounding of the rate chosen over time. If future objectives are determined to be very important, high discount rates will minimize their importance in the resulting information given to decision makers. Given that groundwater moves slowly in many locations and, in these same places, it is expensive and time consuming to remediate when contaminated (long-lived costs and subsurface adjustment), potentially affecting future generations, these conditions may suggest that a low or zero discount rate should be applied to groundwater in these situations. Even a small change in discount rate may suggest a significantly different objective (e.g., shifting from agricultural use to obtain an alternate water source) with the resulting benefits correspondingly adjusted (Raucher, 1983). Daly and Farley (2004, p. 274) suggest that if natural capital is being reduced by an action, for example, depletion of an aquifer or removal from use because of contamination, and the remaining resource has increasing marginal utility, a negative discount rate should be applied.

An example of such an analysis for a two-year project, in which the annual net benefit (NB) (benefits minus costs) is $1000, and adjusted for projected inflation follows

Net Benefit in 2003	Multiplied by	Inflation Factor	Multiplied by	Discount Rate Factor	Equals	Net Present Value in 2002
\$1000	×	1.02	×	[1/(1 + .07)]	=	\$953 (rounded)

The second net benefit is to be received in 2004, requiring a further calculation to obtain the additional funds flow, assuming the same inflation and discount rates are applied:

Net Benefit in 2004	Multiplied by	Inflation Factor	Multiplied by	Discount Rate Factor	Equals	Net Present Value in 2002
\$1000	×	$(1.02)^2$	×	$[1/(1 + .07)^2]$	=	\$909 (rounded)

The project's net present value of this particular funds flow is \$953 + \$909 equaling \$1862 in 2002 dollars (or other monetary units applicable). The general form of the discounting equation (for calculating the benefits or costs in future years) is

$$\text{NPV}_t=\{\text{NB}_{t+1}\times(\text{IF})^{t+1}\times[1/(1+\text{DR})^{t+1}]\}+\{\text{NB}_{t+2}\times(\text{IF})^{t+2}\times[1/(1+\text{DR})^{t+2}]\}+\cdots \tag{13.22}$$

where

NPV is the net present value

NB is the net benefit received in the $t + 1$ year, $t + 2$ year, and so on into the future for the duration of the project

IF is the inflation factor (1 plus the inflation rate)

DR is the real discount rate

t is the year to which the future net benefits are discounted

Or, even more generally,

$$\text{NPV}_t = \sum_{t+1}^{t+g}\left\{\text{NB}_{t+g}\times\left[1/(1+\text{DR})^{t+g}\right]\right\} \tag{13.23}$$

where

Σ_{t+1}^{t+g} is the sum of the inflated and discounted net benefits in future years 1 to year g

g is the next year in the funds (net benefits) flow (years 2, 3, 4, 5, and so on to the last year g), the last year being the end year of the planning cycle or effective life of the project

Under what circumstances would these calculations use an inflation factor? An inflation factor might be used when budget funding is adjusted to keep pace with inflation, if the calculation was for future costs. An inflation factor might also be used in circumstances where the estimator has specialized information on resource scarcity, such as increased demands on groundwater and declining water tables and quantities available, which would increase the rate of inflation in the water supply sector. In these situations, the factor might be considered a demand-side driven interest rate reflecting increasing value of the resource. If inflation is not considered into the future, the inflation factor can be dropped from the equation.

In all cases, care should be taken in deciding whether to adjust for inflation or not and being consistent with all monetary calculations in this regard. Nominal discount rates already reflect an expectation of inflation. Interest rates in the financial markets are nominal rates. Real discount rates are rates for which an adjustment for expected inflation has already been made, computed by subtracting the expected inflation rate from the expected nominal interest rate.

Are there any circumstances in which a deflation rate (a negative inflation rate) would be used? In industries where costs are known to be declining over time and expected to continue into the future might warrant use of a deflation factor. Witness the prices of computer equipment falling in real terms in recent years. Mathematically, a negative rate of inflation (or deflation) would result in an inflation factor less than "1" and a smaller number would result for use in future years. It is not clear how this would apply to groundwater resources, but it may be possible that in areas that are flooded, groundwater might be imputed less value temporarily for some amount of time for both quality and quantity reasons.

INTERGENERATIONAL CONSIDERATIONS

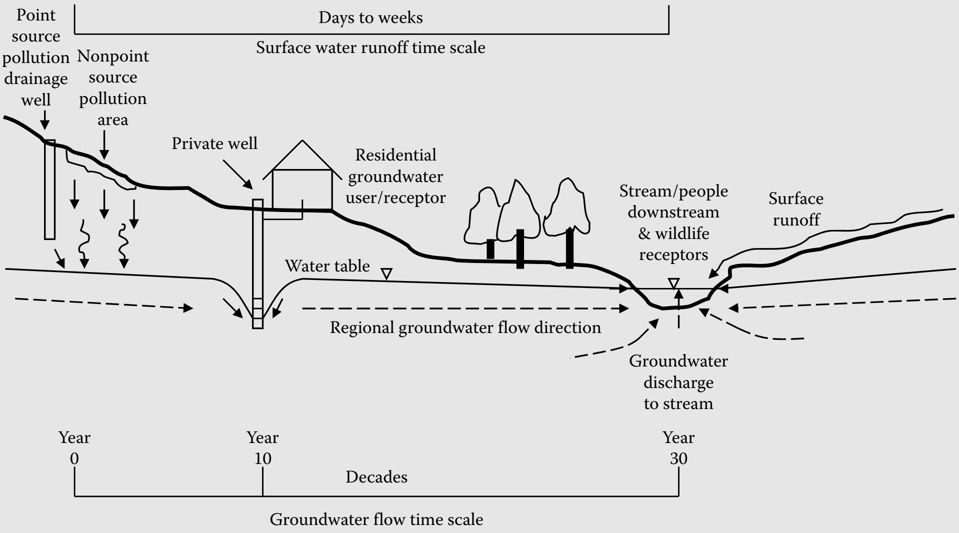
Discounting also raises an intergenerational issue. For benefits arising from actions focused on the groundwater resource, this matter may be significant (Raucher, 1983, p. 323). A dollar (or other monetary unit) will always be worth more today than one or one hundred years from now, because of an individual's time preference for money. To take actions promoting objectives having future benefits from services of groundwater as a commodity introduces a perverse result that discounted dollars of benefits 100 years from now will be worth nothing today. Since we cannot know the impact of inflation or returns on investments in the future, one way to present results is in both discounted and undiscounted formats to ensure a fair description of benefits and costs that promote objectives of sustainability. Furthermore, we do not know the level of risk that would be acceptable to future generations (Daly and Farley, 2004, p. 359). Undiscounted costs and benefits translate into a discount rate of "0" (zero). Small discount rates may be appropriate for long-lived projects with significant public good to allow future benefit flows to be considered.

LAG TIME BETWEEN COSTS AND BENEFITS

By the nature and condition of most groundwater, a significant lag time exists between the activities that incur costs to improve their quantity and quality and the benefits derived from these actions. For example, the streams conveying water to the Chesapeake Bay in the United States are often maintained by groundwater discharge. Depending on the location in the watershed, changes in the use of fertilizers and chemicals in the watershed may not be manifest in the quality of the groundwater used by receptors or discharged to streams for 30 or more years. Exhibit 13.22 depicts this circumstance for pollution sources in a watershed affecting groundwater quality to a residential receptor after 10 years and to downstream and wildlife users in 30 years. Potential changes in pollution control in a watershed would not have an effect for these periods of time in this hypothetical situation. In a real watershed/aquifer relationship, these timeframes could be longer or shorter. Benefits of changes in chemical use, cultivation techniques, irrigation, and other practices accruing which, when discounted far in the future, may have little value in the present. Groundwater mining and depletion effects may have similar time lag effects, such as in the case of a decision for the quantity of water consumed from conservation pumping to become less than recharge to an aquifer with long periods of time required for the aquifer to recover to earlier levels. This circumstance will distort a resource manager's perspective of the relative worth of such activities that may have implications on the scale of water use unless he or she is required to take a longer view. An economist's response to such a situation might be to show undiscounted cash flow analysis next to the discounted one to inform decision makers. Otherwise, decisions might be less than fully informed, resulting in ignoring or shifting effects to future water users that current water users would not want to endure.

For example, if a $4,000,000 groundwater project generated $5,000,000 in undiscounted benefits beginning in year 30, but with a discount rate of 5%, those benefits become less than 1/4th of the original amount, becoming $1,156,886 after discounting. This represents a considerable loss of

EXHIBIT 13.22 DEPICTION OF HYPOTHETICAL LAG TIME IN GROUNDWATER EFFECTS RELATIVE TO WATERSHED AND AQUIFER TIME SCALES



value owing to time to the decision about such an action, whereas when undiscounted, the benefit is 25% larger than the cost. In this case, the question might also be, "What is the value of the groundwater service from this project to a future generation?"

Regional Variability

Regions of the United States, other countries, or the world will have different inflation rates, discount rates, and other factors that will cause the analyst to need to obtain region-specific information. Even though the prices for delivered drilling equipment may be about the same across large areas of the country, the prices for providing the same volume of water in different but adjacent regions may vary significantly. Physical conditions affecting access to sites and groundwater can also result in delivered water price differences unrelated to inflation. For example, the hydrogeologic conditions affecting groundwater production on Cape Cod, Massachusetts, are different than in Amman, Jordan: Glaciofluvial sand with a shallow aquifer versus a deep bedrock aquifer and many smaller shallow wells compared with fewer large, deeper wells. Labor rates in more densely populated areas may be much higher than for more rural areas, with substantial effects on well installation prices and operation and maintenance.

Regional Multiplier Effects

Regional economic multiplier effects of a water project or program are the projected indirect effects of that activity on the economy. These effects are derived from anticipated backward and forward linkages among industries due to increases in demand for output and from increased consumption because of anticipated income gains in the area of the water activity (World Bank, 2005, Section 9.3). Whether it is appropriate to use regional multiplier effects in a CBA depends on the analyst's conclusion about whether resources in the economy being affected by the water project are fully employed. In the United States, the Office of Management and Budget recommends that resources in the economy be generally treated as fully employed for the purposes of national-level analyses (OMB, 1992, p. 4). This is interpreted as meaning that any projected multiplier effects in one area (or several areas) due to a water project or program (with several or many resultant water projects) are just a transfer from somewhere else in the economy, so no net benefit is derived within an economy in which resources are considered "fully employed." For an economy in which resources are unemployed or underemployed, the result would therefore be different. However, as noted previously, Young (2005, pp. 88–98) indicates that inclusion of these indirect effects may result in overestimation or misspecification of benefits due to the potential inclusion of taxes and user fees that are variable production costs.

An alternative view is that multiplier effects may be as much as 90% of direct benefits and thus are a substantial consideration within a region (World Bank, 2005, Chapter 9). Such a region may be an area within a country (a subnational area) and have unemployed or underemployed resources. Large multipurpose water projects (dams) in Brazil, India, and the Arab Republic of Egypt had multiplier effects ranging from 1.4 to 2.0. Relating these values to the value added directly from the projects translates to $1.40 to $2.00 resulting from direct and indirect effects for each dollar spent (World Bank, 2005, Section 9.3) (see also Smith, 2004, relative to poverty reduction and unemployed resources). Exhibit 13.23 describes the potential progression of multiplier effects of an agricultural water project.

EXHIBIT 13.23 REGIONAL MULTIPLIER EFFECT FROM AN AGRICULTURAL WATER PROJECT

"Water releases from a [project] to irrigate crops increase agricultural output. Raised output requires more seed, fertilizer, pumpsets, diesel engines, electric motors, tractors, fuels, electricity, and so on. Increased output also encourages entrepreneurs to set up food-processing (sugar factories, oil mills, rice mills, bakeries) and other industrial units…water releases from a [project may] generate new demand for appliances and prompts the establishment of new businesses and factories. Changes in industrial output require more inputs from sectors such as steel, energy, and chemicals, among others. In sum, water releases for…irrigation generate demand for inputs and opportunities for processing."

"Increased industrial and agricultural output generates additional household incomes. Higher incomes raise consumption of goods and services, which, in turn, encourages production of agricultural and industrial commodities. Changes in wages and prices have both income and substitution effects on expenditure and on saving decisions of owners of the various production factors, which further affects demand for outputs in both the region and the wider economy. Induced impacts reflect the feedbacks associated with these income and expenditure effects and also include impacts on government revenues and expenditures."

$$\text{Project's regional multiplier value-added estimate} = [(RVA_{WP} - RVA_{WOP}) + VA_{DMO}]$$

where

RVA_{WP} is the regional value added "with project"

RVA_{WOP} is the regional value added "without project" (a baseline)

VA_{DMO} is the value added from the sectors directly affected by the major outputs of the project (such as agricultural output and water supply)

A simple hypothetical example may demonstrate how such a regional multiplier for a groundwater project might be calculated:

$1000, amount Bank B loans to a local farmer's water cooperative to construct 10 wells for crop irrigation in Region A

(*continued*)

EXHIBIT 13.23 (continued) REGIONAL MULTIPLIER EFFECT FROM AN AGRICULTURAL WATER PROJECT

$500, amount of $1000 going to wages of local workers to install wells (the other $500 spent outside Region A for well-drilling-equipment rental, well casing, and pumps): primary local effect

$600, amount spent by farmers in the water cooperative within Region A for additional seed, farm equipment, planting and harvesting (additional farm labor), and crop transportation (after groundwater is produced and used for irrigation): an induced local effect

$300, amount of $500 + $600 spent locally in Region A for other food items, additional nonagricultural transportation, cultural events, and other expected targeted local expenditures: an induced local effect

Assuming no baseline regional value added without the project in this agricultural example,

$$\begin{aligned}&\text{Hypothetical example groundwater well project multiplier}\\&\quad = \{[(\$500 + \$600 + \$300) - \$0] + \$1000\}\\&\quad = \{[(\$1400) - \$0] \div \$1000\}\\&\quad = \{[\$1400] \div \$1000\}\\&\quad = 1.4\end{aligned}$$

for Region A government’s estimate of the local effect of the $1000 loan to its farmers’ water cooperative.

Source: World Bank, *Sourcebook: Shaping the Future of Water for Agriculture, 2005*, URL: http://go.worldbank.org/OBREFXF8Y0 (accessed July 15, 2007) Section 9.3.

RISK AND UNCERTAINTY

Risk and uncertainty will affect the magnitude of costs and benefits used in calculating net benefits or the net present value. Risk is associated with circumstances in which the probability of an event or the probabilities of a series of occurrences are known. Uncertainty relates to events for which the probability is not known but might vary within a range. Based on information (for risk) or informed estimates (for uncertainty), one may assign probabilities to outcomes to provide a more useful value for costs or benefits in establishing a net present value.

Risk

Gough considers risk relative to groundwater systems and describes a structured process to analyze actions as (Gough, 2006) follows:

1. Risk assessment includes
    a. Risk identification—specifying the range of possible outcomes from a particular action
    b. Risk estimation—utilizing analytical methods to calculate the probability of the outcomes and the extent of their adverse effects
    c. Risk evaluation—synthesizing the technical information with other pertinent information for evaluating alternative actions available to determine the significance and acceptability of risks (including perception of risk), possibly incorporating risk–benefit studies

2. Risk management focuses on proactive response to risk: eliminating, reducing, mitigating, transferring, or learning to live with risks, such as
    a. Integrating processes of risk assessment and risk control
    b. Controlling risk after risk assessment is done

Note that economic analysis typically assumes that people will allow themselves exposure to greater risks solely in the circumstances that they expect to receive greater compensation as compared to times of lower-risk exposure. The size that this expected compensation must be is associated in part with the probability of an unwanted result and on whether the risk taker prefers alternatives with low risk ("risk averse"), is indifferent to risk ("risk neutral"), or is attracted to risk even if the risky alternative has a low return ("risk seeking") (LBS, 2006).

For a particular project or program, multiple causes of risk may exist that could reduce or negatively affect the forecasted net benefits of its products and services (Fritz, 2004). Risks to projects may result from changes in market prices or interest rates (market risk), contrary or unfavorable operational circumstances (operational risk), volatility in net revenue or benefits from changes in consumer demand (market risk), and defaults (credit risk). Incorporating risk in estimating benefits and costs should consider the range of factors that can be identified to have unintended but potential consequences on quantifying or monetizing a project's or program's results.

The risk and uncertainty should be documented for all steps in a CBA (Lave, 1996, p. 128). This approach allows the decision maker to understand the implications of imperfect knowledge of future results (Anderson and Settle, 1977, p. 99). For example, if a project has costs that are certain (100% probability [1.0]) to be incurred over two years, but the benefits flow is uncertain but estimated based on a survey or some other information, such as a 95% certainty (.95) in year 2 and a 50% certainty (.50) in year 3, these probabilities can be used to weight the costs and benefits. This circumstance could be expressed in the following way:

$$\begin{aligned}\mathrm{NPV}_t = {} & \{(-1.0C_{t+1})\times(\mathrm{IF})^{t+1} \times [1/(1+\mathrm{DR})^{t+1}]\} + \{[0.95B_{t+2}\text{-}1.0C_{t+2}]\times(\mathrm{IF})^{t+2} \\ & \times[1/(1+\mathrm{DR})^{t+2}]\} + \{\, 0.5\mathrm{B}_{t+3}\times(\mathrm{IF})^{t+3}\times [1/(1+\mathrm{DR})^{t+3}]\} + \ldots\end{aligned} \tag{13.24}$$

where

NPV is the net present value in year t
C is the cost incurred in the t + 1 year and t + 2 year of the project
B is the benefit received in the t + 2 year and t + 3 year, and so on into the future for the duration of the project
IF is the inflation factor (1 plus the inflation rate)
DR is the real discount rate
t is the year to which the future costs and benefits are discounted

An additional way to incorporate greater uncertainty or risk, especially if the decision may involve irreversible consequences, is to use a larger discount rate. This has the effect of minimizing future costs and benefits in the more distant future. Howe (1979, p. 161) cites the example of the Everglades, a unique ecological wetland resource used for research and recreation, from which groundwater was diverted for agricultural production. That decision may now be irreversible, but future benefits were seen as driving the decision. Some species of wildlife are slowly disappearing from the Everglades and may only be saved at considerable public (social) expense, if it is possible at all to change that course. Exhibit 13.24 shows the comparative risk of nitrate contamination to groundwater across the United States. Areas having the greatest risk for nitrate contamination to shallow groundwater are those with high nitrogen input, well-drained soils, and less extensive woodland relative to cropland (USGS, 2001).

EXHIBIT 13.24 NITRATE CONTAMINATION RISKS TO GROUNDWATER

"The risk of groundwater contamination by nitrate varies across the United States. The risk of groundwater contamination by nitrate depends both on the nitrogen input to the land surface and the degree to which an aquifer is vulnerable to nitrate leaching and accumulation. Variables describing nitrogen input and aquifer vulnerability were estimated and compiled in a national map using procedures described by Nolan and others (1997). The map shows four levels of contamination risk of shallow groundwater (less than 30 m deep):

1. Low nitrogen input and low aquifer vulnerability (green area on the map);
2. Low nitrogen input and high aquifer vulnerability (yellow area);
3. High nitrogen input and low aquifer vulnerability (orange area); and
4. High nitrogen input and high aquifer vulnerability (red area)."

" 'Nitrogen input' refers to nitrogen deposited on the land surface, and 'aquifer vulnerability' indicates the likelihood that nitrate from a nitrogen source at the land surface will reach the water table. Nitrogen inputs comprise the following two factors: 'loadings' from agricultural and nonagricultural sources; and 'population density,' a variable used to indicate additional nonagricultural sources of nitrogen in urban areas."

"Aquifer vulnerability depends on soil-drainage characteristics—the ease with which water and chemicals can seep to groundwater—and the extent of cropland versus woodland in agricultural areas. Denitrification and plant uptake can occur beneath forests bordering streams near cropland (Lowrance, 1992), and precipitation seeping through forest soils to groundwater contains less nitrogen than seepage beneath an agricultural field."

Sources:

1. Lowrance, R., *J. Environ. Qual.*, 21, July–September 1992, 401.
2. Nolan, B.T. et al., *Environ. Science Technol.*, 31, 1997, 2229.
3. U.S. Geological Survey, A national look at nitrate contamination of groundwater, Nolan, B.T. et al., Eds., 2003, URL: http://water.usgs.gov/nawqa/wcp/.

An extension of this latter approach of using a higher discount rate for projects with a high risk of outcome, but for a different reason, is the use of a risk premium, clearly a higher discount rate. A risk premium is an additional rate added to the discount rate to take into account the higher level of risk associated with an outcome (a monetized cost or benefit). This higher rate would be applied to projects that receive public funds but the benefits are concentrated in a particular locality rather than to the larger economy. A risk premium may ensure that faulty projects are not started or "bailed out" using this economic analytical information (Howe, 1979, p. 164).

Because of the need to deal with risk more completely, economists have evolved and refined theories for managing risk. Risk management utilizes a range of approaches to modify the extent of risk being faced. These approaches include hedging, diversification, and insurance (LBS, 2006). Hedging involves offsetting one risk with another risk, such as injecting wastes down a deep well below an aquifer used for drinking water rather than releasing the waste to a stream used for water supply downstream. Diversification takes advantage of multiple opportunities for reaching an outcome, such as using both an upland well and a pipeline from a stream for water supply, or use of multiple wells. Insurance responds to addressing negative outcomes should they occur. Insurance in the context of groundwater might mean incurring the cost of establishing protection zones around wells or their recharge areas to reduce the probability of contaminating the groundwater used in the near term. These costs are not simply of establishing the zoning restrictions, but also the potential results from controlling the revenues from or profits to the land, which might otherwise have been developed for other purposes.

These economic approaches to managing risk to groundwater can be applied under preventive and precautionary conditions. Preventative management of risk to groundwater might focus on conservation measures to ensure a long-term supply or eliminating physical, chemical, or biological waste and residuals where they are generated (Gough, 2006). Managing risk relying on the "precautionary principle" would potentially require steps to be taken prior to damage occurring (Gough, 2006). For groundwater this might include mandatory controls on volume of use during dry seasons or zones in which chemical handling except for *de minimus* use is prohibited near the wellhead or in recharge areas.

Uncertainty and Sensitivity Analysis

Uncertainty is a lack of knowledge about the outcome or results of an event or process. Two types of uncertainty may be associated with a water project or program: (1) the inherent variability of natural processes ("natural variability") and (2) incomplete knowledge ("knowledge uncertainty") (CGER, 2000, p. 41). It may not be clear which of these two types of uncertainty might apply in a particular case. Reasons for uncertainty may include mathematical and model specification not being a reasonable reflection of reality and parameter measurement incorrectness, inconsistency, and nonrepresentativeness (CGER, 2000, p. 44). Not knowing about outcomes can create economic inefficiencies, which have costs. Relative to uncertainty, we can only make a best estimate of probability based on the information we have from associated circumstances.

A helpful way to test the robustness of cost–benefit calculations relative to any assumptions about the information used relating to uncertainty is to apply sensitivity analysis. Using sensitivity analysis, the analyst can determine the effect on costs or benefits to changing parameters related to the project or program. Modifying probabilities, discount rates, timing of costs or benefits, and other factors would allow the analyst to evaluate the strengths and weaknesses of the approach taken. For instance, using the example of the Aguaflujo watershed, applying a discount rate of 7% (0.07) to the combined set of projects results in costs of $12,679 and benefits of $12,521. With costs slightly higher than benefits under discounting at the selected rate, the set of projects may be sensitive to interest rates. The timing of the costs and benefits also can have a similar effect on the NPV. The timing of activities is within the realm of the decision maker–manager, and such information is useful to his or her decisions.

Double Counting

Inadvertant double counting of benefits or costs should be avoided. Double counting could occur in evaluating groundwater-related actions in which improved management of drilling operations results in lower costs for well installation. The costs might be computed using the lower figures. If a calculation of the cost savings from what they might have been is added to benefits of the production, the effect is to double count the effects of the reduced costs (counted as both lower costs for well installation and then cost savings added to benefits). The result, in this case, would increase the apparent net benefits (i.e., benefits with costs subtracted) substantially over the actual amount. Decisions about assigning what might be considered an otherwise ambiguous result should be made at the beginning of a CBA, such as for "cost saving" and whether it should be a reduction in costs or an addition to benefits.

OPERATIONALIZING INHERENT VALUE

What nature intrinsically provides through the ecosystem, balancing physico-chemo-biological relationships over time, is difficult to replicate in a cost–benefit spreadsheet balance. An effort to transcend previous accounting exchanges to make sense of the current understanding of the limited natural capital of ecosystems and implications for people must continue in even imperfect forms. Such an endeavor would attempt to capture for a portion of the water media, groundwater, which also relies on the other media, soil geology, atmosphere, and biosphere in such a schema. Certainly the earth's ecosystem is more dynamically productive than systems humankind has constructed. Raucher (1983) noted in similar regard "the aggregate benefits of groundwater protection may well exceed the sum of its parts." These changes in the subsurface hydrologic environment are presented as interceptions and withdrawals from the groundwater stock and flow that does not add humanly accounted value, but is incorporated in ecosystemic balancing, automatically transforming these changes in intrinsic natural processes that cannot be expressed in cost–benefit terminology but are all invaluable in their seamless, symbiotic service and support that people believe they can manage. The balancing in the extra-long term leaves behind no waste, which becomes a transitory phenomena in quaternary geologic time of concentrating less stable human-organized elements of nature that have negative consequences for people and the ecosystem until rebalancing takes place. So, the accounting might follow the effects of construction in a groundwater recharge zone, contamination of a portion of an aquifer, and depletion of an aquifer through the hydrologic cycle and subsurface ecosystem processes. At a microeconomic level (with aggregation at a macroeconomic level for cumulative effects), the following primary resources and environmental effects (not a complete or exhaustive listing, obviously) can be tracked relative to groundwater in the hydrologic cycle:

1. Changes in recharge
2. Changes in aquifer storage
3. Changes in evapotranspiration
4. Changes in groundwater—surface water flux
5. Changes in quality
6. Changes in microorganisms and degradation rates
7. Changes in quality in the groundwater—surface water flux zones

Changes in these aspects of groundwater have costs and benefits for people. People affect these changes and subsequently the environmental balance. Thus, at a minimum, these changes in the ecosystem should be documented in any CBA, even if they cannot be monetized. Where they can be monetized, they should be. Where no information is available, the effects should be extrapolated to the extent they can be, and they lend credence to the analysis. Clearly, future research in this matter is necessary.

INFORMATION COMPLETENESS

As suggested in the preceding section, information completeness to allow description of the ecosystem effects, or even adjacent community effects, is a significant element of a CBA. In the cases of particular ecosystem effects or the marginal value of groundwater to an adjacent community, we may not have complete information. We may be able to quantify benefits from installing a wellfield or from using chemicals that degrade into unknown by-products, but we cannot define the effects on generations yet to come or on animals we may consume that ingested contaminated leachate from a stream. These inequalities in knowledge are referred to as "asymmetric information" (Tsur et al., 2004, p. 19; Daly and Farley, 2004, p. 405), which subsequently affect our preferences that in turn influence resource allocation. We must be ever vigilant to document projected effects in as much as we can foresee them. In the future, new knowledge can transform past actions in ways unanticipated. For example, scientists saw few problems with disposing of waste chemicals on the ground in the first part of the twentieth century; scientists in the latter half of the century documented significant problems related to major health concerns with this practice and developed techniques to reverse what had previously been done. The use of asbestos as a fire retardant devolving to the nonuse of asbestos because of major health effects from its use is another case in point (Daly and Farley, 2004, p. 40).

Thus, documentation of what is done today to the subsurface may be important to future generations as they try to maximize use of a scarce resource for survival (e.g., see Linden, 2006, p. 265, for a discussion of climate change and future unavailability of water to produce food in currently humid, agriculturally productive areas). This information transfer should not be left out of CBAs because of our current ignorance. This information may be a critical resource in itself, shaping a future generation's perspective on supply and demand of groundwater and subsurface resources and the services they provide.

REVIEW OF KEY GROUNDWATER FACTORS AFFECTING CBA

While many considerations affect CBA, key factors distinguish analyses associated with groundwater projects, programs, and policies. These factors should be included in organizing any economic analysis of a groundwater project in addition to other factors and methods that may be applied. The factors include the following:

1. The relatively slow movement of groundwater affects the time frame (planning horizon) and therefore the discount rate applied to groundwater projects, typically having longer time frames.
2. In cases of depletion, the discount rate may be negative, reflecting the increasing value of the remaining groundwater.
3. Although most groundwater projects are local, even shallow wells can draw water originating at long distances from the pumping site. Likewise, contamination affecting a groundwater user may have an origin from distant locations. Evaluation of hydrologic and economic considerations should therefore focus on watershed and aquifer scales.
4. In defining the accounting area for economic evaluation, planning horizon and travel distance within an aquifer and even between aquifers should affect the population and area that a project or activity will influence, with at least the area and its subsurface zone lying above and within the entire aquifer boundary being considered for occurrence of effects and economic accounting. This accounting unit may cross and include multiple political jurisdictions and even into other countries.
5. Because of the varying watershed and geologic conditions from location to location, each project and activity should be evaluated for its geophysical, chemical, biological, and ecological effects.
6. Groundwaters may discharge to and be recharged by streams, lakes, and oceans, and as a result, aquatic effects must be considered beyond the site of use.
7. Because of intensive production of "fresh" groundwater (often leading to depletion), "brackish" or "saline" undergroundwaters may now be considered sources of water supply (very likely with treatment) resulting in different scenarios of subsurface water withdrawal or waste disposal—these brackish and saline groundwaters will now have value not previously considered.
8. Since aquifers may be expected to supply water for long periods of time transcending generations, intergenerational accounting should be incorporated in the results.
9. Time lags in potential actions affecting groundwater may alter the view of future benefits from current changes in pollution controls or groundwater consumption. Undiscounted effects should be considered along with discounted monetary evaluations to provide a fuller perspective to decision makers so as not to ignore benefits to future generations.
10. Owing to groundwater interactions with wetlands, streams, lakes, and oceans, the ecological effects of a groundwater-related project or activity—including nonquantified and nonmonetized effects—should be described in anticipated detail, magnitude, and duration. An indication of severity of these ecological effects should be part of the evaluation.

SUMMARY

CBAs may be applied to a range of groundwater actions and provide important information to decision makers. Cost effectiveness compares the relative costs and effects associated with two or more courses of action. CBA portrays the symmetry of costs and benefits as the changes in individuals' utilities. Care must be taken in making and documenting assumptions concerning measurements and estimates of costs and benefits, especially when public goods may not have a market price and externalities are not reflected in market prices. Ecosystem and social effects should be accounted and frameworks have emerged to do so, such as ecological footprinting. Ranges of methods are available to estimate costs and benefits, but benefits are a particular challenge and care should be taken in their calculation. Critical factors to consider include discounting (future dollars are worth less), intergenerational equity, risk and uncertainty, regional variability, accounting area, and completeness of information. Notably, we are ignorant of many ecosystem effects. However, in considering potential effects in a hydrologic cycle context, we may identify them more comprehensively across a watershed and its underlying aquifers. We need to document specific steps taken in using and interacting with the groundwater resource even if they cannot yet be monetized (e.g., releasing a measurable volume of a particular chemical with unknown biodegradation properties or improving the recharge capability of a specific area). Effort should be made to supplement monetized economic analyses with ecosystem and social equity measurements to the extent they are understood and quantifiable, or at least with qualitative descriptions. Future generations may be able to use this information to make critical decisions about needed resources, including those not considered useful in the past, such as brackish or saline groundwaters.

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Part V

Groundwater Future

Part V addresses aspects of groundwater use in the future with a special focus on

1. Sustainable development, building on concepts of macroscale considerations and of types of actions to pursue in order to provide a high-quality source of water for the range of uses previously examined.
2. Transboundary considerations of groundwater as it moves across local, state/provincial, and international boundaries in the future, and the potential relationship to climate change as it affects groundwater quality and mobility.
3. Identification of key points affecting economic perspectives on the use and management of groundwater for the next generations.

14 Sustainable Development

Major questions from previous chapters related to long-term resource availability include: How do macroeconomic considerations affect the natural capital stock of groundwater for the future service of humankind? What is sustainable development? Is sustainable development of groundwater possible? What steps could be considered in obtaining sustainable development? In response to questions like these, a U.S. Council on Sustainable Development prepared a plan, which noted that the rising pace of groundwater depletion in the United States affects a major resource factor as an input to meeting our society's needs (Sitarz, 1998, p. 7). The independent Heinz Center has raised fundamental questions about the ability of society to maintain society's provision of goods and services from the ecosystem sustainably, recognizing that increased human demands are creating stresses on the natural system (Heinz, 2008) and that basic data to manage groundwater is lacking (Heinz, 2006). The European Union has implemented a research plan for sustainable water resources. Thus, sustainable development now has an economic and policy context, with some activities on the international level specifically targeted at groundwater.

The goal of preserving the range of choice of the present for future generations is certainly central to sustainable development, but it would be naively altruistic to think that each person acting on their own would use groundwater in that manner. Protecting the range of options for the future is probably best addressed at the macro, social–political decision level, affected through economy-wide policies such as conservation zoning (Turner et al., 1993, p. 60), limiting the scale of natural capital throughput (Daly, 1996, p. 15), or State growth policy specifically recognizing limited water supply as a factor (WWPRAC, 1998, pp. 5–17). The principal question to be addressed in this section is, Which alternatives protect the range of future options for groundwater availability and use while providing the services needed through a market economy?

DEFINING SUSTAINABLE DEVELOPMENT

Sustainable development recognizes the maintenance of necessary and critical resource services that the ecosystem provides while addressing equitable treatment of others in the current generation of people (intragenerational equity) and of future generations (intergenerational equity) (Daly and Farley, 2004; Common and Stagl, 2005). The World Commission on Environment and Development defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (UNWCED, 1987, p. 43). It also underscored that the basic needs of poor people must be a priority. With such a broad definition, a range of approaches responding to it have evolved. The United Nations more recently defined (2003, p. 4)

> Sustainable development [as] development that ensures nondeclining per capita national wealth by replacing or conserving the sources of that wealth; that is, stocks of produced, human, social, and natural capital.

A more specific, if not idealized, definition of sustainability was proposed by Hartwick (1989, p. 96):

> in a special case, accumulation of reproducible capital can offset a steady decline in resource use and allow per capita consumption to be maintained at a constant positive level indefinitely. This case involves society investing all rents from exhaustible resources reproducible capital instant by instant.

Known as the "invest resource rents for sustainability" rule, it applies to both renewable and nonrenewable resources and requires that society invest an amount equivalent to the value of the remaining stock. As the stock declines with continued resource use through time, its value rises and that change in value is the resource rent (Markandya et al., 2002, p. 20). This required investment approach is a constraint on individual behavior because individuals will not save sufficiently to attain the sustainability envisioned in such an economic model. The point is that "interporal efficiency is not sufficient for sustainability" (Common and Stagl, 2005, p. 352). This result also applies in other related contexts, such as technological advances, which do not ensure some constant consumption level for a resource (Common and Stagl, 2005, p. 352). A further challenge is measuring the resources of concern at some aggregate level so that we might be able to devise an approach or model that could enable achievement of sustainability. Drawing on many of these concepts and more specific to groundwater, its "sustainability" has been defined as (Alley et al., 1999, p. 1)

> development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic and social consequences.

The measurement of sustainable development is a "sustainable flow of income" (Turner, 1993, p. 56). Calculating income "give[s] people an indication of the amount which they can consume without impoverishing themselves" (UN, 2003, p. 4, citing Hicks, 1946, p. 172). A sustainable national income level should not result in depreciation of the national capital, including natural capital, i.e., endowments of the ecosystem. Exhibit 10.1 defines natural capital and ecosystem inputs in an economics context as natural resource stocks, land, and ecosystems providing resource, sink, and service functions. All these functions are attributable to groundwater, in addition to it being an economic product or commodity. To more properly measure sustainable national income, revisions to the national income accounting system could guide policy for sustainable development, as described by the United Nations handbook on national environmental and economic accounting (2003). These revisions should address (1) depreciation of natural capital (a quantity measure) consumed and depleted by production and (2) degradation of natural capital (a quality measure) calculated through defensive expenditures on undesirable by-products of production and consumption (Turner et al., 1993, p. 56; Daly, 1996, p. 100). Since either gross or net national product treat natural capital depletion or environmental remediation as products and services adding value, rather than as costs to the nation or the ecosystem, society will believe that it has more national product to be consumed than what exists.

A number of authors have provided a range of operational responses or approaches to this definition of sustainable development (Turner et al., 1993; Reid, 1995; Daly, 1996; WRI, 1997; Sitarz, 1998; Markandya et al., 2002; Daly and Farley, 2004; Common and Stagl, 2005). Several key factors affecting the approaches emerge from these perspectives:

1. Scale is important (Daly and Farley, 2004): The scale is the ecosystem and the services it provides for the economy. The economy is a subsystem of the ecosystem, not a separate realm, and the economy draws its raw materials from the ecosystem. Relative to the earth's ecosystem, the world economy has grown over time, consuming an ever increasing amount of ecosystem resources (or natural capital). Significant depletion of aquifers underlying extensive interbasin, interstate, and international areas is a major example of scale effects relative to groundwater use.
2. The ecosystem provides services that are intrinsic and are valued by people (perhaps unknowingly) as providing basic livelihood (Turner et al., 1993, p. 58): "Primary products" such as drinking water; "assimilative capacity" such as the ability to break down or process some pollutants; "life support" such as the hydrologic cycle, which provides rain for crops; and "amenities" such as "satisfactions" from recreation on a river maintained by groundwater or the visual pleasure of seeing water flowing from a spring running down a hillside at the headwaters of a stream (Reid, 1995, p. 90).

3. Natural capital is used up in the production and maintenance of man-made capital. Therefore, natural capital and man-made capital are complements rather than substitutes (Markandya et al., 2002, p. 27; Daly and Farley, 2004, p. 232).
4. Preserving natural capital will provide services and income into the future for a stable population whose demands on the ecosystem are within its carrying capacity (Daly and Farley, 2004).
5. Economic policies and technology must be flexible and adaptable to provide alternatives for responding to ecosystem stresses (UNWCED, 1987, Ch. 2; Daly and Farley, 2004, p. 362).
6. Certain ecosystem functions and services are critical for human survival and cannot be replaced (Turner et al., 1993, p. 56). These functions and services include photosynthesis and the hydrologic cycling of water. More data are needed to evaluate changes in the ecosystem and their effects on people and societies (Heinz, 2008), including data on groundwater (Heinz, 2006).
7. Uncertainty with potential irreversibilities for environmental outcomes are economic costs that must be recognized in decisions involving trade-offs between near-term economic benefits and sustainable flows of income (Turner et al., 1993, p. 57; Daly, 1996, p. 16).

DEFINING ECONOMIC GROWTH

Economic growth is usually defined at the macroeconomic level as the increase in gross or net national product, which measures the value of all goods and services produced and provided. In recent years in the United States, the GNP has grown an average of 2%–4% annually, adjusted for inflation. This measure, used as the yardstick by most economists and financiers, counts all production growth in the same way, regardless of what is produced. By definition of the economists that espouse GNP as the measure of national productivity, more GNP is better, if the goal is economic growth. In the accounting perspective of this process, man-made capital stock, which is produced from consumed natural capital stocks or throughput, provides services recognized economically. As the man-made stock requires maintenance, it consumes more natural capital stock that can no longer provide its ecosystem services. In the economic growth vision, producing and using more natural resources is good, regardless of how well—efficiently—they are used, and regardless of the effects on the future availability of natural capital stocks for the next generations. Based on the present economic policy, then, economic growth must go on indefinitely. This circumstance assumes that technology will address any resource, capital, and labor shortages, that natural capital is completely substitutable with man-made capital, and as a result, the ecosystem has no limits or constraints on carrying capacity for economic activities.

AN ALTERNATIVE APPROACH TO MEASURING NATIONAL PRODUCTION

Exhibit 14.1 provides one alternative perspective for measuring production for a nation, state, or other area. It considers first that natural capital and man-made capital are complementary, with the latter using up the former, in some cases, irretrievably. Its concept is that man-made capital services gained are at the expense of natural capital services lost, and explains the relationships involved. Importantly, the approach recognizes that natural capital extracted (produced, as in mining, for example) should not be counted the same as man-made capital in our accounting system of national production. Thus, they are not additive. Man-made capital services can be produced at some rate of natural capital services sacrificed. Some natural capital services can be counted but others not currently known cannot. The point of the alternative approach is that we should conceptually get the accounting correct or we will mislead ourselves into believing that we can continue producing more indefinitely.

Another critical point in responding to this alternative approach is that some level of natural capital may be used to replenish the ecosystem services lost where nonrenewable resources are involved. While this is a "defensive" use of the capital, it prolongs the services of the remaining natural capital. Thus, recycling and reuse are not just "nice to do" but imperative, especially in situations where the natural capital is being depleted to a point of nonexistence or prohibitively expensive extraction. Technological advances are therefore important not solely on economic efficiency grounds, as considered in current economic analyses, but to preserve the natural capital for future support of humankind in the ecosystem.

EXHIBIT 14.1 NATURAL CAPITAL—MAN-MADE CAPITAL COMPLEMENTARITY

As discussed previously, since man-made capital requires natural capital, the two types of capital are complementary. Because of this complementary relationship, services gained from man-made capital are at the expense of natural capital services lost. Herman Daly describes such fundamental relationships affecting economic growth and sustainable development through the "comprehensive efficiency identity" (Daly, 1996, pp. 84–86; Daly and Farley, 2004, p. 423):

$$\frac{\text{MMK services gained}}{\text{NK services sacrificed}} = \underbrace{\frac{\text{MMK services gained}}{\text{MMK stock}}}_{\text{Ratio 1}} = \underbrace{\frac{\text{MMK stock}}{\text{thruput}}}_{\text{Ratio 2}} = \underbrace{\frac{\text{thruput}}{\text{NK stock}}}_{\text{Ratio 3}} = \underbrace{\frac{\text{NK stock}}{\text{NK services sacrificed}}}_{\text{Ratio 4}}$$

where
MMK is man-made capital
NK is natural capital

Thruput is "the entropic physical flow of matter and energy from nature's sources, through the human economy and back to nature's sinks; it is the flow that is accumulated into [man-made capital] stocks and funds and out of which [man-made capital] stocks and funds are replaced and maintained" (Daly, 1996, p. 111)

Service is "the satisfaction experienced when wants are satisfied" (Daly, 1996, p. 110)

MMK services gained/NK services sacrificed is the "overall ecological economic efficiency" describing the amount of service obtained from each unit of man-made capital per amount of NK services sacrificed for each unit of natural capital used up from being transformed into man-made capital

MMK services gained are the satisfactions received from the application of man-made capital to human wants

MMK stock is the "inventory" of man-made "things" that are used up gradually

NK stock is the "inventory" of natural "things" that are used up over time

Ratio 1 is the "service efficiency of man-made capital stock" derived from technology and resource allocation efficiency as well as distributive efficiency within the population (Daly, 1996, p. 84). For groundwater, this technical ratio might be the number of persons served (for drinking, cleaning, waste disposal, and recreation) per unit of water treatment and supply capacity (such as a 5000 m^3/day plant). For distributional equity, a measure of the number of low-income persons served at lifeline rates per 100 customers might be included. Allocative efficiency might indicate the quantity of lower quality water used for nonhuman purposes per unit treatment and supply capacity.

Ratio 2 is the "maintenance efficiency or durability of the man-made capital stock." For example, this could be the treatment and supply capacity per units of water, energy, steel, concrete, and chlorine used to provide the ready water supply.

EXHIBIT 14.1 (continued) NATURAL CAPITAL—MAN-MADE CAPITAL COMPLEMENTARITY

Ratio 3 is "the growth efficiency of natural capital in yielding an increment available for offtake as throughput." This ratio is a measure of economic growth. The more units of water, energy, iron, and limestone as concrete that are sent through the economy to maintain water wells and supply systems, along with maintaining the other man-made capital, the larger the economy gets. As throughput increases, NK gets smaller. As groundwater is used for irrigation (throughput) in many parts of the High Plains Aquifer to produce crops in the midwestern United States, the aquifer is depleted (natural capital is smaller).

Ratio 4 "measures the amount of natural capital stock that can be exploited for throughput per unit of other natural services sacrificed." This "ecosystem service efficiency" is defined by the bound or limit of the natural environment as a source of low entropy resources or sink for high entropy wastes. The more natural capital stocks are used, the more natural capital services are sacrificed. In the groundwater environment, the mining of groundwater lowers the water table, which may cause wetlands to dry up, trees to die, and streams maintained by groundwater to disappear along with their wildlife, while using more and more energy to pump the water further up the well (for example, see USGS, 1999b).

Thus, in an economy that values more water production at least cost, the result is gaining MMK services by organizing to produce more water to satisfy more water-related wants while losing groundwater stocks, wildlife, and limited hydrocarbon stocks, as well as services provided by the ecosystem that are not easily recognized, quantified, or monetized. In depleting groundwater sources, future groundwater services may not occur at all, or occur at a significantly reduced level.

Economic production growth focuses on only one part of the equation: ratio 3, throughput/natural capital stock, ignoring natural capital services losses. Man-made capital services grow only if natural capital services are lost, some in perpetuity, and therefore, irretrievably. Certain aspects of groundwater supply may appear to correspond to irretrievable loss from macrolevel development. For example, zones of salt water intrusion have expanded around centers of large past groundwater pumpage in the United States and Europe (USEPA, 1999; EU, 1999b). The stock aspect of the groundwater resource as a freshwater supply is gone in these locations. Furthermore, areas of groundwater table decline have expanded in the United States and Europe (USEPA, 1999; EU, 1999b), as well as in other parts of the world. Therefore, nations that are groundwater users cannot continue to focus on only one part of the "ecosystem efficiency" equation, but rather should consider the entire equation and its further refinement. This focus at a macrolevel would reflect the perspective that the economy does not exist independent of the ecosystem, but is in fact highly dependent on the ecosystem as its source of groundwater and other critical resource stocks and their services. This would reflect that the economy is a subsystem of the ecosystem. Nations, states, and localities that are groundwater users would need to formulate policies consistent with limits to certain resources, recognizing the fact that technologies, while available, may not be able to be deployed equally everywhere to fully sustain groundwater or any other natural resource stock for future services.

This "comprehensive efficiency identity" suggests, and seemingly the world requires, that efficiency be redefined. For sustainability purposes, the redefinition may not be in monetary terms for the final calculations. Current traditional economic methodologies are still needed to perform assessments of production processes and to inform such service and capital flows as in the identity from the underlying economic processes to point to necessary resources adjustments critical to NK maintenance.

Source: Reprinted from Daly, H.E., *Beyond Growth: The Economics of Sustainable Development*, Beacon Press, Boston, MA, 1996. With permission.

CAUTIONS ON COST–BENEFIT EVALUATIONS

The use of conventional cost–benefit analysis also assumes that society has a full understanding of the ecosystem relationships, which can be addressed through technology if any of the relationships becomes broken and that correction of market failures resulting in resource misallocation can be accommodated through efficiency pricing. That is, society, through the market, can establish prices for the perfect allocation of capital and labor—a truly unlikely occurrence, since science has not uncovered all the natural balances of micro and macro forces of the earth's ecological system to inform each individual consumer so he or she can make rational choices now or into the future about how much they are worth in the market that will be affected by these environmental balances in the future, or how resources should be valued in the political arena that influences their use. As Sagoff (1990, pp. 92–94) suggests, attempting to price unknowable, or at least currently unknown, natural balances of the ecological system as private transactions suffers from "category mistake." The aggregation of individual decisions in the marketplace is not the same as the establishment of public value and expressly stated objective for such natural balances to be achieved through decisions resulting from discourse among scientists, engineers, theologians, businesspersons, philosophers, and preservationists in the public places of congresses, parliaments, legislatures, or councils.

Recognizing the limits of cost–benefit evaluation in general and as applied to a particular project or program, decision-making is important in considering just how efficient the decisions are with positive benefit-to-cost ratios. However, we should continue to pursue understanding the ecosystem balances and requirements as they affect natural capital's goods and services, since they are critical to maintaining the economy overall and to our individual lives. We may obtain information to enable valuing some, albeit, very small, portion of the ecosystem to improve our interaction with it for a sustainable future. In doing so, we should recognize that net benefits of a project or program do not imply sustainability, but rather one possible efficient outcome as defined by our limited but growing understanding of the ecosystem and our economy within it. Notably, ecosystem experts have documented the inadequacy of available groundwater data for decision making (Heinz, 2006).

NATURAL CAPITAL SHORTAGE

Since in the United States and Europe, there have been few periods in the last 50 years that have been characterized by shortages of natural capital, production growth has appeared to be limitless. However, as shortages have appeared, they may have not received sufficient attention by most people because their magnitude has not been large enough to cause widespread concern. One area of shortage in the United States is groundwater, and its shortage currently often appears somewhat local or regional: the declining water table levels of the High Plains Aquifer in the midwestern United States; locally in coastal areas, excessive groundwater production has caused saltwater intrusion, making the aquifers less usable in certain areas for freshwater supply and resulting in higher cost replacement water supply; and declining aquifers across the country because of various local, State, and federal policies, such as central wastewater treatment and discharge, with limited regard for the value of this potentially reusable water, which has already received some level of treatment.

PRINCIPLES OF SUSTAINABLE DEVELOPMENT

Principles Applying to All Waters

Based on the considerations outlined here, several principles for sustainable development can be identified (adapted from: Turner et al., 1993, pp. 59–60; see also Sagoff, 1990, pp. 74–98; WWPRAC, 1998):

1. Achieve exigent macrolevel control while maintaining as much microlevel choice and discretion as possible (Daly and Farley, 2004, p. 361)—In situations where groundwater is limited and as a result allocated, people may still choose among the uses they decide for their allocation. For example, Westminster, Colorado, United States, had a legal limit to its groundwater production and implemented a water reuse program with an investment in a parallel water distribution infrastructure that allowed it to achieve local economic objectives: the city supplied more users with same groundwater allocation through wastewater reclamation for reuse. The city has a limit to the water available to it.

   In a similar vain, California (United States) has developed a policy that provides for conservation and mitigates revenue problems for the water supplier. A law enacted in 2009 provides for (Hildebrand, 2009)
   - Metering water use
   - Establishing "basic" water use appropriate for essential consumer needs through criteria including number of users per dwelling, land use type, irrigated area, and meteorological conditions
   - Setting water volume rates for the "basic" allocation based on "proportional cost of water service" considering customer category, basic use, metering, and incremental cost of water supplied
   - Implementing a "conservation charge" applied to all water use above the "basic" allocation on a volumetric basis to allow the water supplier to encourage conservation and recoup conservation costs

   This approach provides flexibility to the water supplier and the consumer, allowing for micro- and macrolevel decision making to arrive at a mutually acceptable result.
2. Correct market failures due to pricing and property rights—Examples might include eliminating water supply subsidies and modifying groundwater use rights that allow withdrawal without consideration of effects on adjacent users (e.g., WWPRAC, 1998, pp. 3–17, 3–20, and 5–10, 6–3*; EU, 1999b, p. 113; Daly and Farley, 2004, p. 361). Also, the European Union and the state of Connecticut (United States) require delineation and management of drinking water source protection areas. Localities can choose the level of regulatory activities in these areas, providing rights or constraints to chemical use and water management in these areas within guidelines for groundwater protection.
3. Ensure regeneration and waste assimilation of natural capital—Basically, groundwater use should require management around safe yield, and waste disposal should consider specific capabilities of natural degradation prior to the disposal (e.g., WWPRAC, 1998, pp. 3-2, 5–8, 5-13–5-15).
4. Develop technologies that change resource use from nonrenewable to renewable natural capital—For example, in areas of irrigation, manage groundwater use around safe yield of the aquifer through technologies such as drip irrigation gauged on local evapotranspiration rates (e.g., WWPRAC, 1998, pp. 5-4–5-17). Water reclamation and reuse technologies also support this and principle 5 below.
5. Utilize renewable natural capital only at levels allowing replacement by substitutes including recycling—Water use rates above the safe yield that would deplete an aquifer may be offset by artificial recharge of the aquifer by clean water (e.g., WWPRAC, 1998, p. 5–6).
6. Use the carrying capacity of natural capital to bound the scale of economic activity and where uncertainties of this limit exist, incorporate a margin of safety to ensure maintenance of natural capital and potential irreversible consequences of its loss—For example, when disposing of sludge on agricultural lands applying less than the agronomic rate may

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* The WWPRAC (1998, p. 3–17) notes: "The whole system [of western water (management)] encourages inefficient use. Federal water subsidies, hydropower subsidies, crop subsidies, the doctrine of appropriative rights, constraints on water transfers, fixed, or declining block rates—a whole gamut of conservation disincentives has given the American West the most prodigious thirst of any desert civilization on earth" (Reisner and Bates, 1991, p. 7).

better take into account uncertainties of the subsurface environment to reduce the potential of groundwater contamination in known hydrogeologically sensitive areas, or setting standards for irrigation return flow to protect instream uses (e.g., WWPRAC, 1998, pp. xiv, 5-11–5-15, 6–21; USGS, 1999b; Daly and Farley, 2004, p. 361).

7. Utilize the appropriate political/institutional entity for the area or resource being addressed (Daly and Farley, 2004, p. 363)—For example, early United States policy encouraging development of the western states territory through irrigation of homesteaded land was done with limited knowledge of the groundwater resource capability in the longer term. The United States Congress and state legislatures could debate the level of sustainability of this fundamental resource, considering more recent information in all areas of geological and hydrological sciences and economics, and beliefs stemming from theology, philosophy, and culture associated with the resource—all of which affect individual tastes and preferences now and in the future (e.g., Sagoff, 1990, Ch. 5). From a water quality standpoint, the European Union has decided from a social–political perspective that the lowest levels of pesticides and other man-made chemicals possible can only be permitted in drinking water and the member States have spent billions of dollars to achieve high levels of treatment of public water supplies and for protecting sensitive areas around and upgradient of public groundwater supply wells (e.g., NWRI, 1998, pp. 209–230 and 295–304).
8. Organize around hydrologic systems and their entire water resource (WWPRAC, 1998, p. 6-4)—Applying sustainable principles at the hydrologic system level (aquifers and watersheds) would ensure the entire water resource (groundwater and surface water) (USGS, 1999a,b; EU, 2000; USEPA, 2007a,b) was considered in water use decisions and that effects on other resources are taken into account (WWPRAC, 1998, pp. 1-1, 3-2; USGS, 1999b). This principle reflects a sound science approach to implementing policies of sustainability for groundwater resources. While it may be difficult to address issues that cross political boundaries, governing bodies have developed and implemented such policies (for example, the operation of the Delaware River Basin Commission provides regulatory control within a river basin that includes water catchment in four states (DRBC, 2008)). This principle can embrace the concept of "total water management" (TWM) for all water flows including recycling and reuse of water on the continuum of conservation measures (Jeffcoat, 2009). Orange County, California (United States) has implemented this expanded concept through its "groundwater replenishment system" to treat wastewater and use it to create a saltwater intrusion barrier as well as provide water for groundwater recharge to the larger groundwater basin (Markus, 2009). Such an approach may be important to coastal communities' management of groundwater resources in responding to the effects of climate change and rising ocean levels.

SPECIFIC SUSTAINABILITY PRINCIPLES FOR GROUNDWATER

Groundwater sustainability was previously defined as "development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences" (Alley et al., 1999, p. 1). Such consequences may embrace a wide range of factors, but using hydrologic principles established on recent years of improved understanding of water in the subsurface, principles of sustainability specific to groundwater may include the following:

9. Understand the status of the resource as the basis for taking actions for its sustainability—The European Union is establishing a groundwater monitoring network to implement the groundwater aspects of the Water Framework Directive for all member states (EU, 2007). In 2007, the United States Advisory Committee on Water Information began developing a proposal for a national groundwater monitoring network, recognizing that the demands of drinking water, food and energy production, and climate change require "information necessary for the planning, management, and development of groundwater supplies to meet current and future water needs, and ecosystem requirements" (ACWI, 2008). In addition

to establishing the condition of the subsurface portion of the ecosystem, such monitoring is a necessary and fundamental input to the economic baseline information essential to evaluating efficiency of future projects and programs through cost-benefit analysis.

10. Consider the natural sensitivity and contaminant vulnerability of the overlying unsaturated zone (e.g., USEPA, 1993a,b; USGS, 1999b; EU, 1999b)—"Earth materials vary widely in their ability to transmit and store groundwater" (USGS, 1999b, p. 10). This variability is manifest on the ground surface and in the soil zone, as well as deep in the subsurface. Areas of more rapid infiltration of precipitation in the ground can be in proximity to those that induce more runoff. Contaminants, once in the ground and entering the saturated zone, may present great difficulty in being extracted from aquifers or aquifer zones that are characterized by slow groundwater velocities. Such physical factors heavily affect the cost of removing contamination from groundwater.
11. Consider the status of the well—Whether it is damaged through time, use, abuse, or neglect (abandoned), well condition can contribute to contamination of groundwater (e.g., Jorgenson et al., 1998).
12. Consider low groundwater velocities—Because of slow movement of water or contaminant to discharge points, contamination may remain a long time, slow movement makes it difficult to treat, and subsurface conditions may reduce degradation capabilities (e.g., USGS, 1999b, p. 59).
13. Effects of production or recharge occur over long periods of time (USGS, 1999b, p. 3; EU, 2007, p. 15, Annex. 1)—Water balance and quality should be evaluated over time, considering local and extended areas affected, which can be long distances from the point of use.
14. Groundwater may be renewable or nonrenewable, depending on use and recharge rates over specified timeframes—Losses from storage must be considered in the period for which sustainability is to occur (e.g., USGS, 1999b, p. 3).
15. The deeper the well, the more distant the effects on and from other water and associated resources and activities (USGS, 1999b, p. 37)—Deeper wells may provide a larger or cleaner water resource, but deep wells pull water from larger areas and longer distances, potentially affecting more distant streams, wetlands, and other surface waters, or are affected by them if contaminated. These situations may be caused by and affect individual water users and the costs of and the benefits derived using these waters. Aquifer modeling is being refined over time to address concerns such as these.
16. Consider all potential recharge areas or zones and contaminant pathways—Recharge zones from streams, wetlands, lakes, coastal interfaces, seepage ponds, adjacent brines, past and current injected wastes, and other pathways should be evaluated when projecting future water quantity and quality effects (USEPA, 1990; USGS, 1999b). Exhibit 14.2 identifies some of the most significant effects of not considering the entire water resource for planning and management purposes.
17. Consider the degradation potential of any product or waste introduced on land, into the subsurface or discharged to streams recharging groundwater (e.g., USEPA, 1993a,b)—Decisions made ahead of the time of use of products or disposal of wastes relative to whether their capability to degrade in low-oxygen and no-sunlight environmental settings is sufficient or not may affect the long-term use of groundwaters that become sinks for these chemicals. These decisions affect the cost of using these groundwaters and whether future users will derive benefits from their use.
18. Perhaps most importantly and considering the other principles above, establish that groundwater and the subsurface environment have a positive nonzero value—This value can be established through specific resource policy performance objectives and then once human and ecosystem requirements are met, through other economic processes, including market exchange and tradable rights to groundwater and subsurface services.

These general and specific principles may provide a substantial basis for implementing sustainable development and use of groundwater as a component for the ecosystem's natural capital. Each

EXHIBIT 14.2 SOME POTENTIAL EFFECTS OF POLICIES NOT CONSIDERING THE ENTIRE WATER RESOURCE

Quantity Effects

Loss of water supply
Lower groundwater tables from excessive pumping
Adjacent land owners' property values reduced from inadequate water supply
Stream flow reduced from nearby or distant groundwater pumping
Headwaters of streams shortened from lower water tables
Lake levels reduced from lower groundwater tables
Vegetation (relying on shallow groundwater) changes or dies from lower groundwater tables
Loss of habitat for local and endangered species requiring groundwater
Shallow wells dry up from lower groundwater tables
Deeper wells needed to reach water when shallow wells dry up
Wetlands dry up from lower groundwater tables
Wildlife not supported when streams, lakes, and wetlands dry up
Land subsidence from lower groundwater tables which previously provided structural support
Highways, private and public structures, subsurface infrastructure damaged by subsidence

Quality Effects

Groundwater quality deteriorates from chemical (product/waste) release, microbial infestation, or brackish or saline water intrusion
Groundwater users cannot use water source for drinking water
Adjacent land owners' property values are reduced by deteriorated groundwater quality
Stream quality reduced by deteriorated groundwater discharge
Lake quality reduced by deteriorated groundwater discharge
Loss of local and endangered species requiring groundwater within a specified range of quality and/or temperature
Surface water users cannot use water source for drinking water or swimming
Riparian land owners' property values are reduced by deteriorated surface water quality
Wetland quality reduced by deteriorated groundwater discharge
Wildlife not supported when streams, lakes, and wetlands have deteriorated water quality
Public use of public lands reduced by unsafe water supply unable to support public use

Sources:

1. Adapted from U.S. Geological Survey (USGS), Sustainability of Ground-Water Resources, U.S. Geological Survey Circular 1186, 1999b.
2. Adapted from Western Water Policy Review Advisory Commission (WWPRAC), Water in the West: Challenge for the Next Century, 1998.

principle has a cost and benefit associated with it. These costs and benefits would need to be evaluated for each project and program to identify the most efficient way to achieve sustainability of the groundwater resource in those situations.

RANGE OF ALTERNATIVE APPROACHES

Sustainable development at the macroeconomic level in practice embraces a range of policies from pollution taxes (i.e., raise the price of activities that are not desirable) to regulation and standards (i.e., set a performance objective for the resource and for water-using activities). The basis for these alternative approaches might be characterized at one extreme as very weakly sustainable to very strongly sustainable at the other end of the spectrum (Turner et al., 1993, p. 60). Exhibit 14.3

EXHIBIT 14.3 SUSTAINABILITY APPROACHES AND PRACTICES

Characterization (Overlapping Categories)	Features Used in Alternative Management Approaches	Rationale for or Shortcomings of Management Approach	Example Policy Instruments Used with Approach	Potential Tools for Groundwater Sustainability
Very weakly sustainable	Conventional cost–benefit approach: Correction of market and intervention failures via efficiency pricing; potential Pareto criterion (hypothetical compensation); consumer sovereignty; infinite substitution	Technology can solve supply problems; correct pricing can be known and applied; near-term benefits of greatest value	Pollution taxes, elimination of subsidies, imposition of property rights	Taxes based on degradability of contaminants or volume of use; groundwater use rights for all property owners
Weakly sustainable	Modified cost–benefit approach: Extended application of monetary valuation methods, actual compensation, shadow projects, etc., systems approach, “weak” version of safe minimum standard	Continued reliance on market and technology for substitutes; relies on discovery of total costs and benefits of system	Pollution taxes, permits, deposit–refunds; ambient targets	Releases to subsurface controlled; set range for ambient conditions for acceptable water table levels or chemical application rates
Strongly sustainable	Fixed standards approach: Precautionary principle, primary and secondary value of natural capital rule; dual self-conception, social preference value; “strong” version of safe minimum standard	Relies on standards that are broadly applicable	Ambient standards; conservation zoning; process technology-based effluent standards; permits; severance taxes; assurance bonds	Specific concentration limits for contaminants in subsurface set; bonds required for chemical use and waste disposal on or in the ground
Very strongly Sustainable	Abandonment of cost–benefit analysis; or severely constrained cost-effectiveness analysis; bioethics	Relies on knowledge of specific ecosystem relationships to guide decisions	Standards and regulation; lifestyle directives	All uses of the subsurface controlled through strict withdrawal and discharge limits and near-real-time water use adjustment requirements

Source: Modified from Turner, R.K. et al., *Environmental Economics: An Elementary Introduction*, The Johns Hopkins University Press, Baltimore, MD, 1993, 60. With permission.

presents this range of approaches and portrays some practical policy outcomes. Notably, approaches that rely on individual preference are characterized as weakly sustainable, whereas approaches that set performance requirements are considered strongly sustainable. In practice, all the approaches may be necessary, depending on the circumstances, emphasizing stronger measures of macrolevel policy where critical natural capital may be irreversibly withdrawn from providing a continued flow of income or where uncertainty about environmental outcomes is high.

Decision rules for inclusion of sustainability in macrolevel actions to maintain natural capital address both renewable and nonrenewable resources (Common and Stagl, 2005, p. 378, citing Costanza and Daly, 1992):

1. For renewable resources—Limit consumption to sustainable yield of the resource (this would be analogous to safe yield for groundwater) for renewable groundwater, typically shallow aquifers, but this only deals with the quantity supplied. Relative to quality, natural degradation rates would need to be established for different subterranean environments over a range of time periods to satisfy interests for groundwater use in a range of quality conditions.
2. For nonrenewable resources—Reinvest the proceeds from nonrenewable exploitation into renewable natural capital. Nonrenewable groundwater would most likely be deeper aquifers or shallow aquifers being used faster than naturally recharged, but could also include brackish and even saline groundwaters to be treated through desalination technology in arid and water resource-limited regions. For example, a portion of profits from mineral mining that deplete groundwater in the production process could be used to treat groundwater and artificially inject it back to the aquifer, if subsurface conditions permitted this.

TARGETING SUSTAINABLE GROUNDWATER POLICIES

Most communities or nations may not be able—politically, institutionally, or financially—to address every aspect of sustainability that is of concern in the near term. However, they can be aware of the historical conditions and existing institutions affecting sustainability and begin aligning their policies and activities, after examining the larger picture of resource use and extraction from the ecosystem, to focus on priorities for maintaining their natural capital for *both* current *and* future generations. This is happening in European Union with the management of its water resources. Several policy alternatives previously discussed and elaborated further below address intermediate steps that localities or nations could take to sustain their groundwater stocks to reduce the possibilities of future ecosystem service losses. These policies should be targeted at the largest categories of groundwater use for maximum results: (1) irrigation, (2) public water supply, (3) industrial use, (4) mining, and (5) domestic water use (USEPA, 1996; Solley et al., 1998; EU, 1999b).

Additionally, the United States Council on Sustainable Development identified a range of policy changes that could potentially result in steps toward a sustainable future if action is taken. The policy changes that appear most related to groundwater, although not specifically identified as such in each proposed policy, are addressed in Exhibit 14.4.

The European Union has also implemented an "Energy, Environment and Sustainable Development Programme for Research, Technology Development and Demonstration [RD&D] under the Fifth Framework Programme" (EU, 1999a). This RD&D program specifically targeted "Sustainable Management and Quality of Water" as its "Key Action 1" for years 1999–2002, and budgeted 62.5 million Euro specifically for sustainable water projects in 1999, which grew to 175 million Euro in 2002. These projects are summarized in Exhibit 14.5 and reflect a value for sustainable water—albeit, unquantified at the natural resource level—within the policy-making European Council.

Since sustainable development has to do more with the long-term existence and viability of goods and services from the ecosystem to maintaining economic functions, the first priority of sustainable groundwater policy has to be for establishing the sustainable scale of the resource, rather than monetary or fiscal policy. This requires information from scientists, engineers, planners, and other disciplines to enable political institutions to establish water policies that provide for sustainable water resources and their use. Once the resource has become scarce, ownership and distribution become issues. Just distribution of water is a social, ethical, and moral concern to ensure our fellow earth inhabitants have sufficient water to meet their needs, given current technology and institutions for accessing and using it. Policy instruments related to efficient allocation of the resource, especially if scarce, are the priority for sustainable policy implementation once sustainable objectives are set.

EXHIBIT 14.4 SUMMARY OF PROPOSED POLICY CHANGES FOR SUSTAINABLE DEVELOPMENT IN THE UNITED STATES POTENTIALLY APPLICABLE TO GROUNDWATER

- Shift tax burden toward consumption, and goods/services of major environmental risk
- Encourage economic and material-use efficiency
- Offset impact on poor with reductions in payroll taxes
- Determine if subsidies are still needed
- Ensure responsibility for the environmental effects throughout a product's lifecycle
- Enhance efficient and clean technologies
- Provide incentives for recycling and finding substitutes for troublesome materials
- Make use of market incentives (e.g., emission reduction sales, charges, fees, deposit-return charges, and tradable permits)
- Adopt accounting practices that link environmental costs with the products, processes, and activities that generate them
- Develop sustainable development indicators
- Develop immigration policy to address negative impacts on sustainable development from national population distribution
- Use the best ecological, social, and economic information to manage natural resources
- Users of public resources should pay the full cost associated with the depletion or use of those resources
- Weigh the benefits of public infrastructure projects against the full costs
- Reform natural resource pricing
- Protect prime farmlands production
- Promote education focusing on interrelationships among the environment, economy, social equity and long-term thinking, hands-on projects and life-long learning, and schools as sustainable models
- Support community sustainability planning processes and technology information to local governments and communities
- Manage geographical growth of the existing communities and siting of new ones to take into account carrying capacity and protection from natural hazards
- Eliminate governmental incentives that encourage development in vulnerable areas
- Create diversified local economies, which are built on unique local advantages
- Capitalize on economic development opportunities that target environmental technologies, recycling, and pollution prevention
- Revitalize brownfields—contaminated, abandoned, or underused urban land
- Support research and encourage other nations to participate more in international research on critical issues relevant to health and the environment
- Continue to promote and encourage global trading systems that mutually reinforce environmental protection and other social development goals
- Look for innovative technologies that allow for more cost-effective and efficient pollution protection and resource use
- Pursue efforts to mitigate potential effects of global warming and to adapt to those effects

Source: Abstracted and adapted from Sitarz, D. (ed.), *Sustainable America: America's Environment, Economy and Society in the 21st Century*, EarthPress/Nova Publishing Company, Carbondale, IL, 1998. With permission.

EXHIBIT 14.5 SUSTAINABLE RESEARCH PROGRAM OF THE EUROPEAN UNION

Key Action 1: Sustainable Management and Quality of Water

- 1.1 Integrated management and sustainable use of water resources at catchment scale
  - 1.1.1 Strategic planning and integrated management methodologies and tools at catchment scale—To account for complex interactions of natural and man-made environments, for water quality and quantity in various uses, and for consideration of uncertainties of water availability and quality and effects on aquatic ecosystem functioning
  - 1.1.2 Socio-economic aspects of sustainable use of water—Assessing pressures and barriers hindering sustainable use of water resources; evaluating the dynamic relationships between water management, policy, and institutions; understanding people's perception of water as a resource and economic good; analyzing the economic and ecological efficiency of different technological and managerial options; developing guidelines and indicators for sustainable water use
  - 1.1.3 Operational management schemes and decision-support systems—For integrated water management, including validation and demonstration of management schemes, improved awareness of water problems, defining best management practices, and effective transfer of knowledge to water users
- 1.2 Ecological quality of freshwater ecosystems and wetlands
  - 1.2.1 Ecosystem functioning—Through evaluating the differences between natural variability and anthropogenic impacts; developing indices of ecological quality, functionality, and biodiversity; improving and validating methods to maintain and restore regulative functions of degraded aquatic ecosystems
  - 1.2.2 Ecological quality targets—In support of water quality surveillance and monitoring schemes, environmental policy, and integrated water management, through development of indicators of ecological water quality and ecosystem health
- 1.3 Treatment and purification technologies
  - 1.3.1 Management of water in the city—Including evaluation and optimum design of water systems and water exchange between supply and use regions; development of advanced treatment, rehabilitation, and biohazards removal technologies
  - 1.3.2 Wastewater treatment and re-use—to minimize environmental impacts of wastewater treatment through use of nonpotable water by industry close to source, develop strategies for local, safe, publicly acceptable, and economically feasible re-use, novel sludge treatment, and impact reduction techniques
- 1.4 Pollution prevention
  - 1.4.1 Abatement of water pollution from contaminated land, landfills, and sediments—Including development of novel in situ and on-site remediation technologies for contaminated sites, groundwaters, and sediments and techniques to enhance natural attenuation
  - 1.4.2 Combating diffuse pollution—By developing and validating land practices to prevent or reduce diffuse [nonpoint source] pollution loads
- 1.5 Surveillance, early warning, and communication systems
  - 1.5.1 Pollution surveillance and control—By developing software, measurement systems, sensing devices, and early warning systems of hazardous pollution in soils, aquifers, and sensitive aquatic ecosystems

EXHIBIT 14.5 (continued) SUSTAINABLE RESEARCH PROGRAM OF THE EUROPEAN UNION

- 1.5.2 Improved flood and drought forecasting—Through integration of processes and use of ground-based and remotely sensed information, in cooperation with other hazard observation techniques

1.6 Regulation of stocks and technologies for arid and semiarid regions and generally water-deficient regions

- 1.6.1 Water resources use and management—Through assessing environmental impacts of drought, groundwater exploitation, large-scale water transfers, and socio-economic factors affecting water supply and demand, and developing criteria for preventing water stresses and water use conflicts
- 1.6.2 Prevention and mitigation of saline water intrusion—Through improved understanding of subsurface water movement and chemical processes
- 1.6.3 Technological development and management levels—Through harmonizing water data collection, maintenance and analysis, cost-effective and environment-friendly methods and tools for regulation of groundwater and surface water, improved knowledge base for implementing artificial recharge and alternative water sources, technological and cost-efficient changes to provide alternative supplies and apply water conservation in agriculture and industry, and developing *improved techniques to characterize karst aquifers*

Source: Abstracted from European Union, Energy, Environment and Sustainable Development Programme for Research, Technology Development and Demonstration [RD&D] under the Fifth Framework Programme, 1999a.

Some specific policy approaches for sustainable groundwater use may include, but will need further analysis before implementing decisions relative to any particular project or program.

COMPREHENSIVE INTEGRATED WATER RESOURCE MANAGEMENT

Groundwater should be more completely integrated into water resource and watershed management, planning, and implementation with conjunctive management of groundwater and surface water, thus reflecting the full range of economic factors, costs, and benefits affecting the use of the water resource (El-Ashry and Gibbons, 1988). As the review of national laws and policies indicated, most nations have a law that integrates the knowledge that groundwater and surface water are on a continuum of the hydrologic cycle, rather than two separate realms, with possible exception of deep groundwaters. Concerns about climate change indicate that meteorologic conditions must also be considered. In arid areas that may suffer further drought in the manifestation of climate change, brackish and saline groundwater (and surface water) should be included in an integrated approach to developing critical resource information and policies. A more comprehensive integrated approach will help ensure that all major alternatives for water supply are considered in establishing water management laws.

SET CLEAR AQUIFER MANAGEMENT OBJECTIVES

As part of a comprehensive integrated water resources management policy, aquifers should have clear management objectives, as they are natural capital assets. These objectives are considered “strongly sustainable” in the framework of Exhibit 14.3 (Sustainable Approaches and Practices) above. Groundwaters are mobile—flowing under boundaries, supporting baseflow of streams, maintaining the quality of estuaries and wetlands for habitat, and influencing local climate as well as flowing to wells for human, plant, and animal water supply, as part of the hydrologic cycle. Aquifers are depletable through both consumption and degradation, with consequent loss of the purposes just listed, others identified elsewhere, and still some ecosystem functions unknown and yet to be defined by research. Of all these purposes, human water consumption, food production, and degradation of aquifers have become the greatest concern relative to the necessary continuance of water supply and irrigation in locations of aquifer depletion. Surface waters are mobile and have clearly defined objectives reflecting public goals in law to be supported through water management based on best science. A comprehensive integrated water policy should likewise consider the public trust associated with the provision of groundwater through physical and legal means, recognizing best science, and incorporate specific and measurable objectives for its management, enforceable measures where appropriate, to ensure groundwater's availability for significant uses and future generations for its range of purposes. Certainly, legal entanglements will occur in sorting out the impact of assuming the public trust responsibilities in setting specific resource objectives in relation to individuals affected, but the larger water supply issue should be addressed to support the ecosystem and the multitudinous communities it maintains in a natural–human balance. Such action by the applicable jurisdictions will recognize the value of groundwater to the ecosystem and the societies it supports and incorporate that value in decisions about its use. Once long-term ecosystem objectives are met, the remaining water can be priced through water markets or can have its value substantiated through cost–benefit or cost-effectiveness analyses to provide signals and guides to efficient allocation.

El-Ashry and Gibbons (1988) point out that states having public trust responsibilities for their waters do not necessarily follow management policies for long-term sustainability of the resource. In arid regions, substituting urban use for agricultural use without changing underlying policies affecting the overall resource use may not be responsive to the future, such as a comprehensive water management policy that addresses future population changes in setting specific resource objectives. For example, the Arizona Groundwater Management Act requires achieving safe yields in aquifers by 2025, with the implicit expectation that continued depletion will be stopped and the economic adjustments will have occurred to accomplish this objective.

For the largest groundwater users, investment in efficient water-using technology will be critical for the long-term viability of the resource. However, as El-Ashry and Gibbons (1988) note, no opportunity costs exist for agricultural users, and otherwise no incentives promote change to efficient technology in the agricultural sector. Thus, without clear resource performance objectives, the benefits of more efficient water use may not occur.

Exhibit 14.6 provides a perspective on possible ecosystem objectives that could be set for groundwater.

SOURCE WATER PROTECTION

This concept is old, at least dating back to an ordinance adopted in the colony of Virginia prohibiting disposal of human waste near town wells. Additionally, the European Union has had policies of delineating protection areas and managing chemical substances around drinking water wells and conducting monitoring in what are now referred to as "drinking water source protection areas" since 1979. Its "Groundwater Directive" (EU, 1979) has been revised by a new directive (EU, 2006) to set standards for groundwater quality. In the United States, these zones are called "wellhead protection areas" under the Safe Drinking Water Act (U.S. Congress, 1986). Monitoring of groundwater in these protection areas is not required under U.S. federal law (however, some states do require it), and federal groundwater quality standards do not exist; however, drinking water standards have been applied to groundwater for remedial purposes. The concept from a water quality protection standpoint is to keep wastes and chemical use away from areas that allow water to carry the wastes

EXHIBIT 14.6 SOME POSSIBLE ECOSYSTEM OBJECTIVES FOR GROUNDWATER (LIST NOT EXHAUSTIVE)

Water Source

- Maintain certain minimum water elevation in the aquifer
- Limit boundary for cone of depression
- Maintain hydraulic head of aquifer within specified range (to recognize seasonal variation)
- Permit use at the rate of replenishment (safe yield)
- Ensure minimum groundwater discharge to spring, stream, wetland, or coastal zone

Water Quality

- Maintain no statistically significant change in water quality (or for a contaminant or set of contaminants)
- Establish contaminant concentration limit in groundwater not to be exceeded
- Set limit for contaminant plume advance to control threat to groundwater quality and receptors

Habitat

- Maintain areal extent of endangered species habitat
- Maintain specified biodiversity level
- Maintain wetlands area

and chemicals to the well before they can be bound up in the subsurface or degraded. The challenge is that for some wastes and chemicals, it takes a long time for them to degrade and certain naturally sensitive areas allow such substances to reach groundwater quickly (in hours or days or months), which can then be drawn to the well and consumed without treatment in many cases, especially through private wells with limited treatment located in more rural areas. Zones describing the time it takes for contaminants to reach wells can be developed through hydrogeologic measurement, calculations, and models.

From a quantity or supply standpoint, localities can enact zoning measures that control the amount of impervious surfaces per unit area that prevent percolation of precipitation into aquifers and maintain or even increase recharge (Communication, City of Westminister, MD, 1992; MSC, 2007, p. 6). Such a policy can benefit all major groundwater uses and surface waters receiving groundwater discharge supporting baseflow. Setting a standard for implementation of Drinking Water Source Protection is a strongly sustainable policy. Furthermore, use of aquifer storage of water injected into the subsurface for future use increases the need to protect larger water zones in aquifers from contamination.

Beyond protecting underground freshwater resources, because of demands in arid regions or areas experiencing significant groundwater depletion, brackish groundwaters (1,000–10,000—and higher—parts per million of total dissolved solids) are being used or considered as sources of water supply after treatment (Olsen, 2008), especially as desalination costs are dropping. An integrated water resources policy that includes surface water, groundwater, and brackish and saline waters is necessary to provide a comprehensive approach to future water management and protection of current and future water sources. A major drawback to future use of brackish water as a water source is the absence of policies, laws, and regulations for its use and management (Al-Hadadi, 1999). Brackish sources are often deeper, which might provide a level of protection. However, with wastes being injected into the ground rather than discharged to streams, brackish groundwaters will need to be protected as future sources of water supply, perhaps even from the wastes that their treatment generate, which may be injected into the subsurface for disposal. While brackish water sources are not sustainable as a water supply and receive no or little recharge, they will have value in arid locations in times of drought as a source of last resort. Some arid areas (e.g., State of New Mexico, United States) may have more available brackish and saline groundwaters than fresh groundwaters (Livingston, 2004), indicating a need for policies to use and protect these potential water sources.

RESTRICTIONS ON CHEMICAL USE IN VULNERABLE RECHARGE AREAS

The practice of restricting chemical use in vulnerable recharge areas is somewhat taken into account in the United States and the European Union by restrictions on certain chemicals' use in areas known to recharge groundwaters used for public water supply (e.g., U.S. Congress, Safe Drinking Water Act provisions for underground injection control; European Union, 1991 Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources requires Member States to designate vulnerable zones; and Council Directive 80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances). While setting a standard for this practice might be considered, it ideally would be more thoroughly considered for all groundwaters potentially usable for potable or other economic supplies, including maintenance of flora and fauna. Protecting only those areas that are currently in use and forgetting the others because of their service for perceived current lower priority uses may be viewed as short-sighted from a sustainable perspective, and potentially costly later when needed, but contaminated. To reinforce the vulnerability of groundwater from a policy perspective, the EU states in the 2006 Groundwater Directive that "Groundwater is the most sensitive and the largest body of freshwater in the European Union … [and] must be protected in such a way that deterioration in the quality of such bodies of water is avoided in order to reduce the level of purification treatment required in the production of drinking water…" (EU, 2006).

MONITORING GROUNDWATER STATUS

From an economic efficiency standpoint, providing water users with adequate information on which to make rational decisions is a fundamental element of allocating scarce resources. However, these data will be undersupplied if left solely to the private sector. Their existence would be useful as a public good in which the private sector would not invest except for its own purposes, in particular not motivated to provide monitoring of third party effects nor to give to the central water authority or government as trustee for the public to use in decision making. Monitoring of aquifers is the equivalent of obtaining essential data on the status of natural capital assets of local, regional, and national importance. As noted above, the EU has requirements for monitoring the chemical status of groundwater, especially around drinking water supply wells. The state of Connecticut has a similar requirement in the United States and other states have done selective monitoring in wellhead protection areas. This monitoring creates a baseline with which to measure the physical and economic effects of future actions affecting groundwater levels and quality. Additionally, some states have a network of wells for drought monitoring, such as Pennsylvania (USGS, 2007). Benefits of monitoring include advance warning of pollution or drought conditions to avoid the costs of responding to those conditions and of any health effects to people and animals. Monitoring also helps ensure that contaminant releases are routinely checked for enforcement purposes across the state or nation. This regular checking precludes creation of "pollution zones" that would attract and concentrate releases of harmful substances. Ideally, the value of the costs avoided in the state or nation from the "early warning" information from monitoring would be greater than the cost of monitoring.

Use of Low-Impact Development

Techniques to improve water balances to increase infiltration and to facilitate natural biodegradation are now being installed and used to reduce the impact of development on watershed and aquifer hydrology. Methods include bioretention, cluster building, reduced impervious area, swales, permeable pavement, vegetated landscaping, wetlands, and green roofs. Such approaches have been shown to be effective and reduce capital costs from 15% to 80% over conventional approaches to manage stormwater (USEPA, 2007b). Recognition of these "best" practices across the industry is an economy-wide approach to reduce the "scale" of impact on the natural capital of groundwater. A more strongly sustainable approach would be inclusion in a standard for all site design engineering, such as in the state of Maryland, United States (MSC, 2007).

Widespread Use of and Incentives for Efficient Water-Using Technology

The technology is available to obtain the benefits of more efficient water use in agriculture irrigation. For example, the irrigation technique known as "drip irrigation" has been used for many years as a documented physically efficient method. With new electronic technology, water can be precisely delivered to plants to meet their water needs at a particular time. Typically, irrigation is done by flooding fields with water, losing valuable irrigation water to infiltration past the soil zone, or evaporated and not used by the plants at all. Flood irrigation has also concentrated pollutants in the soil zone, contaminated groundwater and, through groundwater return flow, surface water (WWPRAC, 1998, pp. 2-30 and 2-31). This technology is very wasteful of water, especially water priced at zero or some very low value. The introduction of drip irrigation may be expensive initially, but taxing or use fees can encourage pricing water at a value that makes price in use at a particular location fit its circumstance, rather than wasting it to depletion or contaminating other resources. Clearly, more research is needed to mitigate groundwater losses from irrigation to grow food necessary to maintain the world's population.

Other improved efficiency technologies can be broadly applied. Water-saving kitchen and bathroom devices have been available for many years. Certainly, these mechanisms could be further refined. Composting toilets have been developed. This equipment may be expensive, but may be worth the cost in situations in which pumping is depleting the water source. In the United States, the Environmental Protection Agency announced in 2006 a program to reward water conserving devices and practices with recognition, so the larger public was aware of the options available to it (USEPA, 2006).

Sufficient incentives may not be given by the market for water to encourage their application more fully. However, many utilities have distributed at no cost to customers low flow faucets and shower nozzles to conserve water and energy (heating less water flow). The incentive to the utility was to reduce capital in not having to expand water and wastewater treatment facilities and decrease fuel supply needs for hot water. Such actions reduce the ecological footprint of groundwater use by reducing water use, energy consumption, and greenhouse gas (carbon dioxide) release.

One macroeconomic approach would be to provide credits to industry and customers for retrofitting their water-using fixtures not only for installing but also for using these water-conserving devices by demonstrating their lower level of water use documented through water bills. These economic incentives would reduce "scale" impacts. Additionally, grants could be given to low-income and poor people to allow them to make such plumbing replacements, or giving larger credits to owners of multidwelling units to expand the effect of water use reduction where people do not own their residences, thereby addressing intragenerational equity. The case study "Balancing Ecosystem, Water Use and Pricing: San Antonio and the Edwards Aquifer" describes one community's efforts to address an ecosystem maintenance requirement through water conservation retrofit devices and continuing reductions in water throughput.

WATER RECYCLING IN MANUFACTURING

Industries manage costs to increase profits. Manufacturing is a large user of water. While recycling technology has been available for many years, in many applications it is less expensive in the short run to continue to use large amounts of water rather than recycle or conserve water. Governments at all levels can induce recycling by taxing increasing water use or large water uses. A more strongly sustainable policy would be for governments to set required water recycling goals for industry, which might ultimately demonstrate technology applicable to and economic for residential applications, based on the objective of groundwater resource maintenance. Taxing large water uses would support reducing "throughput" of the resource by encouraging less of its use by making water waste more expensive, encouraging them to find less costly alternatives that would conserve water. A national water use tax may be necessary to provide a level playing field for all industries that use water. Otherwise, industries in which water is a significant raw material input will continue to move to locations that offer water at the lowest price. Since most industries are engaged in interstate commerce, national governments can act on this matter within their constitutional authority. The location of industrial water users would also be affected by the policies of other nations willing to deplete their natural capital of groundwater, which may be contrary to the long-term economic viability of those countries.

A more strongly sustainable policy would be for governments to set required water recycling goals for industry, which might ultimately demonstrate technology applicable to and economic for residential applications, based on the objective of groundwater resource maintenance. Then, technologies may evolve to use the water more efficiently, allocated in water markets or substantiated through cost–benefit and cost-effectiveness analyses.

WATER REUSE FOR PUBLIC SUPPLIES

Most communities using public water systems treat their wastewaters and discharge them to a stream, using gravity or pumping stations, which consume large amounts of energy to transmit water to move the wastewater to the treatment plant and then to the stream. Communities relying on groundwater for their public water supplies and having declining water tables may be encouraged to reevaluate their position on use of treated wastewater and pump it back into the ground upgradient of the location of municipal water production. Careful evaluation of the quality of the treated wastewater may be necessary to ensure that other natural flora and fauna will not be adversely affected and/or that injection of treated wastewater will not bring naturally occurring contaminants of the underground environment into solution. Treated wastewater from many treatment plants is of higher quality than the water into which it is being discharged. This water may be ideal for groundwater recharge, as long as federal and state prohibitions against waste injection into an aquifer that is a public water source can be adequately addressed. The city of Westminister, Colorado, United States, with a limited groundwater supply, as of 2007, provides one-third of that supply from treated recycled wastewater distributed to water users through a parallel set of pipes (Westminster, 2008).

FULL COST PRICING

While classical economists would indicate that, for economic efficiency, price should equal marginal cost (P = MC), only financial marginal costs for water are known in most cases (USEPA, 2007a). If governmental entities are providing the water, they may not be charging their full financial cost of producing the water, thereby subsidizing consumers. In some circumstances, other ecosystem costs of producing the water may be known (but often difficult to quantify), or if not known, could be valued at some level through a user fee or tax, albeit imprecisely established, to provide for resource maintenance. At the very least, the full financial cost of pumping, treating, and delivering groundwater should be accounted for along with an informational and educational program on the value of groundwater and the ecosystem externalities of producing it to make consumers aware of these values and costs in their economic decisions. Full cost financial pricing, while economically theoretically least satisfactory (UN, 2003, p. 301), addresses a portion of the allocative efficient value, but still does not respond to scale or distribution considerations identified for macrolevel policies. However, a groundwater use tax at some level would overcome "free" (no-cost) consumption of this natural capital and its ecosystem services that are not valued in the market, thereby being closer yet to a "fuller" cost price. Revenues from such a tax could then be used in ways to replenish the resource, make it more sustainable, and begin to capture a fuller portion of the economic cost of producing it, reflecting groundwater's role in the ecosystem: water supply to communities and wildlife, the baseflow and quality of streams in watersheds, and the habitat of wetlands and coastal waters, among others. Unless there would be industry standards for pricing of water, reliance on the utility pricing, which could be done based on political response, is weakly sustainable.

NEW NATIONAL ACCOUNTING

By establishing a new national accounting practice measuring depletion losses and costs for remediation of groundwater (and other resource) contamination, the government may spur creation of rights in maintenance of natural capital. In the United States, endangered species have been recognized as needing habitat preservation, including species in groundwater (EARDC, 2006; also, see Chapter 2 and Case Studies). The United Nations expressed global concern about loss of ecosystem endowments from economic growth by issuing a handbook detailing a system of national environmental and income accounts that nations can use (UN, 2003) and which some countries have adopted (Markandya et al., 2002, p. 68). The UN system responds to the question: "Is [the] use [of "environmental endowments"] posing a threat to economic development now, either by being used up too quickly with no prospect of replacement or by generating a level of pollution which threatens human health and the existence of species?"

State and national governments may further encourage creation of rights in maintaining groundwater (and other natural) capital. The State of Arizona has established in its Groundwater Management Act the goal of attaining safe yield in three major groundwater use areas of the state by 2025 (Smith, 1989, p. 44). While many options may exist for adopting policies for sustainable development, one national approach might be to establish federal boards for water (or other) resource maintenance, similar to the Federal Reserve Board system or establish River Basin Commissions for all large watersheds with actual water authority (such as the Delaware River Basin Commission) in the United States (e.g., see WWPRAC, 1998, pp. 6-4 and 6-28). Different regional boards could specialize in different aspects of water use, costs, pricing, and ecosystem sustainability. Such boards could meet monthly or other regular interval to set prices for water based on use, location, environmental and resource effects, and weather patterns, with the principal national trust of maintaining natural water capital, elimination or minimization of depletion and degradation, and encouragement of reuse and recycling, where practical. These practices could then be accounted for in a new national accounting system that kept track of natural resources and their values, including losses from depletion and degradation. Such an approach, with State participants on the boards, could then provide a level policy field for groundwater use and pricing, instead of pricing groundwater at zero or some low value.

New national accounting could allow targeting of taxes on natural capital drawdown (depletion) or degradation. Funds from natural capital use taxes could be used for natural capital maintenance and replenishment.

Exhibit 14.7 provides one list of potential accounting categories for water and an example accounting table for water assets. Exhibit 14.8 explains the possible monetary valuation of environmental accounts, indicating the use of price times physical units is one method of valuing water and other environmental assets. Using these categorizations and valuation techniques (see Chapter 13, "Cost–Benefit Information and Analysis") and constructing national account tables to address (1) depletion (loss of domestic product from consumption), (2) defensive expenditure (costs to protect the health of humans, fauna, and flora and the quality of natural resources on which they depend), and (3)

EXHIBIT 14.7 POTENTIAL NATIONAL ACCOUNT CATEGORIES FOR WATER AND WATER ASSET ACCOUNT TABLE

Water Account Categories

Supply

1. Total abstractions
2. For own use
3. Leakages during use
4. Available for own use
5. For delivery
6. Leakages during distribution supply table
7. Recycled water and imports
8. Water supplied to users

Use

9. Water received by users
10. Water available for use
11. Recycled water
12. Wastewater to sewerage
13. Returns from irrigation
14. Treated wastewater
15. Untreated wastewater
16. Cooling water
17. Water used for hydroelectricity
18. Other returns of water
19. Consumption

An Asset Account Template for Inland Water—Constructed Example (Units = Million m^3)

		Surface Water				
		Reservoirs	**Lakes**	**Rivers**	**Groundwater**	**Total**
Opening stocks		1500	2700	300	150,000	154,500
Abstractions		1580		972	765	3,316
Residuals	Returns from					
	Irrigation			47	50	97
	Wastewater			441	268	709
	Lost water in transport			141	300	441
	Others			1457		1,457
Net precipitation (+)			100	2175	2,275	
Inflows (+)				9000	1,100	10,100
Net natural transfers (±)		1650	110	−1715	−45	0
Evaporation from water bodies (−)		170	216	133		519
Outflows (−)	To other country			2300	380	2,680
	To the sea			8000	1,000	9,000
Other volume Changes	Due to natural disaster					
	Discovery (+)					
Closing stocks	Others	1400	2694	300	149,229	153,623

Source: United Nations (UN), *Handbook of National Accounting: Integrated Environmental and Economic Accounting*, Publications Board and Exhibits Committee, New York, 2003, 333–335. With permission.

degradation (accounting for the loss of stocks of natural resources from contamination) (UN, 2003) in successive years, environmental accountants will be able to refine approaches to recording the use and maintenance of natural capital and ecosystem services. This accounting should be essential and useful to future generations as they act to maintain their welfare in societies.

EXHIBIT 14.8 MONETARY VALUATION OF ENVIRONMENTAL ACCOUNTS

Monetary accounts

Monetary accounts cover monetary valuation of flows, environmental expenditure, and resource management accounts, and issues related to the valuation of water resources taking into account the particular nature of water, and specifically changes to the water source from policies or actions.

Monetary valuation of flows

The physical supply and use of water (covered in Exhibit 14.7) have monetary counterparts. Water supply and use in monetary units records the major economic output of industries related to water. Typically, the price as given to the consumer or stated by the supplier, in the case of residuals management, could be multiplied by the units of physical stock, flow, and quality accounted in the asset table. Other methods of valuation may be employed.

Categories of activities for monetary valuation

1. Environmental protection activities—For soil and groundwater, they include activities that target the reduction or elimination of polluting substances that may be applied to soil and percolate into groundwater, decontamination of soil, and activities related to monitoring and controlling soil pollution.
2. Natural resource management and exploitation activities—This covers expenditures related to abstraction and purification of water. They include information on current expenditures such as intermediate consumption, compensation of employees, taxes, and subsidies related to water, on capital expenditure, and, when possible, on consumption of fixed capital, stock of fixed assets, and labor inputs.
3. Environmentally beneficial activities—These accounts cover expenditures related to abstraction and purification of water. Environmentally beneficial activities related to water include those activities aimed at saving water, whether for final consumers, industries, services, or agricultural users. They may take the form of investment (irrigation systems, facilities, and appliances to reduce water consumption, recycle water, etc.) or the use of products adapted for lower water consumption. Other activities include, for example, direct abstraction of water by manufacturing industries for cooling purposes or by final consumers for own use.
4. Minimization of natural hazards—Expenditures to minimize natural hazards related to water include expenditures to prevent flooding, such as the construction of dams to restrict water flow, management of water retention areas, measures to avoid droughts, and so on. These accounts may provide an indication of the effects of alteration of landscapes and water systems or global warming.

Source: United Nations (UN), *Handbook of National Accounting: Integrated Environmental and Economic Accounting*, Publications Board and Exhibits Committee, New York, 2003, 340. With permission.

Several countries have employed an integrated national income and environmental accounting framework as described in the UN handbook to promote more sustainable natural capital. In one case, Mexico found that resource depletion reduced national income by 5.7%. When resource degradation was included, the reduction was 13% for the year analyzed (Markandya, 2002, p. 68). Mexico has significant groundwater mining for irrigated agriculture. Adopting such an approach as a national standard of accounting would be strongly sustainable in informing decisions affecting resource use, depletion, and degradation.

SAFE YIELD AND SUSTAINABLE DEVELOPMENT

The hydrogeologic concept of "safe yield" aligns with "sustainable development." Safe yield is defined as "the amount of water [that can be] withdrawn from [an] aquifer roughly equals the amount of water returning naturally or artificially to the aquifer over an extended period of time" (Smith, 1989, p. 10) and "can be withdrawn from the aquifer without producing an undesired effect" (USGS, 1985, p. 463). The USGS definition of "groundwater sustainability" includes indefinite use without unacceptable environmental, economic, or social problems and "must be defined within the context of complete hydrologic system of which groundwater is a part" (USGS, 1999a, p. 2). Thus, safe yield addresses an action (use of an aquifer for water supply or wastewater release) over time that maintains the resource without adverse impacts. Sustainable development, as defined here, concerns maintenance of natural capital to maximize future services. The concepts appear synonymous as applied to groundwater. The question, then, is how to achieve "safe yield"?

Safe yield is imbedded in the water balance equations developed earlier. While this observation may seem obvious, one might ask, why cannot it be achieved if the concept is clear? The concept may be clear, that is, balancing water withdrawn or discharged with water recharging the aquifer, but the problem is with rights of use of the aquifer and the subsurface environment, the timeframe considered for "sustainability," and suffiency of measurements with the necessary accuracy. Unless a state or federal government declares its policy to be maintenance of groundwater capital, depletion or degradation of the resource may occur. Depletion occurs when abstraction of groundwater is greater than recharge of the resource. These abstraction and recharge relationships can be established over regions with past and current data. The USGS publishes water balances for areas it has investigated (for example, see USGS, 1999a, pp. 25 and 28). Also, the timeframe necessary for sustainability of groundwater resources must be specified, since withdrawals may not be balanced by recharge in the same period, such as a season, year, decade, or century, taking into account hydrologic variation, as well as the long periods of time necessary for an aquifer and affected surface waters to respond to either recharge or withdrawal. Climate changes from global warming due to "greenhouse" gas emissions makes this situation even more challenging. Adequate monitoring must be planned and implemented.

Degradation of groundwater occurs when waste or chemical residue exceeds the assimilative capacity of a subsurface zone and results in contamination of the groundwater resource. Such situations exist when excessive amounts of sludge above agronomic rates are applied to the land surface for disposal, leachate carrying landfill chemicals escapes from a disposal site, or pesticides infiltrate beyond the root zone and the control of the crop manager. In these instances, the immediate sink for these waste or chemical releases is the first aquifer, which may be used for public water supply, industry, and stream baseflow, in each case potentially causing further unanticipated damage and economic loss. While much work is still needed in understanding "quantity" management for safe yield, this field is more developed than that of "quality" management for sustainable development. Certainly, the subsurface is just now beginning to be characterized relative to its ecological significance and ultimately its economic importance in the larger ecosystem (Gibert et al., 1994). Research is discovering how previously unknown organisms act to break down wastes in the subsurface environment. The implications for the value of these organisms in the subsurface are enormous, as we have unknowingly relied on them to "process" our wastes placed on or in the ground. Indeed, some chemicals may kill these waste processors. Thus, it is important to find out what the balance for subsurface or groundwater quality is on a sustainable basis that can continue to provide the services the ecosystem requires and the economy needs. Research is necessary to address this balancing of contaminant disposal and processing. Monitoring is needed to provide a baseline and track changes over time for natural capital and its economic management to occur.

Developing plans for safe yield of groundwater as a component of a larger community, state, or national sustainable development policy also should incorporate total economic value of both costs and benefits associated with it. Since "total" translates into "everything," this consideration is a significant requirement. However, if it is to be successful, the costs and benefits need to be described as fully as possible, given current science and technology, even if they can only be quantified but not monetized.

MAINTAIN CAPITAL, MAXIMIZE SERVICE, MINIMIZE THROUGHPUT

In summary, sustainable development of groundwater is comparable to safe yield. To implement safe yield, water policy should be modified to recognize the limits of the resource. The limits of the resource can be incorporated in policy by establishing the objective of maintaining the natural capital of groundwater to provide ecosystem and economic goods and services as a cornerstone of future water policy. The water policy should be directed toward maximizing the service of the resource, employing more efficient and conserving technologies in the near and long term. Actualizing the constraint of safe yield by these technologies will minimize throughput, which otherwise shifts groundwater more quickly to the atmosphere and the oceans than would otherwise occur. It will also reduce continued irreversible risks that future generations would have at least current quantities and qualities of a fundamental resource that will need to provide services to more people.

Is sustainable development a better state than economic production growth? Sustainable development uses currently undefined natural resource limits as targets for supporting the economy. Production growth has targets of increased natural capital throughput as a positive barometer of the economy, with more being better than less growth, assuming no limits on natural capital and unlimited substitution of man-made capital for natural capital. Sustainable development recognizes given resource capacity as a management constraint, which guides technology to restore, replenish, and maintain the resource. Under sustainable development, everyone would ideally have the groundwater they need through qualitative improvements in lifestyle. Under production growth, anyone could take as much groundwater as they can afford, perhaps leaving some persons without the amount they need. Some path of the economy that takes an intermediate approach in transition may be necessary, as suggested in the policies above. The question of which is "better" may need to be addressed in the context of which addresses the essential needs of the population, and a growing one at that!

WHO BENEFITS AND WHO PAYS THE COST OF THE DIFFERENT POLICY APPROACHES—AND HOW MUCH?

The production growth approach benefits the individuals and corporations that are allowed to produce crops and manufactured goods that require water while paying little or nothing for the water. The benefit they receive is water of lower or no cost, providing a subsidy to their operations. Whether the water should be used for other social purposes that might have higher social values has not been addressed. However, federal laws providing quality standards and species maintenance are being recognized as expressing and incorporating some of these values (see, e.g., WWPRAC, 1998, p. 5–42). The costs of producing water considered to have no value may be borne by adjacent neighbors at a different time. For example, in the western United States, land subsidence from overdrafting aquifers for many years for irrigation has subsequently caused a range of social and private costs, including damage to an interstate highway and other roads, surface water reservoirs, railroad tracks, use of cropland, wells, and stream channels (Smith, 1989, p. 39; USGS, 1999a, pp. 55–58). Pumping resulting in declining water tables can eliminate wetlands dependent on groundwater influx providing habitat for terrestrial and aquatic wildlife (USGS, 1999a, p. 42), and, consequently, to a wide range of outdoor enthusiasts from bird watchers to duck hunters. Management of aquifers, knowing of their depletion, occurs "with little thought of the future consequences and foregone opportunities" (Smith, 1989, p. 15) and is unsustainable in much of the western United States (WWPRAC, 1998, p. 3-2). Other foregone opportunities include the range of advantages of groundwater identified in Chapter 1. All of society—a nation, state, and locality—pays the cost of such an outcome in terms of lost production for higher value uses.

Sustainable development, focusing on improvement in the quality of use, provides the benefit to this and future generations of a long-term water source where safe yield is obtained. The safe yield approach ensures that a range of future groundwater uses are preserved, while allowing present uses through a consciously applied, objective-driven decision-making framework of policies designed to supply current needs and preserve the services of natural capital. The costs will not only be incident on those whose use of groundwater is subsidized by current water law, but also on others affected in the long term over which groundwater effects take place. These costs serve as potential benefits supporting sustainable development policies. Marginal producers whose existence is predicated on low or no value of water will most likely go out of business. The United States Western Water Policy Review Advisory Commission recognized that such marginal water uses were part of the challenge the western United States must deal with and that the federal government should not support through subsidies (WWPRAC, 1998, pp. 6-34–6-35). Moreover, the cost to polluters to supply clean water in cases where they are liable for providing alternative safe water will rise.

It is difficult to estimate the value of the costs and benefits of these policy alternatives. This matter should be the focus of considerable research. One study has begun to estimate such values on a macrolevel (Costanza et al., 1997), but only took the first steps in addressing the web of interrelationships that exist in nature and its economic subsystem to project macroeconomic results.

SUMMARY

Sustainable development is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Economic growth usually applies the measure of current national production, gross national product, as a signal of well-being. However, this measure combines national production benefits and costs into one number and assumes that unlimited natural resources may be extracted from the ecosystem for this production. The sustainable development of groundwater is constrained by the lack of recognition of its limited presence even though it is the largest store of freshwater in the world. Groundwater supports the ecosystem in ways we do not understand, having value in these unknown services that manifest certain aspects of balance in nature. Groundwater is undervalued as natural capital and produced and provided in a way that imputes no cost for it. Water is needed for future generations and groundwater is most likely a critical source at that time. Sustainable development means considering scale and distribution of resources within current and to future generations, relying on economic efficiency to deliver the services of groundwater and other critical natural capital in a least-cost way. Policies for providing groundwater include those that are strongly sustainable, such as natural capital maintenance objectives and production and quality standards, and others that are weakly sustainable, such as taxes and subsidies. The benefits of economic growth policy accrue to the present population, leaving fewer resources for the future with greater costs to fend for themselves with what remains. The benefits of sustainable development accrue to the present and the future generations by recognizing that current extraction of services from the ecosystem must be minimized to provide for a fair distribution to people in the future. Groundwater can be managed sustainably and policies for states and nations have been devised to do so, including policies to conserve and protect the resource.

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15 Transboundary, International, and Climate Change Considerations

While groundwater occurs under all the lands of the world, it does not follow political boundaries and is influenced by human action of pumping from wells. It may be the only water source in many locations. Groundwater overuse and misuse threatens the resource for water supply around the world. Even though it is an essential substance of life, over 1 billion people out of the current 6 billion world inhabitants lack adequate water supply (UNESCO, 2003). "Some 47% of the land and 40% of the population of the world live in transboundary river basins and therefore competition over the water resources in these basins is expected to be intensified over the coming years" (Tsakris, 2003). Since the earth can only support the food requirements of 500 million people without management (UNESCO, 2003), irrigation, the largest water use worldwide, will continue as a necessary practice. Furthermore, wastewater as well as other wastes, if improperly disposed, can reduce the amount of safe water available for use. In these contexts, we will examine groundwater use and its transboundary and international implications. Clearly, national claims on the use of groundwater have economic consequences for this subsurface resource shared by neighboring countries. Conflicting claims indicate the value of groundwater in these situations. Climate change may focus greater attention on transboundary concerns related to groundwater.

GLOBAL GROUNDWATER USE

Groundwater, including its interaction with surface water, would typically be shared in two ways: among uses, such as drinking, irrigation, or waste conveyance, and among users, such as upgradient farmer and downgradient city (UNESCO, 2003). For most of the world, groundwater use expanded dramatically beginning in the 1950s, with greater understanding of hydrogeology and progress in drilling and pumping technology (UNESCO, 2003). The largest use of groundwater globally is for irrigated agriculture, as indicated in Exhibit 15.1 (UNESCO, 2003). The statistics given here indicate the importance of groundwater in world use.

INTERNATIONAL AQUIFERS—A SHARED RESOURCE

The international significance of groundwater resources is that millions of people rely on them for their daily needs as well as important economic infrastructure, such as irrigation, process water, and maintenance of baseflow in navigable waterways along boundaries between countries. The land area and mass over aquifers that are of mutual interest among neighboring nations may be large or small, shallow or deep, and are physical manifestations of the stratigraphical upper portion of the river basins of which the aquifers are a part. Transboundary aquifers may be defined as the natural occurrence of groundwater in subsurface zones or reservoirs that are intersected by a border shared by two or more political jurisdictions, which may include water districts, municipalities, counties, states or provinces, and nations (Campana, 2000; UNESCO, 2003). Transboundary groundwater, then, is subsurface water, which may exist in an aquifer that moves across a boundary between any two or more of these jurisdictions naturally or by induction from pumping operations, which draw

EXHIBIT 15.1 SELECTED STATISTICS DESCRIBING GLOBAL GROUNDWATER USE

Estimated annual groundwater production worldwide: 600–700 km^3/year
Proportion of potable water supplies: 50%
Proportion of self-supplied industry demand: 40%
Proportion of irrigated agriculture use: 20%
Number of urban dwellers depending on groundwater sources: 1.2 billion

Source: United Nations Educational, Scientific and Cultural Organization (UNESCO), *Water for People, Water for Life*, The United Nations Water Development Report, UN World Water Assessment Programme, 2003, 78.

the water along subterranean interstitial pathways, fractures, or channels (in the case of karstic limestone or dolomite aquifers). Thus, such an international water system is also considered to include the subsurface formations and their geologic structures (such as fractures and solution channels) which convey groundwater (Barberis, 1986, p. 35).

The list that follows in Exhibit 15.2 provides a perspective of the magnitude of shared groundwaters associated with some of the 263 river basins that are transboundary watersheds in 145 nations around the world (UNECA, 2000; UNESCO, 2003). The first step in dealing with internationally shared aquifers from economic and environmental standpoints is to determine their extent and geological structure (Barberis, 1986, p. 34). Concerns about transboundary groundwaters include both issues of quantity and quality, as evidenced here.

International law has progressed with the science of water, acknowledging groundwater as an integral portion of the hydrologic cycle (Barberis, 1986, p. 37). In 1967, the recommendations of the European Water Charter recognized groundwater as part of the larger water cycle (cited in Barberis, 1986, p. 27). Several eastern European international agreements of the 1950s and 1960s refer to groundwater along with surface water in a basin or watershed context, as did the Lake Chad Commission in 1964 (Barberis, 1986, p. 31). The United Nations Environment Charter (Stockholm, 1972) and the Organization for Economic Cooperation and Development (OECD) considered water resources in the international realm to be both ground and surface water (Barberis, 1986, pp. 31, 33).

TRANSBOUNDARY ISSUES

While transboundary issues can be salient at any level—among adjacent property owners, between counties or states, and at the international level, such matters can provoke conflict between the parties. A transboundary issue is a disagreement between two legal entities, which may be individuals, states, or sovereign nations concerning a matter affecting the wellbeing or economic livelihood of persons living on each side of a shared border about which either one or both parties consider of sufficient significance to raise it for resolution at their particular level. In the case of groundwater, such a situation may result from the use or misuse of water from a shared aquifer. Typically, transboundary groundwater issues result from groundwater mining or contamination that affects people and their health, wellbeing, or economic welfare in an adjacent jurisdiction. Groundwater exploitation—whether for consumption or residuals disposal—can even be manifest under a large flowing river, with the people's groundwater use on one side of the stream affecting groundwater availability and use on the other side (McCabe et al., 1996; World Bank, 2003).

Recognition of groundwater as a shared resource among nations and subnational jurisdictions for which they must mutually agree on its use for sustaining their residents and economies can be a tool for peaceful cooperation. To understand the scope of shared groundwaters across borders, reliable information is needed which is not available today (UNESCO, 2003, p. 317). While local pollution that has migrated across borders has presented challenges to collaborative protection and use of

EXHIBIT 15.2 INTERNATIONALLY SHARED AQUIFERS

Since political boundaries do not always follow aquifer or river basin boundaries, groundwaters in these hydrologic situations are shared by two or more countries, each with economic interests in protecting its use for their respective purposes. The list given here is partial and not exhaustive, but suggests that groundwater use, depletion, pollution, and management cannot be solely left to local jurisdictions to address their individual economic interests in a comprehensive way that considers all potential users or purposes, including sustainability and ecological factors, but must be viewed in the larger context of long-term balanced conditions that recognize the shared nature of the resource among nations, peoples, flora, and fauna. Other examples of transboundary issues among jurisdictions within countries, such as the extensive Ogallala Aquifer affecting the economic interests of seven states in the United States, would make the list longer. Many of the largest aquifers receive minimal recharge, being the result of water percolation deep into sediments deposited prehistorically.

Aquifer Name	Sharing Countries	Water Volume/Land Area/ Pop. Served	Concerns
100 Shared aquifers[1,2]	Europe (25 countries reporting)		Depletion, pollution, ecology
Guarani[1]	Brazil, Paraguay, Uruguay, Argentina	40,000 km^3/1,200,000 km^2	Depletion
80 transboundary river basins with aquifers[3]	Africa		Depletion, resource management, pollution
Nubian Sandstone[1]	Chad, Egypt, Libya, Sudan	540,000 km^3/2,200,000 km^2	Depletion
North Sahara System[2]	Algeria, Tunisia, Libya	78,000 km^2	Depletion
Ob-Irtysh basin aquifer[4]	Kazakhstan and Russia		Depletion, pollution
Nogales Wash Aquifer[5]	Mexico, United States		VOC contamination
San Pedro Basin Aquifer[6]	Mexico, United States		Depletion, ecology, resource management
Abbotsford-Sumas aquifer[7]	Canada (BC), United States (WA)	200 km^2/Pop. 100,000	Nitrate pollution
Mexicali Valley aquifer[8]	Mexico, United States		Recharge reduction, depletion, subsidence
Jurassic Navajo Sandstone aquifer[9]	Kaibab Paiute Tribe, United States		Groundwater management
Coastal Aquifer[10]	Palestine-Gaza Strip, Israel		Pollution, depletion, resource management

(*continued*)

EXHIBIT 15.2 (continued) INTERNATIONALLY SHARED AQUIFERS

Sources:

1. Tujchneider, O. et al., *The 2003 Seattle Annual Meeting of the Geological Society of America*, November 2–5, 2003.
2. United Nations Educational, Scientific and Cultural Organization (UNESCO), *Water for People, Water for Life*, The United Nations Water Development Report, UN World Water Assessment Programme, 2003, 317.
3. United Nations Economic Commission for Africa, Transboundary River/Lake Basin Water Development in Africa: Prospects, Problems and Achievements, 2000, URL: http://www.uneca.org/eca_resources/Publications/RCID/Transboundary_v2.PDF (accessed September 13, 2003).
4. World Bank, *International Conference Devoted to the Problems of Ob-Irtysh River Basin,* Ust-Kamenogorsk, Kazakhstan, June 18–21, 2003, URL: http://www.worldbank.org.kz/ECA/Kazakhstan.nsf/0/1A3F2FD4A51F0D00C6256D5E0028E6A0?Opendocument (accessed September 8, 2003).
5. URL: http://www.utep.edu/rio/Nogales_Ground_Water_Monitoring.htm (accessed September 8, 2003).
6. Glennon, R., *Water Follies: Groundwater Pumping and the Fate of America's Fresh Waters*, Island Press, Washington, DC, 2002, 314.
7. Mitchell, R.J. et al., Transboundary transport in the Abbotsford-Sumas aquifer: British Columbia and Northwest Washington State. *Groundwater and Watershed Analysis Across Political Boundaries,* Geological Society of America Conference, Seattle, WA, November 2–5, 2003.
8. Moser, D.E. et al., Radar satellite (INSAR) monitoring of groundwater dynamics near the All-American Canal (Calexico/Mexicali region, Rio Colorado*). Groundwater and Watershed Analysis Across Political Boundaries,* Geological Society of America Conference, Seattle, WA, November 2–5, 2003.
9. Sabol, T.A. and Springer, A.E., Delineation of source water protection areas for tribal water supplies, Kaibab Paiute Reservation, Arizona. *Groundwater and Watershed Analysis Across Political Boundaries*, Geological Society of America Conference, Seattle, WA, November 2–5, 2003.
10. El Sheikh, A. and Hamdan, S.A., *Management of Aquifer Recharge for Sustainability*, AA Balkema Publishers, Lisse, the Netherlands, 2002, 413–417.

groundwaters, armed conflict, wars, and weapons testing have damaged groundwaters affecting their future use (Campana, 2000). Transboundary aquifers are affected by the same natural circumstances and human demands as under individual or local situations: aquifers are used to supply water, transport water and waste, mine chemicals, filter and degrade wastes, store water and wastes, and provide energy through heat exchange, necessitating consideration of groundwater's roles and interrelationships in the larger hydrologic cycle (Tsakris, 2003). These circumstances and uses of transboundary aquifers can lead to four principal categories of outcomes if not addressed through international (or interjurisdictional) agreement (Tsakris, 2003):

1. Reduced availability: Excessive groundwater production leads to depletion decreasing the accessibility, quantity, and/or quality of the resource in the future.
2. Adverse quality: Residuals handling and disposal without due care to subsurface conditions can contaminate groundwater and even preclude its future use.
3. Ecosystem deterioration: Undisciplined utilization of aquifers may damage ground and surface water existence and habitat, such as draining and eliminating rivers and wetlands or intrusion of and replacement by salt or brackish water from oceans or more saline groundwaters (Glennon, 2002).
4. Unconsidered adjacent impact from narrowly focused beneficent activities: Engineered facilities and mineral production may reduce or eliminate ground and surface water interaction necessary for stream baseflow and aquifer recharge and provide conduits for aquifer contamination or clogging, respectively (Glennon, 2002).

Challenges to overcome in moving toward sustainable groundwaters in transboundary situations (at all levels) include (Tsakris, 2003)

1. Inadequate data to characterize groundwaters (also UNESCO, 2003, p. 319)—Regular monitoring of water table levels and quality changes can be costly and is not routinely sufficient in time or location to support management of many aquifers and the modeling that relies on such information.
2. Addressing uncertainty in knowledge of the subsurface environment—Modeling complex hydrogeologic settings for decision making is demanding, requiring special expertise and knowledge of complex subsurface environments.
3. Recognition of ground and surface water interaction—The water cycle and groundwater's roles in it are not recognized in many laws (Glennon, 2002) and international agreements (Matsumoto, 2002) to provide the framework for a holistic systems management approach to effective groundwater management.

International frameworks to address transboundary waters have evolved to address these issues and, hopefully, the challenges posed by human economic and ecological demands.

COSTS AND BENEFITS RELATED TO TRANSBOUNDARY AND INTERNATIONAL GROUNDWATERS

The costs and benefits relevant to transboundary groundwaters include microeconomic and macroeconomic aspects. Some numerical estimates (UNESCO, 2003) are instructive relative to the economic implications of groundwater:

- 1.2 billion of the world's urban residents (out of 2.9 billion) in 2000 rely on groundwaters for potable water supply—a large proportion (perhaps 80%–90%) of the world's 3.2 million rural dwellers rely on groundwater for their needs.

- Groundwater supplies:
  - 50% of the world's potable water use
  - 40% of the world's self-supplied industry demands
  - 20% of waters used for the world's irrigated agriculture
- 1831 interactions involving waters between two or more countries, including 507 events entailing conflict of varying degrees (e.g., diplomatic, economic, or military hostilities and acts), suggest that most nations see cooperation as the path of choice in resolving water disputes.

While many of the costs and benefits associated with transboundary aquifers are similar to other locations relying on groundwater, some particular costs and benefits apply to groundwaters crossing international (or interjurisdictional) borders:

- Costs can include the following:
  - Groundwater depletion and degradation effects are not addressed while the nations work to resolve their water conflict.
  - Needs of populations poorly served by the waters in conflict may be ignored, including resource management investments, especially if they are not vocal in the politics of the countries.
  - The flora and fauna that use and facilitate maintenance of water quality may continue to be destroyed or eliminated.
  - The negotiations to resolve the water conflict are a transaction cost to ensure future water supply or quality or ecological sustainability.
- Benefits may count the following:
  - Greater certainty of water supply and quality for the range of economic purposes of interest through conscious planning and management for the collective well being of the nations' residents relying on the aquifer.
  - Defined socioeconomic–political relationships among aquifer-sharing nations that avoid costs of conflict through defined processes for resolution.
  - Peaceful, stable sharing of groundwaters provides a foundation for economic investment for participant nations, with the potential for mutually advantageous commercial activities that strengthen support of their respective communities' infrastructure and fabric.
  - Balance may be brought to the economic and ecological purposes of the shared aquifer for its sustainability.

EVOLUTION OF INTERNATIONAL WATER LAW

The evolution of international water law has paralleled the increasing demands on the water resource, moving from a perspective of defending absolute ownership to recognition of the needs of others for a shared resource. Eckstein (1995) provides an overview of this evolution in international water law applied to transboundary groundwater. Eckstein notes that groundwater has largely been left out of the international "legal regime" of water law because its ownership and use are considered different from that of surface water, rather than incorporating the interaction of ground and surface water in the water cycle as a basis for transboundary legal frameworks. Again, legal basis sets the foundation for value, addressed by the political processes manifest in law. The international water law framework has progressed through a set of principles described as (Eckstein, 1995)

1. Absolute territorial sovereignty—"Right to unrestrained use of resources found within [a nation's] territory, regardless of the transboundary consequences of [the] use," largely rejected at this time in the international realm.
2. Absolute territorial integrity—"Lower riparian [nations] have the right to the continuous or natural flow of a river flowing from upper riparian [nations]," basically giving downstream

(or downgradient) nations a measure of control over how upstream (or upgradient) nations use their water. Legal analysts have viewed this as inequitable and biased to downstream nations.

3. *sic utere tuo ut alienum non laedas*—Latin terms with the basic meaning of "[nations] [will] not use, or allow the use of, their territory for acts contrary to the rights of other [nations]." Legal decisions and documentation indicate that when one nation's activities cause or may cause harm to another nation's territory, the harm must be "appreciable" or "substantial" for international law to have effect. This principle is widely considered the standard at this time.
4. Reasonable and equitable utilization—This principle relies on cost–benefit analysis in weighing beneficial results to the gaining countries "in reasonable and equitable share" versus adverse effects. This principle does not necessarily consider the most efficient or productive result, but is generally accepted in international law.
5. Community of interests—This principle considers all waters of a basin as an integrated hydrologic system and unique economic setting. This "natural law" approach, ignoring special interests of one country over another, has not gained much international application.
6. Prior notice and good faith negotiation—By implementation of the principles of 3, 4, and 5, countries sharing water resources have a responsibility to inform potentially affected countries before using the resource. The information should be sufficient to allow the other countries to fairly assess the activity's outcome on them. Further, should adverse effects be anticipated by a notified country, then the informing country is obliged to negotiate in good faith to reach an outcome agreeable to each affected country, and no activity should begin until a resolution is achieved.

As Eckstein (1995) notes, this set of international legal principles applies to groundwater, since most international streams are connected to groundwaters, both of which cross national and other jurisdictional boundaries. As the principles indicate, use of the resource by one nation may have economic consequences for adjacent riparian countries.

INTERNATIONAL FRAMEWORKS FOR TRANSBOUNDARY GROUNDWATERS

While over 3600 treaties address water resources among nations sharing watersheds and 400 of them are relevant to freshwaters occurring along international borders, just 109 international treaties refer to groundwater (Matsumoto, 2002, p. 19; Giordiano et al., 2003). Typically, groundwater is dealt with as a "secondary issue" in most treaties (Matsumoto, 2002, p. 26). Prior to about 1950, most treaties referring to groundwater, springs, or wells did so as a landmark or border definition (Matsumoto, 2002, p. 20). For example, the 1864 Treaty of Limits between Portugal and Spain indicates that the countries will share waters from springs situated on their common border (Matsumoto, 2002, p. 20). From the mid-twentieth century, as increasing populations placed greater demands on water resources with expanding needs for water and food production, often from irrigation, treaties have focused on specifying groundwater production levels, apportioning withdrawals and establishing "management principles" for aquifers (Matsumoto, 2002, p. 22). Exhibit 15.3 gives a brief description of nine modern treaties that address specific groundwater resources relative to quantity and quality effects desired. Notably, several organizations to administer the treaties were established under them. All the treaties have economic implications that they addressed or were expected to address, as noted in the last column of the exhibit.

In December 2008, the United Nations adopted the Law of Transboundary Aquifers (Resolution A/RES/63/124). The UN Educational, Scientific, and Cultural Organization's (UNESCO's) International Hydrological Programme has inventoried 273 transboundary aquifers shared by two or more countries. The law identifies cooperation among nations that share aquifers to control pollution (UNESCO, 2008).

EXHIBIT 15.3 TRANSBOUNDARY TREATIES SPECIFICALLY CITING GROUNDWATER MANAGEMENT

Treaty	Groundwater Effect/Treaty Reference-Brief Description	Year	Participating Countries	Assumed Economic Interest
Convention regarding the water supply of Aden between Great Britain and the Sultan of Abdali	Quantity (quality)/Entire agreement—water supply construction should not affect groundwater quantity or quality at wells across border	1910	Great Britain, Aden (Yemen)	Continued viability of communities and commercial enterprises
Johnston Negotiations (agreement, not ratified as treaty)	Quality/3. Division of Water—management agreement on water diversion from saline springs to prevent salinity rise in lake	1955	Israel, Jordan, Syria, Lebanon	Sustained commercial use of lake
Mexico–United States agreement on the permanent and definitive solution to the salinity of the Colorado River Basin (International Boundary and Water Commission Minute No. 242)	Quantity/Article 5—limits groundwater production in the transboundary region	1973	Mexico, United States	Maintenance of agricultural and commercial aquatic enterprises
Treaty concerning the state frontier and neighborly relations between Iran and Iraq and protocol	Quantity/Article 4—schedules assessment of sharing spring waters in border areas	1975	Iran, Iraq	Continued viability of communities and local enterprises
Convention on the protection, utilization, and recharging of the Geneva Aquifer between Canton of Geneva in Switzerland and the department of Haute-Savoie in France	Quantity (quality)/Chapter 1, Article 1, Chapter 4, Article 9—specifies quantity limits on groundwater production	1977	Switzerland, France	Sustained water supply for communities and local enterprises
Convention on cooperation for the protection and sustainable use of the River Danube	Quality/Article 2 (1)—provides for long-term protection of groundwater in protection zones	1994	Austria, Bulgaria, Croatia, Germany, Hungary, Republic of Moldova, Romania, Slovakia, Ukraine, European Economic Community	Long-term viability of riparian communities and commerce

Treaty of peace between the state of Israel and the Hashemite Kingdom of Jordan, done at Arava/Araba crossing point	Quantity (quality)/Article IV—specifies groundwater pumping rates through joint water committee; groundwater use and rights defined	1994	Israel, Jordan	Sustained water supply for communities and local enterprises
The Israeli-Palestinian Interim Agreement on the West Bank and the Gaza Strip: Protocol Concerning Civil Affairs	Quantity/Annex III Article 40. Schedule 8,10—recognizes shared groundwaters, specifies pumping rates, and establishes joint water committee	1995	Israel, Palestine Authority	Sustained water supply for communities and local enterprises
Convention on environmental impact assessment in a transboundary context	Quantity/Appendix I—recognizes that withdrawal of quantities of groundwater affects the circumambient environment	1997	Albania, Austria, Byelarus, Belgium, Bulgaria, Canada, Croatia, Czechoslovakia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Moldova (Republic of), Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Spain, Sweden, Switzerland, Ukraine, United Kingdom, United States	Assessment of long-term ecological and economic effects on adjacent communities and countries from groundwater production

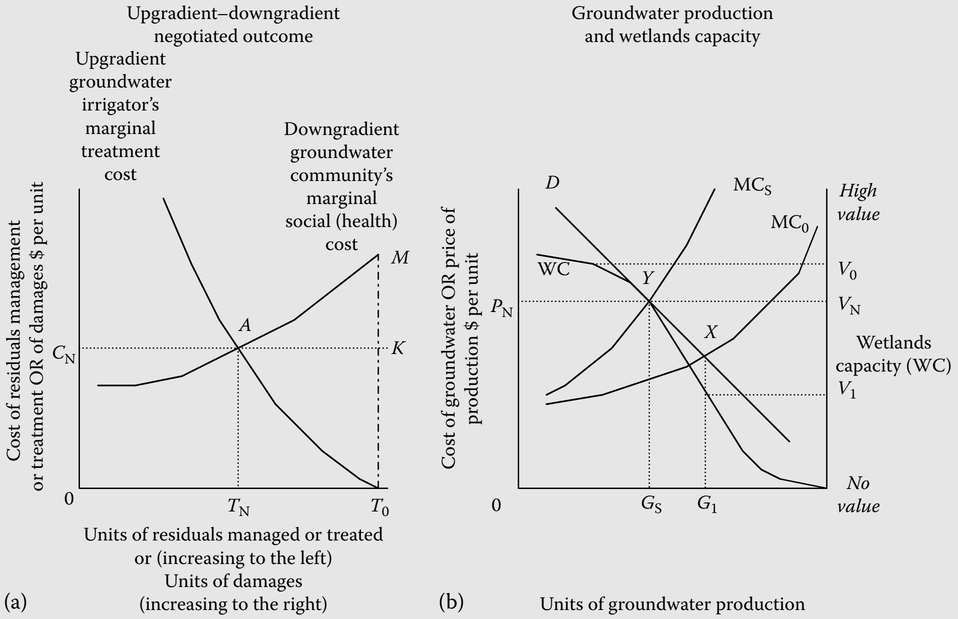
Source: Matsumoto, K., Transboundary groundwater and international law: Past practices and current implications, Research paper/thesis, Oregon State University, Department of Geosciences, December 2002, 73.

ECONOMICS OF LOCAL TRANSBOUNDARY AQUIFER USE

While various scenarios of transboundary use exist, we can consider two fundamental situations along a border that could occur, to which we might apply economic analysis. The first hypothetical situation involves an upgradient agricultural area on one side of the boundary having irrigated groundwater return flow in the subsurface, which percolates back to the water table near the border and raises the nitrate concentration of groundwater before it is used on the other side of the border as a city's water supply. The second example case is an upgradient industrial user consuming groundwater and depleting the aquifer and eliminating wetlands downgradient and across the border, which serves as a fish spawning and wildlife area. These cases are graphically portrayed in Exhibit 15.4.

In the hypothetical transboundary negotiation of the upgradient irrigator and downgradient water supplier (graph a), the irrigator must consider the high levels of nitrate that he is causing and the cost of residuals management to reduce nitrate concentrations crossing the border. The groundwater supplier must now treat her water to reduce nitrate and would like to minimize her supply cost of water by providing only necessary treatment. Both the irrigator and the municipality seek resolution without long legal suits and costs. Since the irrigator uses the groundwater before the municipality, but should have accounted for the harm to other users, an agreement utilizing an economic approach (rather than command and control) might set an objective of T_N residuals in groundwater crossing the border, assuming sufficient information is available on the social cost of health effects to the downgradient water supplier. Further treatment would have to be provided by the water supplier. To achieve this objective, the countries agreed that since both the irrigator and the water supplier shared the aquifer, the two entities working through their respective national governments should negotiate an economic outcome that recognizes prior conditions of use, since harm (residuals release to groundwater) was not intentional but driven by the economics of the circumstances. Viewing the example in Exhibit 15.4a as the situation confronting the irrigator and the municipality, the municipality agrees that it would pay the irrigator an amount equal to T_0T_NA to offset the irrigator's costs of treatment (basically soil monitoring of nitrate on a grid to guide future applications) and avoids costs of AMT_0T_N and associated costs of additional municipal treatment. The irrigator agrees to

EXHIBIT 15.4 ECONOMICS OF TRANSBOUNDARY GROUNDWATERS



work with his government to evaluate other means of reducing nitrate concentrations in the long term that might also allow him to expand production. If the irrigator finds another technology that can reduce the concentrations at less cost, then he can save that money for the remaining years of the agreement. The value of this approach is that it takes a holistic approach to the aquifer management, technology, and costs, utilizing a cooperative approach that considers the overall economic outcome in the longer term, with the backing of the national governments involved.

In the second case, shown graphically in Exhibit 15.4b, a company drawing on groundwater for its process water and consuming most of it as steam will reduce groundwater table levels that maintain a wetland across the border, which is important to national, commercial, and local fishing and other wildlife. If the water table is reduced too much, the wetland will lose most of its value to maintain the carrying capacity for wildlife. The company has already constructed its facility and started operations, and the other nation has observed groundwater flows and levels equivalent to G_1, with a corresponding wetlands carrying capacity value of V_1, a significant reduction from the original wetland value of V_0 before the company began consuming groundwater for its processes. At *X*, the intersection of the company's water process demand curve, *D*, and its marginal cost curve, MC_0, the bordering nations agreed that the company's production could be sold well below the market price because of the less-expensive, high-quality groundwater. Higher production cost to recognize the social cost of losing wetland values is reflected in MC_S, the social marginal cost curve. At *Y*, the company could condense the steam, recycle the water in its process, and only withdraw make-up water needed to replace process water lost within the plant at a higher marginal cost, and still be competitive at price P_N within its industry. In the long run, the company expected that recycling technology would actually reduce its water costs. At the point Y, nearly all the wetland capacity value could be attained. In this idealized scenario, both nations could allow economics to guide them toward an efficient result and achieve their objectives.

Exhibit 15.5 explores the interaction of treaties and agreements affecting groundwater along the U.S.–Mexican border. While the treaties and agreements are viewed as complements to each other,

EXHIBIT 15.5 AN EXAMPLE OF INTERNATIONAL TREATIES: GROUNDWATER AND ECONOMICS IN NORTH AMERICA

Cooperation of the United States and its neighboring countries, Canada and Mexico, on water issues has a long history. Focusing on the relation of the United States and Mexico, nearly two-thirds of the international border between the two countries is from shared rivers. Two sets of treaties and agreements in particular affect groundwater use and quality related to border activities in the two countries. Treaties of the joint International Boundary and Water Commission apply to the waters along the entire 3110 km border. Created in 1889, the IBWC administers a series of treaties, which have established the basis for peaceful resolution of water disputes relating to boundary demarcation, national ownership of waters, sanitation, water quality, and flood control in the border region (IBWC, 2008). The 1992 North American Free Trade Agreement (NAFTA), which phased out tariffs on goods traded among the three countries and removed investment restrictions (OUSTR, 1992), and its companion North American Agreement on Environmental Cooperation (NAAEC), which commits the three countries to protect the environment, have influenced groundwater use for agricultural production.

NAFTA creates inducements for agricultural trade across the U.S.–Mexican border by eliminating tariffs on these goods. The IBWC is organized to address the environmental issues related to water that may evolve from producing food for export to either country, as well as other water quantity and quality concerns associated with the border. While the word "groundwater" not directly mentioned in the Treaty of February 3, 1944, concerning the Rio Grande, Colorado, and Tijuana River basins, the treaty does refer to river waters "whatever their origin," including irrigation and return flows (IBWC, 1944). Nor is groundwater mentioned in NAFTA

(*continued*)

EXHIBIT 15.5 (continued) AN EXAMPLE OF INTERNATIONAL TREATIES: GROUNDWATER AND ECONOMICS IN NORTH AMERICA

or NAEEC, but rather they specify institutional and political processes to plan for or respond to environmental issues that may arise. The NAEEC commits the three countries to protect the environment; promote sustainable development; conserve, protect, and enhance the environment including flora and fauna; and enforce their environmental laws; and does not create new standards, while avoiding trade distortions and barriers. NAEEC focuses on environmental protective actions to minimize impacts of production within the countries, while IBWC deals with those impacts on shared resources at the respective common international border.

NAFTA eliminates barriers to trade among 3 of the 15 largest economies in the world. As measured by gross domestic product in 2006, the United States represents 27.4% of the global economy, Canada 2.6%, and Mexico 1.7% (World Bank, 2008), with annual growth rates from 1990 to 2000 of 5.7%, 2.6%, and 9.1%, respectively (USDOT, 2001). Mexico is the second largest agricultural market for the United States (after Canada) with exports to it doubling from 1993 to 2005 to $9.4 billion. The United States is Mexico's largest agricultural market, with its exports tripling to $8.3 billion over the same period (USDA, 2006). Groundwater, which constitutionally belongs to the collective citizenry of Mexico, is extensively used for irrigating agricultural products traded internationally, resulting in land subsidence and coastal saltwater intrusion (Marin, 2002). In the United States, about one-third of irrigated agriculture relies on groundwater, and this is growing. Aquifer depletion, saltwater intrusion, and land subsidence are likewise issues associated with this production. The challenge of the relationship between these treaties and agreements is that NAFTA encourages production within the bounds of the existing national environmental policy, while the IBWC must address the effects of that production that spill over into potential international conflict—more in the mode of a reactive response to past individual practices for near-term economic gain rather than a proactive agenda to implement actions consistent with national decisions about the long-term use of the shared resource.

As noted below, several major issues along the U.S.–Mexican border are related to groundwater used for agricultural irrigation. Other groundwater issues are associated with water and wastewater management along the border (Campana et al., 2006). The provisions of the treaties and agreements are expected to guide resolution of these issues.

Aquifer Affected	Issues Related to Groundwater
Hueco Bolson and Mesilla Bolson Aquifers	Groundwater pumping for municipal water supply and agriculture has lowered water tables. Salinity is increasing in aquifers.
Hermosillo Basin	Extensive pumping for agricultural production in response to NAFTA has caused saltwater intrusion threatening wellfields.
San Pedro River Basin	Groundwater pumping for municipal water supply, agriculture, and mining has affected significant riparian habitat that supports migratory birds.
Santa Cruz River Basin	Leaking wastewater pipes in Mexico are to be fixed to stop degradation of groundwater quality in Nogales, Arizona, with the project to include groundwater monitoring.
Tijuana River Basin	Inadequately treated wastewater discharged in the Tijuana River flows into California, affecting the quality of recharge to groundwater and health conditions on beaches south of San Diego. Groundwater quality is problematic with greater pressure to use it as a water source.

aspects of them may be creating more challenges as the North American Free Trade Agreement stimulates use of resources while the International Boundary and Water Commission tries to mitigate the effects of shared resource use. The interaction of the two underscores a need for decisions about the long-term use of groundwater at a state or national level before individual decisions about short-term production that causes ecosystem and economic distortion effects, some of which may be irreversible.

EFFECTS OF CLIMATE CHANGE ON GROUNDWATER

Climate change resulting in shifts of precipitation patterns and sea level rise may have a substantial impact on groundwater resources. Since many countries and jurisdictions have adjacent shorelines along the coasts, climate change may have transboundary implications, especially if neighboring countries respond differently. Climate change is the variation in weather patterns across time and place, observed around the world or over large areas. The cause is the release of carbon dioxide, nitrogen, and other gases from combustion of fossil fuels, resulting in world temperatures rising as well as significant and sometimes extreme variations in precipitation. These conditions can contribute to other ecosystem and resource impacts, such as changes in groundwater recharge. The Intergovernmental Panel on Climate Change (IPCC, under the United Nations Environment Program) has been studying climate change since 1988 and has issued a series of reports on its findings (IPCC, 2008).

The IPCC has evaluated a range of scenarios for the resulting variations in world weather patterns (IPCC, 2007). Taken together, the best estimates of the six scenarios are that the world temperature could rise between 1.8°C and 4.0°C over the twenty-first century with a resulting sea level rise of 18–59 cm from the Greenland and Antarctic icesheets melting. If the Antarctic icesheet melting were more consistent, it would contribute even more to sea level rise. Between 1993 and 2003, Greenland and Antarctic icesheets melting contributed to an average annual sea level rise of 3.1 mm/year.

Groundwater itself is a contributing factor to sea level rise. Groundwater mining primarily for irrigated agriculture removed an estimated 1000–1300 km^3 annually from storage. This withdrawal contributed to a sea level rise of 0.2–1.0 mm/year (Goudie, 2006, p. 244).

POTENTIAL EFFECTS IDENTIFIED

Effects of climate change on groundwater are many and varied (IPCC, 2007). In addition to the underground storage of carbon dioxide in deep geologic zones, an estimated 230 candidate storage reservoirs in the United States with a capacity of 3900 + $GtCO_2$ (Battelle Memorial Institute, 2006), the following effects have been identified:

In Coastal Areas

- Inundation of coastal lowlands—In the United States, a loss of 25,900 km^2, approximately 0.3% of the total United States land area
- Inundation of wetlands—In the United States, half of which will be in Louisiana
- Increased flooding in coastal areas with resulting water quality impacts on shallow coastal aquifers (Masterson and Garabedian, 2007)
- Thinning of the freshwater lens in coastal aquifers (Masterson and Garabedian, 2007)
- Increased saltwater intrusion with a rise of the freshwater–saltwater interface (also cited in Masterson and Garabedian, 2007)
- Increased groundwater discharge to streams in areas closer to tidal influence, moderating a rise in groundwater levels (Masterson and Garabedian, 2007)

Across Continents

- Dry areas get drier
- Wet areas get wetter
- Increased area affected by drought
- Increased heavy precipitation

Implications for Nations, States, and Localities

- People move from flooded areas causing large migrations from heavily populated coastal lowlands.
- Increased water demand in warmer areas, including increased irrigation, causing consequent water tables to drop, and loss of natural capital in the form of groundwater.
- In areas of increased precipitation, higher water tables, causing foundation water problems, and upward pressure on objects, such as water and sewer lines, buried below ground.
- Increased salinity of groundwater, necessitating greater treatment, and cost to deliver water in coastal areas.
- Loss of shallow wells due to saltwater intrusion in coastal areas.
- In areas of increased dryness and existing groundwater depletion, potential for increased reliance on brackish and saline water for water supply through water treatment to remove high mineral concentrations.
- More well and pipe installations for locations near coast because of saltwater intrusion for both water supply and management of freshwater–saltwater interface to avoid further intrusion.
- Waterlogged soils in humid areas that receive more precipitation, potentially reducing agricultural production in currently productive areas.
- Loss of wildlife habitat in wetlands and, therefore, loss of spawning grounds for aquatic and terrestrial species.

EFFECTS OF UNDERGROUND STORAGE OF CARBON DIOXIDE

Chapter 7 covered a range of effects of underground injection of carbon dioxide, a “greenhouse” gas contributing to global warming. This proposed method of disposal of CO_2 is also referred to as “geo- or carbon sequestration.” The subsurface storage of this gas may have transboundary issues and costs, while attempting to address a helpful response to the challenge of climate change. The effects include acidification of groundwater, “pushing” saline groundwater into potable water formations, also having potential effects on aquatic life habitat, and migration of CO_2 from the zone of injection perhaps contributing to blowouts that could destroy human and animal life in the adjacent area.

ECONOMIC EFFECTS

The ecosystem and economic costs of the effects of sea level rise have not been fully evaluated but are likely to be substantial locally when they occur. The IPCC (2007) indicates at the global macroeconomic level that

> In 2050, global average macro-economic costs for mitigation towards stabilisation between 710 and 445 ppm CO_2-eq are between a 1% gain and 5.5% decrease of global GDP. This corresponds to slowing average annual global GDP growth by less than 0.12 percentage points.

More saltwater intrusion along coasts may likely translate into greater demand for and pressure on groundwaters in areas currently adjacent to the coastal zone. These demands could increase public and private expenditures for new wells and pipelines to serve an increased population, which has been displaced to inland locations. Along with shifting population is the other added infrastructure—roads, schools, and other public services that are not portable—and its associated costs to serve this population. Disruption to the economic network of long-established small and large population centers and the macroeconomy they represent will need to be evaluated more fully.

The potential economic effects of geo-sequestration of CO_2 may be estimated from the costs of well and pipe replacement in the areas where injection may occur through applying probabilities to the likelihood of occurrence of gaseous movement in different strata to the costs of well and pipe replacement in those locations. These costs may be reasonably well known in the vicinity of such facilities. More work on the probabilities of CO_2 migration is needed, especially in the context of transboundary movement and effects. The transboundary costs to neighboring countries then can be explored to determine their acceptability for injection zones near the borders. The experience of proposing nuclear waste disposal in the Rio Grande River basin in Texas, United States, near the U.S.–Mexican border demonstrated how strongly societal concerns can influence governmental action and cause prior decisions to be changed when potential damages and costs to groundwater users are perceived to be high in the neighboring countries (Campana, 2006).

TRANSBOUNDARY AND INTERNATIONAL FACTORS

Adjacent countries sharing a border in the coastal zone may decide to plan ahead to address sea level rise and inundation of neighboring lands in common shared approaches that preserve the local economies contributing to their citizens' welfare. Similar responses could provide for conserving the natural capital, including groundwater, which may migrate differently under the boundary and need to be modeled under changed conditions. The groundwater resource will be under greater stress from both saltwater intrusion and potentially more concentrated water demand inland. Its use in ways that reflect the future scarcity value of the groundwater and mutual responsibility to promote its stewardship for their collective benefit will contribute to the then-current and future welfare of the people living in these areas. Without collaboration, extremely intense groundwater use that goes unmoderated by one country will exacerbate local economic problems already extant from displacement by sea level rise relative to the use of the land surface. It is in the economic interest of adjacent countries to cooperatively resolve their response to and foster sustainable use of groundwater at their borders affected by sea level rise.

AQUIFER STORAGE AS A CLIMATE CHANGE ADAPTATION

Aquifer storage, addressed in Chapter 4, may be a mitigation and adaption response to climate change (Shrier, 2008). Aquifer storage may offer opportunities to utilize subsurface storage capacity to hold water from extreme precipitation events expected from climate change (USEPA, 2008) for future use during drier periods (Shrier, 2008). This technique may be used to mitigate saltwater intrusion (Reichard et al., 2004), which is expected to be significant in coastal zones by providing a hydraulic barrier to the advance of seawater.

INSTITUTIONAL FACTORS FOR WATER COOPERATION

Utilizing the international principles, institutions of transboundary water cooperation have evolved in response to greater demand for water for a range of human, economic, and ecological needs and, therefore, their increasing value. Past treaties indicate the recognition of the need to share water, including groundwater, as a fundamental resource for all neighboring people and their economic enterprises. As noted earlier, a body of international water law has developed over many years, initially to protect property and its economic vicissitudes and more recently progressing to sharing a limited and valuable resource. International institutions can serve as the means to address transboundary water use, even in situations existing under hostile circumstances. Where the transboundary water effects are not acknowledged by nations in conflict, the likely result is worsening water quality or availability. The greatest international concern exists in locations along borders where people—numbered in millions—lack adequate water (UNESCO, 2003, p. 318). Critically, cooperation must work through the triad of scientific, governmental, and societal processes that exist to ensure an appropriate response to transboundary groundwater issues (Campana et al., 2006). Based on lessons from water management, the United Nations Educational, Scientific, and Cultural Organization has described factors that may provide the basis for cooperative transboundary groundwater management in international institutions (UNESCO, 2003, p. 318) and could apply at other organizational levels, including local and state governments:

- "Adaptable management structure"—As in regulatory approaches, the administration of conditions that govern groundwater use must be fit the circumstances being dealt with and the cost of that administration must be recognized by all parties; the management structure may by necessity vary based on the institutions and hydrologic conditions that make up the situation.
- "Clear and flexible criteria for water allocations and quality"—Such criteria are critical to encourage an adequate economic response. Clear criteria for groundwater allocations and quality are essential for stable conditions that bring about sustained economic response. Flexible criteria provide the ability to respond to changing hydrologic factors and meterologic conditions in ways that allow economic activities to continue despite the existence of less than optimal or target circumstances.
- "Equitable distribution of benefits"—Ensuring that the benefits are appropriately shared among all nations and individuals affected by international agreements is vital to enduring arrangements for using transboundary groundwaters. If a party believes that it has not received an equitable distribution of benefits and a significant disagreement ensues, the conditions for economic investment and activity may become destablized resulting in a local or regional economic downturn.
- "Detailed conflict resolution mechanisms"—Having a range of resolution means and levers at all levels—local, regional, national, and international—provides the possibility that solutions can be achieved at a level at which the legal capability and economic resources are appropriate to the conflict. If resolution cannot be reached on one level or approach, detailing the options in an agreement offers the prospect that a solution can be achieved at some point. Relying on detailed resolution mechanisms allows the economic response to be cognizant of options in addressing the costs of the process and the availability of groundwater, which in turn affects its price and the price of products that are dependent on the water.
- Application of sound hydrogeologic science—Additionally, the endurance of outcomes from governmental and societal processes in the steps described should rely on use of sound hydrogeologic science as the basis for resolving transboundary disputes and concerns (see Campana et al., 2006). Without an adequate characterization of the subsurface and groundwater flow and quality, conflict may only precipitate again because of a deficit of knowledge and information available to all the parties on which to make decisions that recognize all the major costs and values affected over time with changing groundwater conditions.

Institutional examples exist at different levels. The processes of the U.S.–Mexican International Boundary and Water Commission previously described (such as in Exhibit 15.5) provide one model for settling specific disputes relating to groundwater along borders. A different and significant institutional development affecting internationally shared groundwaters is the European Union's (EU's) updated Groundwater Directive, as part of the Water Framework Directive (EC, 2003). The EU's directive establishes a policy that affects all countries in its jurisdiction, in this case, principally contiguous nation-states. The Directive establishes contaminant concentration levels acceptable in water and maintains the groundwater source protection areas that contribute groundwater to wells used for water supply and are monitored regularly to inform groundwater users. In adopting this directive in common, all countries within the EU agree to protect groundwater in mutually beneficial ways.

SUMMARY

Groundwater supplies a substantial portion of all water demands globally and 50% of potable water use. Groundwater withdrawals occur in 263 river basins that are transboundary watersheds of 145 nations around the world, indicating significant competing uses for these waters and their value to those using or seeking to use them. Transboundary aquifers are intersected by the borders of these nations as well as those of their subjurisdictions. Use of transboundary aquifers at the international level has been the subject of treaties over many centuries, which have more recently identified groundwater specifically and how it is apportioned. Historically, nations sought to protect exclusive rights to waters, but have recognized more recently larger international economic and environmental interests in groundwater. Economic efficiency and equity issues are significant in analyzing international groundwater use of shared aquifers. Institutions have emerged to guide management of transboundary groundwater with key features including adaptable decision processes, allocation, and quality criteria allowing response to changing circumstances, consideration of the distribution of economic effects, and well-developed conflict mediation steps. Global climate change may contribute to pressures on groundwater in coastal zones owing to sea level rise and resulting saltwater intrusion and population displacement. Neighboring countries with coastal borders should cooperate in response to sea level rise as it affects groundwater to ensure its sustainable use. Geo-sequestration of CO_2 in adjacent border areas also needs attention relative to potential groundwater impacts. One approach is to establish a commission to respond to international boundary water disputes, such as the U.S.–Mexican International Boundary and Water Commission. Another example of international institutions affecting groundwater is the Groundwater Directive adopted and implemented in common by the member states of the European Union that guides groundwater protection within and among these contiguous nations for their mutual benefit.

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16 Groundwater in the Future Balance

Groundwater is an inherent part of the ever-changing hydrosphere in the ecosystem supporting probably half of the world economy. As groundwater flows from property to property, through communities, underneath boundaries, and interacts naturally between aquifers and streams, it has multiple uses and can serve many users while moving through the hydrologic cycle. The economics of its use and misuse are interconnected with the larger economy and the allocation of resources through prices in the market as a commodity and unpriced values for public services of the ecosystem to sustain life and societies' economies around the world. Prices and nonmarket values are influenced by government policy and regulation. Human interaction with the resources of the ecosystem through the economy can have a positive, sustainable result or a negative, irreversible outcome. For future sustainability, groundwater to support our economies must essentially be in balance with the other intrinsic factors of the ecosystem. The groundwater environment is a condition of water, a stage in the hydrologic and geologic cycles that we intercept for transient and regular purposes of our human needs. With the exception of some deep formations, groundwater flows rather than being compartmentalized for our control. As we have choices at different levels of national, international, watershed, community, business, and individual interest, several key economic principles affecting what and how we decide about groundwater emerge from the previous examination and will be considered here.

To summarize, the key points for balancing future sustainable and economic groundwater use in the ecosystem are

- As a public common property good, groundwater and its services will be undersupplied by the marketplace and should receive a positive (i.e., non-zero) value.
- More information about the resource is critical to inform our decisions and assist us in setting public objectives for our interaction with and use of it.
- Maintenance of the natural capital of groundwater is critical for its sustainability and to allow its use by future generations.
- Aquifers and watersheds are appropriate management units within which can be reflected the accepted scientific information critical to sustaining the resource.
- The resource should be available to all who rely on it through a just and fair distribution of and access to its services.
- Efficient allocation of the resource should follow from decisions of resource sustainability and distribution.
- Communities using groundwater must value the ecosystem in which they exist to be in balance with it.

PUBLIC GOODS ARE UNDERSUPPLIED IN THE MARKETPLACE

A Public Common Property Resource

Contributing to an essential human need for water, groundwater exists in nature as a common property resource and is considered to have at little or no value in most locations. Groundwater is often available in locations where no surface water source exists to satisfy thirst and support crops, provides a media for heat exchange, supports plant life that moderates climate, maintains streamflow when there is no precipitation, provides many other services that simply exist, and is taken with no or little forethought of cost or possible loss to the ecosystem or other people. The marketplace will not provide more of these services, but it will recognize when they are scarce and indicate a higher market-clearing price, which is what the market is supposed to do. Open access, competitive use will ensure that it is undervalued and overused, a market failure.

Some economists suggest that groundwater should be owned to be protected for its best and most valued uses. Many human activities affect its availability and quality, often through a lack of understanding of the nature of its existence and vulnerability. Since surficial and subsurface conditions vary significantly from place to place, even over short distances and spaces, an attempt to legislate its ownership and use seems confounding. However, recognizing that groundwater flows and interacts with streams and lakes, national and state laws can respond to its fundamental characteristics, and provide direction for managing it for the benefit of society and all its citizens, acknowledging that true ownership through law of a flow resource, let alone its services, is misconceived. Legislating objectives for this "public trust" resource with specific rights of access to water to be managed based on hydrologic conditions and sound science recognizing fundamental ecosystem requirements would seem to attach more value to the resource and its service in meeting human needs.

Relying on the marketplace to provide it for its greatest value and benefit means that it is owned by someone or a corporation of individuals. These individuals can then decide to whom to sell it and negotiate the best price for it. If groundwater is scarce or the only water source available, this circumstance of bidding for groundwater seems a terribly difficult position to place a low-income family needing this essential resource. Bidding on it will certainly recognize and raise its value, but it will be undersupplied for essential needs. Ownership means that ecosystem services could also be destroyed by the owner, not recognizing these values, to capture its highest economic and monetary value. While this seems far-fetched to some, large volumes of groundwater are being sold through bidding processes (e.g., see WDNR, 2006; ASLD, 2007). Bidding on groundwater in the marketplace might occur after the nation or state has determined that all essential purposes have been supplied with water. The challenge is determining essential ecosystem purposes on which humankind, flora, and fauna must rely to ensure that the sale is not shortsighted.

The subsurface and groundwater may also serve as a waste sink and its contamination is a public "bad." Resource objectives should define the extent to which aquifers or portions of aquifers—including brackish and saline groundwaters previously at the margin of usefulness but now recognized as a potential resource in extreme conditions of no other alternative water source—may become unusable because of waste disposal needs. Groundwater is vulnerable, often with irreversible quality effects when damaged—considering limited time and funds in most cases to clean it up. Excessive pumping can also induce saline water intrusion in both inland and coastal fresh groundwater zones. For example, Cape May, NJ, pumps and treats groundwater made brackish from saltwater intrusion. (see Figure 16.1, p. 578.) Recognition of this vulnerability in its management would go a long way toward embracing its direct, indirect, and intrinsic values (UNESCO, 2003, p. 331). While this may be complicated, groundwater users should be able to rely on their governmental jurisdictions to protect the resource for safe and necessary uses into the future (UNESCO, 2003, p. 331). The fundamental concern in the use of groundwater as a water source or as a waste sink or conveyance is the cost that individuals or entities withdrawing water or releasing waste to the subsurface inflict on other users or potential users (UNESCO, 2003, p. 330). The legal framework affecting users and their economic relationships should incorporate the best understanding of its science to limit distortions in their economies and maintain balance in the ecosystem.

Thus, setting specific objectives for the resource as water source, waste sink, and ecosystem balance contributor, and addressing equity in access for essential human requirements are initial steps in establishing value for groundwater and the subsurface environment and ensuring adequate supply of its services. Then market exchange can further provide efficient values in allocating the remaining sustainable resource.

POLLUTER PAYS PRINCIPLE

Ensuring that pollution does not go to the jurisdiction having the least-robust environmental law within a country or in other countries, the "polluter pays" principle is recognized internationally as a guide to long-term environmental protection for the economies of both developed and developing countries. The principle is fundamental to the allocation of costs of pollution prevention and control measures and is critical to the sustainability of a common property resource, such as groundwater, which is relied on by so many users. It "means that the Polluter should bear the expenses of carrying out the measures…to ensure that the environment is in an acceptable state. In other words, the cost of these measures should be reflected in the cost of goods and services which cause pollution in production and/or consumption" (OECD, 1974). In the United States, the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA or "Superfund") was enacted in 1980 to ensure that the liability for waste disposal was transferred to the past, present, and future producers of the waste. The European Union updated past legislation in adopting the Directive on Environmental Liability in 2004 to further advance the implementation of the polluter pays principle. These laws and similar ones in other countries are significant for groundwater protection because a substantial amount of waste is disposed in the subsurface as its value is not recognized by potential polluters.

Residuals from accepted chemical and biological activities on the ground surface, such as pesticide use, may result in groundwater contamination if not properly conducted. While these substances have a target result, they also become part of the ecosystem, and in the subsurface are difficult and costly to remediate. Waste disposal costs may not adequately incorporate costs of remediation should significant releases occur to damage other uses of the resource, usually accommodated through limited environmental performance bonds for waste disposal facilities. Vigilance should be applied to ensure that the polluter paying principle is appropriately implemented in the broadest way so that groundwater is not the unseen sink from narrowly focused legal approach to waste and residual management. Future costs may not be foreseen as the regulated products become residuals in a subsurface environment that can be expensive to investigate, resulting in high entrance costs for examination of groundwater effects to potentially concerned individuals and communities that may be impacted.

RESOURCE VALUE PROMOTED BY GOVERNMENT ACTION

National and international levels are appropriate for a range of actions that can ensure that groundwater values are properly included in decisions. In the United States, no clear law ties together the environmental legislation affecting groundwater that focused on issues of concern at the time of adoption. The last comprehensive policy was developed by the EPA in 1992, but did not effectively incorporate economic evaluation in its development or implementation. The United States federal government has promoted a number of policies affecting groundwater and its value, but these have not been examined comprehensively relative to their total economic effect on groundwater before implementation. The European Union has adopted a comprehensive water law, as have a number of other countries, such as Canada, Mexico, and Australia, which also allow recognition of the current science to be applied to groundwater in a holistic integrated water resources management approach in administering it for public benefit. Furthermore, economic policy by its very nature of drawing on, mobilizing, and using the resources of the ecosystem is environmental policy (Sullivan, 1992, p. 16), often enacted without considering ecosystem effects. National, state, and local laws setting clear resource objectives, drawing on current knowledge of hydrologic relationships that cannot be owned, can guide public, individual, and corporate response to using, conserving, and maintaining groundwater and other essential ecosystem services and formally recognizing their inherent values.

MORE RESOURCE INFORMATION FOR SETTING PUBLIC RESOURCE OBJECTIVES

Monitoring is Essential

Critically, the resource must be understood first before its objectives can be set and its use allocated through public objectives and then through economically efficient and effective means. For this significant resource, more information is essential for its rational economic use in response to those public objectives. Monitoring of the groundwater resource is necessary to understand its status for quantity and quality to support domestic, agricultural, industrial, and ecological purposes. Monitoring data is essential for establishing a baseline for evaluating the economics of any action that may affect groundwater. Understanding the quantity and quality of groundwater relative to its range of uses for a growing population allows national, state, and local governments to evaluate options in prioritizing objectives for its use. The most obvious situation is in times of drought when governments declare the priorities for water use. Longer-term considerations will also be important as we experience changes in local water balances from climate change.

In the United States, the U.S. Geological Survey (USGS) organized and implemented a monitoring program in 51 river basins or portions of basins from 1991 to 2001, covering less than half of the country and focusing on high-water-use areas primarily. The cost to operate this program was approximately $60 million per year, of which about one-third was for groundwater monitoring. Through budget reductions and inflation, the USGS has had to reduce this program to monitoring in 42 basins (USGS, 2008). All 50 U.S. states monitor groundwater to some extent. The European Union has also implemented an extensively required monitoring program, including special monitoring in designated vulnerable zones, such as drinking water source protection areas (EU, 1991) and in coastal and transitional waters (Ferreira et al., 2007). These programs must necessarily continue to provide information on the current status of the resource, which is critical for rational decisions about groundwater use in the public and private sectors and to protect the resource for its range of purposes, especially with increased population needing water and with increased use of chemical and microbial substances globally (USGS, 2007).

Physical/Hydrogeologic Relationships

Monitoring of groundwater necessitates recording data for many important subsurface relationships. Each aquifer and overlying watershed is different. As noted in Chapter 2, the subsurface environment of a watershed may be very diverse, perhaps as diverse as or more so than surface water environments with respect to the physical settings. Depending on the placement and completion of wells, groundwater being produced may draw from shallow or deep aquifers, from streams and lakes—even from the ocean, and from other watersheds and surface waters. Similarly, waste reaching the subsurface can be transmitted to those same places depending on groundwater pumping, discharge to streams, the hydraulics of other water bodies as well as adjacent watersheds, and the natural water balances affecting their ground and surface water quality. A benefit from water production or waste disposal in one location of a watershed may be a damage or cost elsewhere in the watershed.

The diversity of watersheds may make the evaluation of the benefits and costs of groundwater relationships in the larger hydrological cycle a challenging process, especially in the context of sustainability of the resource. Therefore, natural physical principles governing groundwater flow* may be a key component of assessing groundwater values. The highly distributed existence of groundwater causes its value to be uniquely different from surface water, with its instrumental value to people affected by the four dimensions of its occurrence—three spatial dimensions influencing a lagged temporal component (UNESCO, 2003, p. 331): aerial extent (two dimensions), depth, and time.

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* These natural physical principles and other factors are outlined in Chapter 2 and in referenced texts.

More information will support where in an aquifer in a watershed that groundwater can be replenished for the greatest effect, as we draw on its natural capital. This replenishment supports long-term sustainability of the resource for our use and that of future users.

GLOBAL CLIMATE CHANGE

Global climate change relating to groundwater must be responded to at all levels—local, state, national, and international. Baseline and projections of physical conditions from modeling will be important to guiding response to climate change. Rising sea levels, based on fundamental hydraulic principles, will exacerbate saltwater intrusion along coasts where groundwater pumping has already induced this effect. In other locations, where pumping near coastal waters is more modest, rising sea levels could begin the saltwater intrusion process. Local, state, and national standards on the volume of pumping in or near the coastal zone or other regions experiencing significant changes in precipitation for recharge may be necessary to preserve the quantity, quality, and other natural capital services of groundwater in these cases. Groundwater discharge to estuaries and coastal areas provides important nutrients and temperature differentials on which near coastal aquatic life rely. Monitoring data will be needed to guide response.

Policies that deplete groundwater causing it to be discharged to streams in excess of that which would naturally occur from surficial aquifers further contributes to rising sea levels and the possibility of expanded saltwater intrusion inland and along coasts—a double loss: first from exhausting the resource to the disbenefit of future generations and second from degraded quality for future groundwater users on the coasts and in inland locations with saline water intrusion from extensive pumping.

Drought conditions may be exacerbated by climate change. Shifting weather patterns may increase precipitation in some locations and decrease it in others. In areas experiencing drought that affects surface water flow, greater reliance on groundwater will likely occur to "smooth out" water availability and fill in the loss of stream flow and surface reservoir supply. An understanding of this phenomenon and its impact on groundwater resources that have significantly less recharge will be critical to the longer-term viability of human health and regional economies in the areas affected.

More monitoring information will be needed as injection of carbon dioxide into deep geologic strata is initiated to reduce the effects of future climate change.* The risks of this injection are not well understood. The needed data will be site specific, based on the geology of the region. More research, which should include monitoring, is needed to understand the probability associated with the risks of groundwater acidification, pressure changes in geologic formations, and brine movements. From this research, costs may be estimated and cost-effective approaches defined.

MARGINAL BRACKISH WATERS BECOMING ESSENTIAL

What were once considered unusable marginal waters—brackish and saline groundwaters—are now recognized as critical resources in arid locations, where aquifers are being depleted. Desalination costs are decreasing to make brackish waters more attractive as water sources. Care must be taken in setting public objectives for these resources, which are also the target for carbon dioxide disposal in response to climate change initiatives to use saline groundwater as waste containers. The potential for confusion in public policy toward brackish and saline groundwaters exists in this competition for underground resource zones, especially in arid metropolises experiencing population growth. More information about these resources is fundamental to setting clear public objectives for their use.

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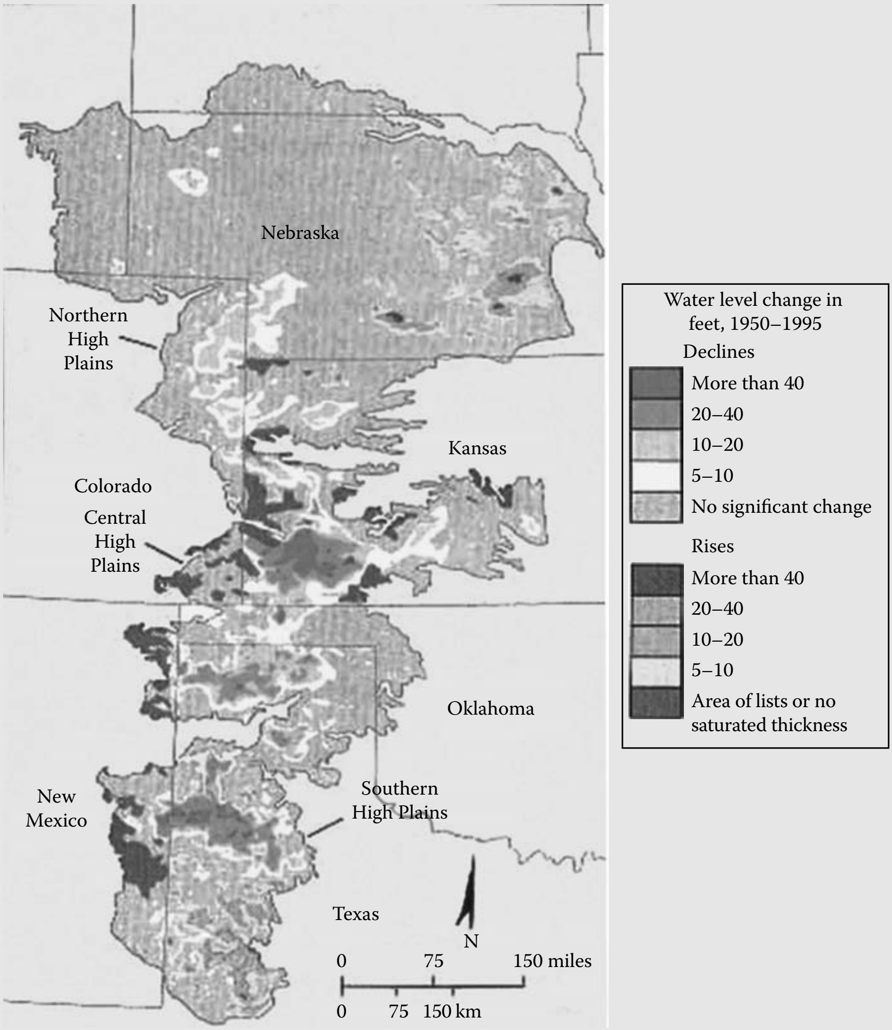
* The United States alone produced an estimated 5.7 million metric tons of carbon dioxide from the burning of fossil fuels by all sources in 2004, about 23% of the world total, and world growth rates are expected to be 1.7%/year (Wilson, 2006).

MAINTAIN NATURAL CAPITAL FOR SUSTAINABILITY

Importance of Scale and Public Objectives

Groundwater represents natural capital that can serve future human and ecosystem purposes, sustainably with conscious effort to do so. While groundwater is essential for people with no other water source and for maintenance of certain subterranean and terrestrial habitats, a single use or disposal action will not by itself deplete or degrade an aquifer. The Ogallala Aquifer underlying approximately 25,900 km^2 in the central High Plains of the United States was *not* being depleted by one or a few farmers operating irrigation wells to ensure crop production. Ogallala Aquifer depletion is shown in terms of water level change in Exhibit 16.1. It was depleted by thousands of farmers pumping from thousands of wells to irrigate millions of hectares of cropland. Each farmer was an economic decision maker

EXHIBIT 16.1 WATER LEVEL CHANGE IN THE OGALLALA AQUIFER OF THE U.S. HIGH PLAINS REGION



affecting this common property resource. Groundwater was produced without a public objective for long-term maintenance of the aquifer to ensure its fullest service to all communities and states that it supplied now or in the future. Furthermore, groundwater production was subsidized by the U.S. federal government, because it provided a depletion allowance for mining it as a public objective, which reduced the tax liability of the farmers and these funds were not used to replenish the aquifer. The cost of aquifer depletion—or degradation—is borne by future generations who will not be able to use the water lost—or who will have to treat it at significant cost. The point is that valuable natural capital was consumed by individuals who held uncontrolled production rights to a common resource that should have been treated as a trust for the future by the state or the nation, given its transboundary-interstate existence. No goals or objectives were established for the aquifer at the onset of its intensive, concentrated use to reflect the ecosystem and macroeconomic contexts within which the aquifer existed. Had goals and objectives for its use been in place, more efficient use directed at sustainable development for its long-term maintenance and support of future generations could have been established. If more hydrogeologic information had been available at the time relative to the aquifer's use, a sustainable use policy might have possibly evolved then. This circumstance implies that monitoring information is necessary and its use should be tracked and accounted. Sustainable development will take concerted political and economic effort to achieve. Consideration of the scale and allowable intensity of use is critical to maintaining the sustainability of an aquifer.

ACCOUNTING

National accounting of the resource's existing condition and of defensive and remedial expenditures in the economy for groundwater-related activities, as well as of the use of natural and ecosystem resources and services, is a fundamental step in understanding the economic significance of the resource. This information is important to support efforts to achieve sustainability at the broad scale of resource use. Groundwater-related expenditures are large but not well accounted. Knowing the current situation with some degree of completeness would help set future direction, and goals and objectives for maintaining the natural capital services of groundwater. Estimates of all pollution abatement and control expenditures have been made for the United States, and their proportion potentially associated with groundwater is substantial. Exhibit 16.2 provides these estimates for 1995 and 2005. In 1993, these expenditures were estimated to be about 4% of the gross domestic product of the United States. Improved estimates of expenditures for groundwater-related activities in the economy should be derived from a full accounting of the use of this natural—and national—resource. The national scale is an appropriate level at which to consider complex interactions of the economy and the exchanges involved. It is also at the proper level to address values that cannot be priced by the market and set policies to respond and attempt to balance costs and benefits, including those that are not quantifiable or monetizable, such as endangered species extinction, native culture ceremony, and permanent loss of natural capital in groundwater. In the United States, federal national policy has attempted to address such comprehensive costs and benefits, but for groundwater controlled at state and local levels, usually a narrow accounting focused on a single activity and its result has precluded long-term considerations with their interconnected economic effects.

REPLENISHMENT OF MINED AQUIFERS

Because of intensive mining of both nonrenewable deep and potentially renewable shallow aquifers, establishing laws and local ordinances to replenish them is warranted in light of increasing population and climate change. Mining groundwater increases current production costs and denies use of the resource to future users. Two aspects of this issue deserve attention: laws that encourage mining and charges to pay for replenishment. Laws encouraging groundwater mining should be reevaluated and if at all possible, changed to discourage this practice, or at least minimize it to the extent possible. Communities using a groundwater source and central collection and treatment of wastewater with

EXHIBIT 16.2 ESTIMATED POLLUTION ABATEMENT AND CONTROL EXPENDITURES RELATED TO GROUNDWATER IN THE UNITED STATES, 1995 AND 2005

	Expenditures in US$ millions (1991)	
Category	**1995**	**2005**
Total pollution abatement and control	$160,112	$239,435
Radiation pollution control[a]	791	1,418
Water pollution control	64,252	90,473
Water quality[a]	57,832	80,655
Drinking water[b]	6,420	9,818
Land pollution control	44,590	67,125
Solid waste[a]	24,406	32,976
Hazardous waste[a]	11,052	18,014
Underground storage tanks	3,504	5,103
Superfund[c]	5,628	11,332
Chemical pollution control[a]	2,967	4,463
Toxic substances[a]	1,343	2,145
Pesticides[a]	1,624	2,318
Multimedia pollution control[a]	2,522	3,176

Source: Sullivan, T.F.P., (ed.), *The Greening of American Business*, Government Institutes, Inc., Rockville, MD, 1992, 212.

[a] Portion of estimate specific to groundwater could not be determined.

[b] Approximately one-third of estimate may be attributed to groundwater based on population served.

[c] Nearly every Superfund site has groundwater associated with it.

discharge to streams may desire to reevaluate this process and further reclaim these waters as a more sustainable practice. Groundwater use with stream discharge may lower water tables, additionally increasing pumping costs. These waters, once treated, could be used to recharge the aquifer or for other economic purposes through reuse, rather than hastening their release to the surface water. Laws giving depletion allowances to income taxes for mining groundwater induce greater use through this subsidy by lowering the cost to produce groundwater. This law primarily has applied to groundwater mining for irrigation on the central plains of the United States. In areas experiencing mining of groundwater, charges could be levied to pay for aquifer replenishment, such as using treated wastewater and injecting or allowing it to percolate through water storage pond bottoms to recharge groundwater. Other practices could also replenish the aquifers with the appropriate economic instruments as incentives.

POLLUTION PREVENTION, RESIDUAL/WASTE REDUCTION, AND COUNTER TO CAUTIONARY TAX

A potentially preferable strategy for business is to pursue elimination of environmental liabilities and costs in their commercial processes, rather than just complying with existing regulations (Sullivan, 1992, p. 145). This approach incorporates the elements of pollution prevention, including waste reduction, resource recovery, and recycling. These activities have substantial relation to groundwater quality protection, since residuals released to the ecosystem are minimized by all these steps in pollution prevention, and the controls on releases to air and water have caused residuals management to utilize land disposal. Utilizing pollution prevention in all commercial, industrial, and agricultural processes to the extent possible implicitly recognizes the value of ecosystem resources that would have otherwise been affected, in particular, the subsurface environment and groundwater. By internalizing these costs, industry may be able to avoid "cautionary taxes" on use of the subsurface as a disposal sink. (Some level of tax may still be considered important if any level of residual disposal occurs above the natural carrying capacity of the ecosystem.) This approach is referred to as an "environmental management system" and is codified in an international voluntary consensus standard, ISO 14001, as described in Chapter 13. In evaluating an activity, project, or product, the least-residuals-generating outcome is preferable to alternatives that produce more residual waste, although recycling wastes may mitigate this result and should be evaluated through CBA. Such an approach preserves natural capital in groundwater for current and future generations.

WATER CONSERVATION AND "GREEN" MANAGEMENT

Agricultural, commercial, and industrial uses of fresh (not saline) groundwater are 76% of all fresh groundwater uses in the United States in 1995, totaling 219.4 million cubic meters per day (USGS, 1998). Expenditures for water conservation, which may raise costs per unit of water used, can reduce total costs of water use and the amount of water used. Such expenditures on water conserving technology to reduce demand by industry may defer government action to use a tax on volume of water used through increasing its price to the user. On the other hand, it may be necessary to raise the price of groundwater if it is being depleted. Rising prices may be an inducement to conserve groundwater. Significant community water conservation practices are being employed in the United States in some groundwater-supplied municipalities, such as San Antonio, Texas; Albuqueque, New Mexico; and Tucson, Arizona.

Beyond water conservation, "green" management techniques conducive to groundwater supply are being widely recognized and researched. These techniques include low-impact development that reduces overland runoff, storm water management, permeable and porous pavement use, bioretention areas, artificial recharge of aquifers, and water reuse. Large commercial and industrial water users that introduce water conservation in groundwater depletion areas as well as providing aquifer replenishment may be viewed as "good neighbors" and "green business" with the possibility of attracting positive consumer attention to their products with a potential beneficial financial result for the company, while internalizing the cost of maintaining the natural capital of groundwater. Water conservation and "green" management of groundwater may be more cost effective than expenditures for new water sources. Water newly conserved and water recently reused serve as additional sources of water supply that may mitigate the need to search for other water sources.

TRADE

Trade across nations and among nations involves decisions affecting the natural capital of the producing areas. Trade decisions are seldom made in the context of evaluating long-term resource allocation projected to be experienced by the producers locally. State and national laws that are narrowly focused on facilitating agricultural production, for example, without fully examining the groundwater and other natural resource effects, may benefit financiers with short-term gain while ignoring the viability of such production on the long-term local and national economy. The North American Free Trade Agreement, while attempting to level environmental standards in production across participating countries, still ignores natural capital allocation decisions and the transfer of natural capital from one country to another in the form of water-reliant, higher-value products whose prices do not reflect replenishment of that capital for the producing country.

INFORMATION AIDS COMMUNITIES IN VALUING GROUNDWATER

Human communities generally operate through legal or political jurisdictions as they affect groundwater. Even if groundwater value cannot be monetized fully in all transactions of significance, communities' policies can recognize this value. First, certain activities can be forbidden, such as

EXHIBIT 16.3 INFORMING COMMUNITIES ABOUT THE VALUE OF GROUNDWATER

The Groundwater Foundation is an international organization with a mission of educating and motivating people to care for and about groundwater. It was founded on the principle that education is a powerful motivator for change and that factually informed people who understand the value and vulnerability of groundwater will act responsibly and responsively on its behalf. A central tenet to this organization is the belief that groundwater education for people is central to its work and that its customers are diverse, including everyone who consumes groundwater or benefits from its bounty. The Groundwater Foundation focuses on education for action: understanding that pollution prevention is the most effective, cost-efficient way to protect groundwater. The Foundation, a nonprofit organization, works with communities to provide a "Framework for Local Action," based on the concept that the real work of groundwater education and protection takes place on the local level. The beginning of local groundwater education and protection efforts through the Groundwater Foundation is establishing a strong local team and a clear framework for action to facilitate communities being successful from the beginning of their initiative.

The Groundwater Foundation has assisted 157 communities in North America in establishing groundwater education and protection efforts. These communities learn from each other through the networking opportunities provided through the Foundation. The Foundation also recognizes communities each year for their work in educating the public on groundwater protection. Communities that meet the Foundation's criteria of (1) forming a local team of individuals, organizations, and agencies, (2) submitting an application and plan of action, and (3) taking action to educate and protect groundwater, are designated as "groundwater guardians." Their progress and successes are posted on the Groundwater Foundation's website at www.groundwater.org/Active/gg_list.asp.

Source: Groundwater Foundation, http://www.groundwater.org/au/au.html (accessed January 30, 2004).

in arid locations, watering lawns may become illegal, at least during certain seasons. Likewise, a significant list of activities might be recognized at the community level to incorporate the value of groundwater into its decisions: requiring the use of water-efficient practices and equipment, progressive user charges for ever larger volumes of groundwater, taxes on potentially groundwater-polluting activities and impermeable surfaces, and state recognition of multicommunity cooperation in groundwater withdrawal and management of residuals. These institutional realignments will effect the inclusion of community economic value for groundwater in local decisions, thereby promoting the sustainability of the resource.

Communities may be effective in providing information to consumers about their groundwater. This information assists water users in valuing groundwater and making choices that affect the quantity and quality of their groundwater. An example of such an organization at the international level that mobilizes interested individuals in communities to obtain information and organize programs to inform other individuals and businesses as well as their jurisdictions about groundwater is given in Exhibit 16.3.

AQUIFERS AND WATERSHEDS—APPROPRIATE MANAGEMENT UNITS

AQUIFER AND WATERSHED PLANNING

National, state, and area-wide jurisdictions are appropriate societal levels to promote comprehensive assessments of groundwater use at the aquifer and watershed levels. In 1978, the United States completed a comprehensive inventory and projection of ground and surface water use by a major river basin. However, no comparable effort has occurred since, with the U.S. Water Resources Council being disbanded. Ground and surface water are under greater stress now and national leadership could facilitate more concerted planning beyond inventorying and projecting uses and pollution potentials. The USGS is conducting a comprehensive assessment of water quality in selected river basins, which could be used as the basis for greater planning to avoid distortions in the allocation of groundwater and surface water that future generations may face.

Most people live above an aquifer in a watershed somewhere on the earth's surface that likely has groundwater in use for economic purposes, whether for water supply or as a wastewater or pollutant release sink, or both. Aquifer and watershed size may be an important factor for groundwater management. Aquifers can be small subsurface lenses of groundwater underlying several hectares or enormous areas of tens of thousands of square kilometers, such as the Great Artesian Basin in Australia, which has an areal extent of 1.7 million square kilometers. Some watersheds may likewise be a few hectares. Including multiple smaller watersheds together in a larger watershed can result in a hydrologic unit the size of the Amazon River basin, 7,000,000 km^2, draining ground and surface water from four-tenths of the South American continent (World Commission on Dams, 2000). The challenge in aquifers and watersheds is to recognize the natural hydrologic and anthropogenic relationships and significant factors affecting the potential for and cost of use and incorporate them into the value of water, and then set policies for and price water accordingly. However, we do not perfectly know these relationships or the way to monetize them accurately for input to decision making. More research is needed to guide the use of our aquifers and watersheds and to appropriately value their role in the ecosystem and economy and in setting appropriate policies.

Aquifer–Watershed "Footprint" as Basis for Use

In many countries, the water balance of aquifers and watersheds has been developed. This represents a "footprint" for that aquifer or watershed. This footprint is one measure of the critical natural capital for the future inhabitants using the aquifer underlying that watershed, their starting point. As suggested in Chapter 14, one of the means to sustainability of the resource when being depleted is to manage it to balance recharge and consumption.

At the aquifer level in a watershed, with information about water use and development, people can begin understanding the extent to which they can pump the aquifer and still have a high-quality water supply for their children and grandchildren. Regional agencies can begin posing questions in public forum and in the media on people's views about using up groundwater today or maintaining its capacity for tomorrow and the future. This is critical feedback. To set policy on pricing and standards for use for an aquifer under stress, decision makers need to know whether or not a nearly depleted, unreliable water supply of lesser quality is acceptable to the inhabitants of the watershed using the aquifer. Once they understand the public's common shared interest, they can identify alternatives and set practices that are more likely to use the water sustainably and efficiently.

Accounting Area of Interest

The aquifer and watershed levels may also be the most productive and protective accounting unit to consider the values of groundwater and their relationship to the principles of natural science. Groundwater can flow in all directions, up, down, and laterally, as well as long distances, and at a range of travel rates, depending on the geologic matrix. These interactions should be accounted for at a level that integrates natural and user effects and costs and benefits of those effects. First, groundwater interacts with surface water in the watershed, which is really the cycling of water as it flows back and forth through different media and conveyances in the watershed. Hydraulic gradients may actually make groundwater flow "uphill," as demonstrated by artesian springs where groundwater appears at the ground surface, as an example. Second, groundwater interactions with other watersheds at the aquifer level must also be considered by communities proposing to develop aquifers, or use them for disposal. Aquifers interconnect adjacent watersheds, similar to, but not equivalent to, smaller streams being tributaries to larger streams.

EXHIBIT 16.4 REPLENISHMENT TIME OF MAJOR AQUIFERS

Aquifer	Location	Replenishment Time (Years)
Nubian Sandstone	Africa	75,000
North Sahara	Africa	70,000
Great Artesian Basin	Australia	20,000
Guarani	South America	3,000
High Plains (Ogallala)	North America	2,000
North China Plain	Asia	300

Source: UNESCO, *Water for People, Water for Life*, The United Nations World Water Development Report, 2003, Table 4.3, p. 79.

Aquifers are also interconnected vertically and wells may increase the connection if not properly installed. A critical point here is that once an ecosystem, especially one dependent on groundwater, is damaged, thrown out of balance by excessive pumping or residual disposal, repair may be too late and costly. Because of the interconnectedness of groundwater and its relation to surface water, the accounting area for groundwater that might be evaluated should be assembled comprehensively yet practically because of these interactions.

Time is also a factor in and reason for accounting to occur at the appropriate level. Natural assimilation of contaminants without treatment may take up to thousands of years. This is the case with the aquifers being exploited and depleted around the world, as indicated in Exhibit 16.4. Also, if a waste release to groundwater includes radiation residuals, tens of thousands of years may be required to degrade it (Bullen et al., 2000). Thus, the flow and vulnerability of groundwater indicate that it should be viewed as a common property resource that flows from place to place, not to be captured or controlled totally by any one property owner or jurisdiction, reinforcing the aquifer and watershed as the minimum unit, and perhaps in most cases the sole unit, for which groundwater should reasonably be managed. Evaluating the economics of groundwater at the aquifer and watershed levels should then be thought of as a standard of best practice in resource, environmental, and ecological economics.

ECONOMIC EVALUATION

Evaluating economic efficiency in allocating scarce resources for objectives in market and nonmarket settings is not necessarily done at an aquifer or watershed level, but could and should be done at that scale to incorporate a fuller perspective relative to costs, benefits, interactions, and information flow. Such an evaluation would provide decision makers useful information in the context of planning and management. This circumstance may be even true when comparing aquifers underlying watersheds in different places, for example, one in an arid environment near one in a more humid zone. An accounting of this type might also incorporate other information on important inputs (such as extent of development, impermeable surfaces, and changing conditions) and could be done through various kinds of electronic programming, such as linear programming with multiple objectives, inputs, and outputs. Economic efficiency analysis is typically monetized, but could be conducted for other types of trading units, “footprints,” such as water units or pollutant loading. These types of alternative efficiency evaluations might make the greatest sense in the context of aquifer and watershed management for groundwater and surface water and their conjunctive use in sustainable ways.

DISTRIBUTION OF THE RESOURCE TO ALL WHO RELY ON IT

INTRAGENERATIONAL EQUITY AND DISTRIBUTION

Ensuring access and availability of clean, safe water for all residents is a responsibility of civil societies and their governments. Poor people need water as much as anyone. This responsibility should be considered in light of the concern for protecting groundwater from contamination in locations where it is vulnerable and once contaminated is irreversibly lost for use for all practical purposes in the lifetimes of those immediately affected whether of lower or higher income. Access and availability also need to be carefully evaluated in situations where water in the ground may be treated as an exclusively owned property that can be traded and not available to others for use. Equity in water access and availability is recognized internationally as a factor in managing water sustainably (WCED, 1987).

SUSTENANCE DURING DROUGHT

Drought conditions may necessitate extreme measures to counter its effects on people depending on their severity and duration. Groundwater is often considered to smooth out supply when surface water is in drought, and thus may be the immediate backstop source. Many water systems that rely on surface water have back up wells, some of which are for peak demand times. Use of groundwater in arid areas or dry periods may be critical to maintaining agricultural production for food for all people, especially those least able to afford it. Additionally, existing infrastructure for residences and commercial purposes are not designed for drought conditions and their extreme measures. Yet larger structures will require more water based on their construction. Should owners of larger structures be able to obtain and use more water than people who do not own property or who rent smaller structures during severe drought? Should basic necessity drive water use during such times? Climate change may prompt debate on equity relative to food supply as well as basic needs and future construction standards that address sustenance of the entire population for a stable economy in a condition of drought.

INTERGENERATIONAL CONSIDERATIONS

Another implication of Exhibit 16.4 is the intergenerational aspect of groundwater use and management at an aquifer level that economic analyses have begun to focus on over the last 50 years. Depletion of one of these aquifers means that future generations would have to find alternative sources of water. In situations in which aquifers are being depleted locally, this condition may require decades or centuries to recover even if conservation measures are implemented, thereby transferring costs of depletion to future users. Thus, the costs of inefficient current users who benefit now from lower expenditures for groundwater supply may multiply and magnify to future water users in succeeding generations, particularly as populations grow.

EFFICIENT ALLOCATION OF THE RESOURCE

EFFICIENT RESOURCE ALLOCATION FOLLOWS NATURAL CAPITAL DECISIONS

Recognizing the essential priority for maintaining sustainable groundwater and establishing goals and objectives for the resource, the implementation of efficient allocation should ensure production with minimal waste or loss of natural capital. Pricing should reflect marginal costs of production, including replenishment of the resource where depletion or irreversible loss from degradation occurs. Benefits of projects and programs should exceed costs. Benefits include quantifiable, monetizable gains in societal welfare. Costs should include all quantifiable, monetizable marginal costs of impacts on human health and ecosystem services. Nonmonetizable and unquantifiable benefits and costs should be explicitly identified to ensure valuing in political and community processes.

ALTERNATIVE WATER SOURCES AND TREATMENTS

At the watershed level, water supply for many different purposes can come from alternative sources. The supply costs should reflect the most efficient processes available. These sources may include groundwater, streams and lakes, and catchment of precipitation. Each of these sources has a benefit—usually derived from the objective of using the groundwater or subsurface for a particular or set of services—and a cost associated with it to store, produce, treat, and distribute the water. The least-cost alternative of production, if only considering obvious monetizable factors, may not consider secondary costs—such as creating dry streams or wetlands, land subsidence, or disposal of wastes from treatment—that may offset the benefits of its use and should be considered in the water price. The challenge at the aquifer and watershed level is to evaluate the costs of production and benefits of services of alternative sources of ground, surface, and atmospheric water to determine which are the most efficient ones after all the impacts are considered. Multiple communities of people, as well as communities of wildlife—flora and fauna—will be affected. The determination of the least-cost alternative to supply, treat, or protect groundwater is consistent with opportunity cost pricing in neoclassical economics and promotes efficiency in the economy. Marginal analysis of alternatives to achieve a common objective is fundamental to economic evaluation of efficiency.

OVERALL RESOURCE PROTECTION AND ALLOCATION THROUGH PRICING MECHANISMS AND TAX POLICY

Since groundwater clearly moves from place to place and can cross state and national boundaries, the national level is an appropriate jurisdiction to address distortions in allocating groundwater in the economy through pricing and tax policy. This can be done through establishing standards for its production, use, and maintenance. Additionally, taxes and charges can be levied to promote a more efficient use of the resource as a production factor and contributor to lifestyle, such as in lawn watering, and to minimize the harmful effects of using the subsurface as a sink for pollutants, passing costs of pollution back to the polluters and the consumers of their products. Communities are an appropriate level to manage local groundwater allocation through pricing. Taxes or surcharges on excessive use can provide price signals to users to influence their water use, such as through

FIGURE 16.1 Historic water tower storing groundwater for Cape May, New Jersey.

increasing block rates utilized by about 22% of community water systems in the United States for residential customers (Biswas and Tortajada, 2005, p. 45).

National, state, and local tax policies can influence the use of groundwater and the subsurface environment as both a water source and a disposal zone. Taxes that account for getting closer to the true cost of utilizing groundwater and the subsurface will motivate the private and the public sectors to be more responsible and responsive in their resource and residuals management decisions. Such use taxes or charges will assist in avoiding economic distortions resulting from the associated imperfections in the market for natural resources. Certainly, groundwater depletion allowances should be reversed as they further exacerbate market imperfections and give the wrong economic signals to groundwater consumers. Tax policy can also reward individuals and companies for actions that maintain groundwater for future use and protect its quality. Environmental tax credits can be a strong incentive for business (Sullivan, 1992, p. 13).

FULL COST PRICING

In the United States, state regulatory agencies play a role in pricing groundwater for public supply by privately (or investor-) owned companies. The concern that the water utility commissions address is that of a private utility charging a price that is too high in a monopolized market. However, private companies that cannot rely on government subsidies, taxpayer support, or lower borrowing rates must charge the full cost of producing and supplying the water. These state regulatory agencies establish a price for water consumers on the basis of economic research and public input. Typically, prices set may not include the marginal cost of depletion addressed through a scarcity rent or any other environmental charge, such as for aquifer replenishment. The full cost may be considerably higher when accounting for ecosystem effects. From an ecological economics perspective considering "just distribution" of resources, full cost pricing should include a social cost component to support water supply to meet the fundamental needs of those people least able to afford paying for water. The challenge with groundwater is that it is usually a locally-supplied product, and local political pressure has proved strong enough to keep prices low reflecting only the cost to produce it, undervaluing the resource and promoting its misallocation.

ECONOMIC EFFECTS BEYOND POINTS OF USE

Because groundwater can flow from community to community, by way of the subsurface, or being transformed to surface water, communities within watersheds and even in adjacent watersheds can be affected by decisions made outside their boundaries (e.g., McCabe et al., 1997; Glennon, 2002). Communities should approach their economic evaluations of proposed activities and projects by considering the benefits to them and their neighbors as well as the costs. Furthermore, extending the concept of community economics more broadly to include wildlife in coincident and adjacent areas, human decisions to pump groundwater may eliminate habitat that support wildlife on which adjacent human populations depend for their livelihood (Glennon, 2002). Thus, the economics of groundwater management should not be thought of as solely local, since community decisions in a watershed affect resources shared with other jurisdictions, even though historically this may not have been or seemed so. These effects are marginal costs to be considered in full cost pricing. Exhibit 16.5 provides a more detailed perspective and examples on this consideration for aquifers around the United States.

PROPERTY TRANSFER SITE ASSESSMENTS

Site assessments in property transactions are a standard business practice. The New Jersey Environmental Cleanup and Responsibility Act (ECRA) (N.J. Rev. Stat. §§ 13:1K-6 *et seq*) is one of the first and probably the most comprehensive of state laws influencing consideration of environmental factors in property transactions. This law creates on the part of the seller of an industrial facility that in any way generates or handles hazardous materials, a requirement to inform the purchaser and the state of environmental risks connected with the real estate and

EXHIBIT 16.5 EXTENDED EFFECTS OF GROUNDWATER USE

The effects of groundwater use can extend well beyond the property on which pumping occurs and certainly beyond political jurisdictions. Glennon has documented some effects that hydrologists and engineers did not predict, including adverse ecological and economic ramifications from uncontrolled pumping in a range of locations around the United States.

Watershed/Aquifer	Location	Pumping Entity	Effects	Legal Factors
Mecan River/Mecan Springs	South-central Wisconsin	(Proposal by) Perrier (Nestle Waters North America, Inc.)	(Projected) Loss of discharge that maintains trout habitat	State "reasonable groundwater use" law did not include pumping effects on streams
Ogallala Aquifer	Central United States	Farmers and ranchers	Water table declines up to 45 m; poorer quality deep water produced; pumping costs increased; land subsidence; reduced property values	Pumping doctrine based on old concepts of groundwater movement "unknowable" and of vast, unlimited supply; pumping law has limited control for adjacent effects
Santa Cruz River	Tucson Valley, Arizona	Farmers, ranchers, municipalities	Water table decline of 60 m; Santa Cruz dried up from lack of groundwater discharge; loss of wildlife habitat; land subsidence; loss of native culture	Laws did not recognize hydrologic cycle
San Pedro River	Southeastern Arizona	Farmers, suburban development, municipalities	Pumping reduced river flow; water table decline; endangered species threatened; local economic plan forestalled; wildlife habitat lost	Local subdivision laws allow uncontrolled well installation and pumping; federal water right challenged; international border issues for water flow
Tampa Bay area	Florida Central Gulf Coast	Municipalities	Pumping caused decline of groundwater levels; saltwater intrusion; lakes and wetlands dried up; loss of fish and wildlife; land subsidence and sink hole creation; property value decline	Legal and institutional factors did not recognize ground and surface water connection
San Antonio River	Central Texas	Ranchers, land and water developers	Pumping caused decline of groundwater levels; San Antonio River dried up; habitat of five endangered or threatened species reduced	Texas law allowed unlimited groundwater pumping
Ipswich River Basin	Northeastern Massachusetts	Individual property owners, municipalities	Pumping caused decline of groundwater levels; Ipswich River dried up; habitat for fish and wildlife lost; wetlands lost	Local building codes allowed development that reduced natural recharge to aquifer; water rate structure encouraged large volume use at lower rates

EXHIBIT 16.5 (continued) EXTENDED EFFECTS OF GROUNDWATER USE

Watershed/Aquifer	Location	Pumping Entity	Effects	Legal Factors
Cosumnes River	North-central California	Farmers	Pumping caused decline of groundwater levels and loss of discharge to river; loss of Chinook salmon and other wildlife; loss of wildlife habitat	State law allowed uncontrolled groundwater pumping by irrigators and land development
Penobscot River	Eastern Maine	Blueberry farmers	Groundwater use only when needed, rather than irrigating with river water, may allow important stream flow for endangered Atlantic salmon	State law and water institutions did not account for hydrologic cycle and interactive effects of streams, groundwater, and aquatic species
Straight River	North-central Minnesota	Potato farmers	Pumping caused decline in groundwater levels and loss of discharge to river; reduced river flow affects temperature and chemistry of river habitat for fish (especially brown trout)	State law and water institutions did not account for hydrologic cycle and interactive effects of streams, groundwater, and aquatic species
Moenkopi Wash (tributary to Little Colorado River)	Northeastern Arizona	Coal producer for coal slurry pipeline	Pumping caused decline in groundwater levels and loss of discharge to stream; Moenkopi Wash flows intermittently; local springs dry; drinking water supply diminished; native culture adversely affected	Arizona law allowed unlimited groundwater pumping
Humboldt River Basin	Northern Nevada	Mining company to dewater open pit mines	Pumping caused decline in groundwater levels and loss of discharge to stream; reduced flow threatens fish species; springs dried up; native culture affected	Nevada water law does not restrict pumping for mine dewatering
Appalachicola-Chattahoochee-Flint River Basin	Florida, Alabama, and Georgia	Farmers	Pumping caused decline in groundwater levels and loss of discharge to stream; reduced flow threatens oysters and aquatic life in Appalachicola Bay	State groundwater law grandfathers past wells and not controlling total water production

Source: Glennon, R., *Water Follies*: *Groundwater Pumping and the Fate of America's Fresh Waters*, Island Press, Washington, DC, 2002, 314.

then to correct the hazard. A criticism of this and similar laws is that they create additional cost and delays in routine property transfers, increasing transaction costs in situations that may not warrant such a process (Sullivan, 1992, pp. 81–92). In other states without such laws, the effect of the New Jersey law is still felt, being exercised through similar practices that the financing companies have incorporated into their lending processes for their own financial protection. Site assessments are the price of responsible action toward neighbors and communities. They help ensure that the full costs of appropriate management of properties that respects the rights and needs of adjacent and future owners are incorporated in the price of the land.

Level Playing Field

Because groundwater is typically controlled at state levels in the United States, policies related to its use are not the same from state to state or region to region. This circumstance causes distortion in the allocation of groundwater resources in the national economy. Where interstate commerce is clearly affected, such as in the potential or actual generation, transport, and disposal of hazardous wastes, the federal government has established laws and policies to provide a "level playing field" for companies engaged in activities involved in these wastes.* The European Union takes a similar policy approach with its member countries. Leveling the policy field on groundwater value might mean eliminating subsidies for groundwater use, such as depletion allowances, and for crops relying on groundwater for irrigation. This "level field" aspect of tax policy, if not affected by special interests, would help in ensuring that no one place "sells out" its groundwater or becomes the "least-cost disposal" site for waste. Policies for returning groundwater to its location of use would take into account its value in the ecosystem, rather than hastening its flow to streams and oceans, thereby promoting ecological balance and reducing adverse results of depletion.

Residuals Management

Water treatment and waste disposal will generate by-products necessitating a release and storage, often in the subsurface of a watershed. Since waste and residuals disposal typically involves chemical, biological, or radiological constituents that are not wanted or cannot be controlled easily once released to the subsurface, such as nutrient fertilizers and pesticides, evaluation of costs and benefits at the watershed/aquifer level embraces the level of interaction among all users of a watershed's hydrogeologic environment. Considerations also include the environmental effects and cost effectiveness of which type of subsurface disposal method to use: percolation through the ground (a default alternative), subsurface placement at a secure landfill, or injection through a well. Some effects will not be capable of being monetized, or even quantified, and so must be depicted or described. As information becomes available to communities about the full range of subsurface uses, alternative water sources, and impact relationships of production and residual release, the management organizations participating in water decisions—governmental and nongovernmental—in a watershed can begin to influence the price of water and uses of the subsurface to more completely reflect its value, and then compare its pricing to adjacent watersheds relative to competitive factors affecting its economy. This is in effect what the European Union has accomplished when a country is approved to join as a member—the European states agree to implement uniform groundwater protective practices so that no country attracts polluting activities that give it an advantage economically over others with lower costs for uncontrolled residual management. The United States has endeavored to mirror the European experience in groundwater protection from potential contaminating residuals through encouragement of wellhead protection in all states at public water systems using groundwater. These approaches usually draw on cost-effectiveness analysis as one input to select the protective steps to reduce risk to the resource.

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* In the United States, these laws include the Resource Conservation and Recovery Act, the Safe Drinking Water Act, and the Comprehensive Environmental Response, Compensation and Liability Act, among other policies.

RESIDUALS TRADING

The watershed level can serve as the appropriate focus for balancing not only water sources and uses, but also the treatment of multiple residual sources. Negotiation among owners and managers of water supplies may seem an obvious way to consider trade-offs. Not so obvious is the trading of pollutant residuals within a watershed. The possibility emerging is the trading of pollutant units or purchase of the results of treatment practices themselves, such as city water systems paying farmers in the uplands to reduce chemical residuals rather than having to construct and maintain expensive water treatment capability. Such a practice may promote economic efficiency in the watershed. Trading in residuals release for carbon dioxide may provide similar efficiencies for the disposal services of the subsurface for carbon dioxide in responding to climate change, providing increased recognition of the value of the subsurface environment's services.

BENEFITS ANALYSES

Benefits analyses at the watershed level afford groundwater and subsurface managers to consider not just the costs and adverse effects but also balance the costs of attaining objectives with positive outcomes throughout an area. Clearly, some of these benefits, such as protection of public health or maintenance of wildlife, may be difficult to monetize, but should be quantified where possible and at least described qualitatively. Multiple values for groundwater may not routinely be monetized; however, more attention is focused on this subject, such as for wetlands. Barbier (1991; cited in UNESCO, 2003) evaluated a tropical wetland for the agricultural, fuelwood, and fishery benefits of maintaining wetland in a natural condition to be US$32 per 1000 cubic meters of water required as compared with the irrigated crop value of US$0.15. Thus, comparison of benefits of a range of actions at a watershed level may be useful in assigning priorities to the appropriate response for prospective uses and users. More research on benefits is necessary to help inform decision makers facing complex issues of use and maintenance of natural capital in groundwater.

MEASURE EFFICIENCY DIFFERENTLY

Beyond the near-term changes in how current economic analyses may treat groundwater, global ecological stresses point to the need to account for efficiency in natural capital use differently, whether the resource being evaluated is groundwater or other ecosystem services. The measures may be in nonmonetary terms, but are still capable of being measured and tracked with current scientific capability. Ecosystem "footprints" offer one approach. For groundwater, a benchmark for most aquifers may be their safe yield from which changes in a nation's or locality's natural capital services can be calculated if the resource is adequately monitored. The "comprehensive efficiency identity" may be used to incorporate not only manmade capital and ecological services, but also the other component of the "triple bottom line," just distribution as well as sustainability of natural capability. Microeconomic and macroeconomic methodologies will continue to evolve for input to decisions on production, welfare, and functions of the larger economy. In the future, they will necessarily interact with measurements around benchmarks of ecosystem balances to allow feedback to and efficient adjustments in meeting resource needs of the economy. Refined efficiency measures will emerge as more research into this increasingly important field unfolds to support sustainable development.

ECOSYSTEM SIGNIFICANCE IN COMMUNITY VALUES

BALANCING ECOSYSTEM AND COMMUNITY VALUES

We all live in and rely on our communities, which in turn depend on the ecosystem for all of our fundamental resource needs, which we value in different ways. People live in communities for mutual support, typically including water supply. Wildlife live in communities for similar natural reasons defined by ecological circumstances. In most countries, water management agencies or districts exist for much of their areas, especially in intensive water use and urban settings. A community may be wholly within a watershed or reside across several watersheds. As water is withdrawn from or waste is disposed in the subsurface environment, the ecosystem works to balance itself, and we in turn must live with that balance whatever results.

Communities value groundwater based on their reliance on it. A community may be the agricultural land owners and producers of the 450,000 km^2 High Plains Aquifer System that includes all or a portion of eight U.S. states who have depended on irrigation waters from the aquifer for their livelihood. A groundwater community may also be a large metropolis relying on groundwater as its sole source of water and a fundamental infrastructure component of its economy, or a small village attempting to protect its groundwater supply from subsurface contamination by its own septic treatment system. Communities have been historical, social, and economic accounting units, since they often initiate projects for the betterment of the population within them, to the exclusion of others beyond their boundaries or jurisdiction. However, groundwater flows and balance in nature will be achieved, even if it means that effects occur in communities beyond their borders. We have mutual interest in maintaining ecosystem balance in our communities and with our neighbors to support their sustainability—and safe, ecologically vital water supply is fundamental to that balance.

MULTIPLE PATHWAYS TO VALUING GROUNDWATER

The first step in valuing groundwater is understanding its role in the ecosystem and as a factor in the economy locally and across the region or nation. At any level of jurisdiction, no one economic instrument or policy will be able to address the range of needs to recognize groundwater's value in these natural and societal processes. Maintaining natural capital, ensuring just distribution, and providing efficient allocation will require several pathways, whether they are standards of use, designation of rights, or market pricing, to accomplish what balance can be achieved in the ecosystem and the economy relative to groundwater. No one approach can accomplish multiple goals of resource use (Schiffler, 1998, p. 342). Each goal should have its own policy instrument to be effectively achieved (Daly and Farley, 2004, p. 360). The policy and the jurisdiction of the entity must fit the resource issue to be addressed (Daly and Farley, 2004, p. 363). To understand the ecosystem–community value relationship for groundwater, research is needed to better understand the ecological and other unrecognized purposes and services of groundwater and their significance to communities and to develop ways of valuing those services to allow their incorporation in decision making at all levels.

VALUE THROUGH ACTION IN THE COMMUNITY

At the same time, if people's need for groundwater is being affected by depletion of the resource from pumping or pollution (both ways of removing groundwater from use), a community's or nation's residents may influence that jurisdiction's policy on groundwater use. Citizens acting together can propose and encourage adoption of laws to conserve and protect groundwater for its best and essential uses, reflecting local preferences. Such action can encourage the evolution of a social value not monetized, but real in accomplishing awareness and affecting use that reflects the cultural and economic requirements of the community. Ideally, such a social value would reflect a full consideration of the services of groundwater for human and ecological purposes, including its relation to surface waters in the watershed and adjacent basins and to wildlife in its many and various forms. As well, this consideration would reflect examining alternative means to achieve community or national resource objectives. One person can make a difference in how a community values groundwater, as demonstrated in the founding of the Groundwater Foundation, which promotes community education and action for informed groundwater use and in introducing the European concept of wellhead protection into United States legislation and then into practice in communities around the United States ensuring a more complete value for maintaining the resource is recognized in our community action to use groundwater responsibly and sustainably.

Education about and action to protect any nation's groundwater resources comes at a price. It is the individuals who will decide whether the benefit is received for the price paid, based on their tastes and preferences. If economics assumes that rational people act in the market, rational people must be informed. Individuals collectively place substantial demand and stress on groundwater at the margin of their use of the resource without understanding the ecosystem implications and other third-party effects. Through the application of the disciplines of hydrology, engineering, economics, and other fields, we can improve our decisions affecting this precious and vital resource and our management of it through setting public objectives for its purposes and then allocating it accordingly through equity and pricing mechanisms. The application of economics to groundwater has often been about individuals and firms taking least financial cost approaches to using common groundwater resources for their own best interests—now we must use our political–economic tools to inform decisions to sustain the resource for the future of our communities in balance with the ecosystem on which we rely.

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Part VI

Case Studies

The case studies highlight aspects of some of the topics in the book from a more practical perspective to provide greater detail for consideration. The case studies cover

1. Production Well Costs and Benefits (Spain and Honduras)
2. Economics of Groundwater Depletion (Jordan)
3. Groundwater Remediation Economics (Illinois, United States)
4. Wellhead Protection Benefits and Costs (United States)
5. Economic Assessment of a National Regulation—Waste Disposal Wells (United States)
6. Contingent Valuation of Municipal Water Supply (Brazil)
7. Determining Water Rates (California, United States)
8. Groundwater Valuation in Rural Settings (United States)
9. Wetland Benefit Calculation (Nigeria)
10. Groundwater Sustainability to Balance Urban and Agricultural Needs (China)
11. Balancing Ecosystem, Water Use and Pricing (Texas, United States)

Case Study 1: Production Well Costs and Benefits

Fundamental to establishing costs and benefits for groundwater production is to determine the costs of installing and operating a well or wellfield. Typically, these data are not routinely published in the literature because of the site-specific nature of these figures and the competitive environment of the well installation industry. Even when documented, the information is often not comprehensive for a complete economic evaluation. However, several country-specific case studies are presented in Custodio and Gurguí (1989) representing costs for years (approximate) 1986–1987 for the countries of Spain, Mexico, Honduras, and Thailand. Two of these (Spain and Honduras) are summarized here to provide a perspective on accumulating and evaluating costs of wells and their production. All costs are expressed in $US1987.

Wells in Spain: Niñerola (1989, pp. 83–98) examined costs for wells in Spain in a range of hydrogeologic settings (therefore, the costs cited are not specific to a particular hydrogeologic setting). This case assumes that the costs of water from other sources, including other groundwater sources, have been evaluated. Factors to be considered in the location of a well to be used for drinking or irrigation water include geologic setting, the characteristics of the aquifer, amount of groundwater available, the demand for water, access to the wellfield for all purposes (well installation, development, testing, wellhead housing, and maintenance), depth from which water must be pumped, the distance that water must be transmitted for use, availability of power supplies, and the cost of energy to pump and transmit water. Use of existing data from other well installations is useful in estimating well location and design. Geologic setting as well as equipment availability will assist in determining the type of drilling used in well installation. Hydrogeologists will need to provide data from pump tests for aquifer yield and drawdown relationships and transmissivity of the aquifer to determine well depth and diameter, length of screen for water to enter the well, and pump size.

Once a well casing and screen are set and the appropriate fill and grout placed around the well, the well should be cleaned. Cleaning wells helps improve their hydraulic efficiency.

Supervision of well installation, cleaning, and testing ensure that the wells are properly developed from an investment standpoint and are useful for their productive life. Supervision costs for well construction of a well in Spain are estimated to be 5%–10% and for development and testing about 20% of total well costs.

Pump requirements are based on volume and depth of groundwater to be pumped and water quality (fine particles and corrosive properties of water will affect pump longevity). Pumps can be submerged in the well or located above ground.

After the well is ready for operation, costs will be incurred for maintenance of the well and its ongoing groundwater production. Distances of both vertical pumping and transmission will determine these costs. [Additionally, if the water needs to be treated to improve its quality for particular uses, these costs need to be included for delivery of the finished water product.]

One example from Niñerola provides perspective on these costs. The parameters of well construction cost Niñerola gives in a series of tables for different drilling techniques as applied in Spain at that time. This example highlighted here selects a particular well-installation type, depth and casing size. These parameters are

Well depth = 100 m
Casing internal diameter = 300 mm
Installation technique = reverse rotary drilling
100 m well cost = $78/m

Subsets of well cost:

- Well casing and screen for casing wall thickness of 6 mm and an internal diameter of 300 mm = $49/m.
- Slotted (intake) screen of similar dimensions to casing = $78/m.

The cost of a pump is affected by the required yield, depth to water, power, efficiency, piping and fittings, electrical cabling, and labor for installation. An example pump for the well described above had estimated costs based on the specifications below:

Yield = 5 L/s
Depth = 100 m
Power = 9 hp
Pump efficiency = 74%
Pump cost = $2400 ($US1987)
Pipes, valves, sensors, other fittings cost = $3000
Electric cables cost = $575
Installation of pump and accessories cost = $615
Total pump and installation cost = $5750

Niñerola reported significant economies of scale for well installation and pump costs. Comparing 100 m well with a 600 m well for reverse rotary drilling indicates a reduction of 74% in the per meter cost for a 300 mm diameter well, fully developed. Using a 339 hp pump in a 100 m well with a yield of 200 L/s compared with the example results in an 82% reduction in costs per liter/second, assuming the aquifer can provide sufficient volumes of water to the well.

Niñerola cites well-cleaning costs using compressed air treatment to reduce fine particles for wells in unconsolidated aquifers of $2,600 or more and hydrochloric acid treatment in limestone formations may cost up to $13,000 or more depending on well size. After well cleaning is done, pump tests should be run, costing $1300–4400 based on well depth and flow for the first 24 h and $85–115/h thereafter.

Wells in Honduras: Benton (1989, pp. 119–120) reports on well costs in Honduras and considers well depth, volume of groundwater produced, drawdown from pumping, total hydraulic head necessary for lifting the water out of the ground, and the energy used in pumping the groundwater to a level 10 m above the ground surface. Several wells were installed in San Pedro Sula, Honduras, in Central America, for which he provides cost information. Based on interpretation of well data from well number 7 Av, compo A-B, well-installation data were estimated for various well depths and diameters, as follows:

Well Number	Depth (m)	Flow (L/s)	Cost ($US)
7 Av (1)	100	70.0	68,000
7 Av (2)	60	66.6	40,800
7 Av (3)	44	51.4	29,920

For well 7 Av (2), a comparison of different diameters and flow-indicated energy requirements shown as

Well 7 Av (2) Diameters	Depth (m)	Cost ($US)	Flow L/s	Flow %	Drawdown (m)	Total Head (m)	Energy kW	Energy %
350 mm	60	40,800	50.77	130	66.6	80.5	127	167
300 mm	44	29,920	34.07	100	51.4	57.1	76	100
200 mm	60	28,560	50.77	30	15.2	80.5	29	38

Benton shows that both capital costs of installing the well and operating costs should be considered in deciding how to proceed with wellfield development. The cost of well 7 Av (2) with 350 mm casing, at $40,800, is $17,680 more than the combined installation cost of both the 300 and 200 mm casing wells, $58,480. The combined flow of the two wells (300 and 200 mm wells together) equals that of the single 350 mm well. However, when the pumping costs are included in the analysis, the result changed. The combined flow of the two adjacent wells is produced with 105 kW of energy, whereas the 350 mm well requires 127 kW for the same product. Benton assumed an energy price of $4.00 per 100 kilowatt-hour (kWh) and no inflation and no time value of money. Annually, the savings of 22 kW less energy resulted in a corresponding savings of $7709 (mathematically: 22 kW × 24 h × 365 days × $4.00÷ 100 kWh = $7,709). After *approximately* 2.3 years, the cost of the two wells with lower energy costs breaks even with the single larger 350 mm well and its energy costs. Thereafter, the combined production costs (considering energy operation costs only) give a continuing a savings into the future. The breakeven calculations are

Combined 300 and 200 mm wells capital and energy cost

Capital cost:
300 mm well = $29,920
200 mm well = $28,560
Total = $58,480

Annual energy cost:
300 mm well = 76 kW × 24 h/day × 365 days/year × $4.00 ÷ 100 kWh = $26,630
200 mm well = 29 kW × 24 h/day × 365 days/year × $4.00 ÷ 100 kWh = $10,162
Total = $36,792

Capital and energy cost after 2.3 years = $58,480 + (2.3 × $36,792) = $143,102

Single larger 350 mm well capital and energy cost

Capital cost:
350 mm well = $40,800

Annual energy cost:
350 mm well = 127 kW × 24 h/day × 365 days/year × $4.00 ÷ 100 kWh = $44,501

Capital and energy cost after 2.3 years = $40,800 + (2.3 × $44,501) = $143,152

Note that the difference in capital and energy cost is within $50 after 2.3 years and the annual savings from reduced electrical need of the combined use of the 300 and 200 mm wells is $7709 thereafter.

Benefits: Benefits were not considered in either of these examples specifically; however, Niñerola (p. 84) clearly indicates that the benefits of groundwater exploitation should be compared with the costs of wellfield development. The benefits in their simplest form may be evaluated as the production of the wellfield multiplied by the price charged to customers for the water. Price would have incorporated amortized capital costs, including any treatment that might need to be added to achieve certain water quality standards for consumption, operation, and maintenance costs, depreciation of capital, taxes, and fees for consumption or depletion of the aquifer, transmission and distribution charges, and an economic return to the owner of the wells and treatment system. At a macroeconomic level of the community or state, regional economic multipliers could be applied to estimate number of jobs and monetary effects throughout the economy using various economic modeling techniques beyond the scope of this text.

Discussion: These examinations of well costs are narrowly focused to allow simplified consideration of more specific installation and obvious, but limited, operation costs for comparison purposes. Clearly, other costs could have been evaluated if the data were available. The ready availability may be a constraint on analyses. However, today, we have access to much more data on a range of costs not previously accessible. Also, as time goes on, research is done on costs of items not previously examined, such as costs to adjacent land owners or for loss of stream wildlife because well drawdown pulls water from nearby streams causing them to have reduced flow or even dry up. These ecological costs are real but have not yet been priced in the market.

Other aspects of cost of operation and maintenance of these wells could have included uncertainty and time value of money. For example, other operating and maintenance costs could be considered and these would change the analysis. These other costs may include wellhead maintenance, casing repair or replacement, pump repair or replacement, and frequency of well cleaning. Sensitivity to these costs in a particular hydrogeologic setting may be significant. Additionally, sensitivity analysis of energy prices could have been done if uncertainty in the power supply market for future foreseeable costs of energy. For example, if energy costs were 50% higher ($6.00/kWh), the breakeven point would have been at 1.5 years, with continuing savings of $11,562/year. If the probability of this occurring was estimated to be a 25% likelihood, then the difference between the annual savings ($3853) multiplied by the probability expressed as a decimal (0.25) would equal the expected savings ($963) for purposes of other analyses, such as discounted cash flow evaluation. Discounting future costs would also reduce the impact of future operation and maintenance costs for net present value of the projects.

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Case Study 2: Economics of Groundwater Depletion

BACKGROUND

The country of Jordan relies on both surface water and groundwater as sources of water supply and is now depleting its aquifers. Jordan with an area of 89,200 km^2 is one of the most water-scarce countries in the world (SPG, 2004). Its estimated 4 million people receive average annual renewable water from precipitation of only 240 m^3/person, but only 200 m^3/person/year that is usable (p. 181), 35% that of neighboring Syria and Israel (SPG, 2004). Documented water use in 1991 was 835 million cubic meters (MCM) per year of which 73% was agricultural, 22% municipal, and 5% industrial (p. 189). This total use exceeded the estimated renewable water of 793 MCM/year by 42 MCM/year (pp. 188–189). Because of variability in supply and insufficient ability to store large volumes of water, surface water sources are not utilized entirely. As of the early 1990s, the total groundwater stock of Jordan has been estimated to be between 19,320 and 24,580 MCM (p. 185). Groundwater sources are being depleted to address the water demand, particularly for irrigated agriculture. Schiffler notes that (p. 182):

> Groundwater in Jordan is both renewable and non-renewable. Renewable groundwater is found in the densely populated northwestern part of the country, where most of the rain falls. Non-renewable (fossil) groundwater is mainly found in the south of Jordan. The average renewable groundwater flow (safe yield) in Jordan is 275 MCM/year.

Schiffler carefully and thoroughly evaluates various groundwater depletion paths for a basin in Jordan, the Zarqa Basin in the northern part of the country, and whether water transfers between categories of water users could improve employment and development in the country. The evaluation also includes consideration of alternative sources, such as piping surface water, seawater desalinization, and "virtual water" from the import of grains and vegetables. The evaluation incorporates hydrologic, economic, social, and political factors. This summary will mainly focus on the economic aspects of situation.

ZARQA BASIN

The Zarqa Basin of 3750 km^2 (an additional 275 km^2 are in Syria) (p. 177) has Jordan's most significant population concentration, the Amman agglomeration (population of 2,743,400 in 2004 (World Gazeteer)), greatest groundwater recharge in the country, and extensive irrigated agriculture (p. 196). The stock of groundwater in the basin in 1990, mainly from limestone, dolomitic limestone, and sandstone strata (MEWDBP, 1994), was approximately 1700 MCM and pumping rates may deplete usable water by 2010 (p. 196). Irrigated agriculture is the largest use of water in the basin (p. 197). The average daily municipal water use (e.g., in Amman) is 85 L per person, less than 1/3 that of Israel and 1/12 of that of Arizona, United States (p. 190). Municipal water pipe loses over 50% of the water from leaks (SPG, 2004). Citing the Water Authority of Jordan, Schiffler (p. 197) shows the depletion of groundwater in 1995 in the Zarqa Basin as 76 MCM/year, resulting from a total use demand of 164 MCM/year that is only offset by recharge of 88 MCM/year. Of the total use demand, agriculture accounted for 90 MCM/year, municipal use for 62 MCM/year, and industrial use for 12 MCM/year.

This overdraft situation varies from place to place, given the differences in interconnection of the aquifers. Some springs in the basin have gone dry. In some areas, the water table has fallen more than 1 m/year (p. 200). Water quality is generally acceptable; however, some locations have experienced saline water intrusion (pp. 198, 200). Some wells were no longer in use because of salinity (pp. 198, 200). While some farming is done by families, large agricultural businesses have operated in the northeastern desert area, installing many deep wells.

Water source alternatives for the Zarqa Basin are not easily and readily available. The flow of the Zarqa River is principally maintained by municipal and industrial wastewater discharge, which is heavily degraded by pollution and insufficient to make up the groundwater overdraft if totally used (47 MCM/year). Pipelines that could carry water from other wellfields in other basins are underutilized but do not have the capacity to make up the overdraft (pp. 202–203). A pipeline to supply groundwater from the Disi Aquifer, the country's greatest underground water reserve (p. 223), has been proposed for many years. The Disi Aquifer, located 310 km south of Amman, consists of water-bearing limestone, dolomite, and sandstone layers interbedded with shale, clay, and gypsum (MEWDBP, 1994) and contains fossil water that would eventually be depleted by major groundwater withdrawal since it receives no recharge. The most recent estimate by the Jordan government is that if 150 MCM/year of groundwater were withdrawn, usable water would be depleted from the aquifer in 30 years, depending on the rate of pumping from the same aquifer in Saudi Arabia and the extent of migration of brackish water from overlying aquifers (p. 223).

Relative price comparisons of alternative water sources cited by Schiffler (except where noted differently) are given in Exhibit CS2.1 and provide further insight into water supply and demand.

Implied in some of these numbers reported in Exhibit CS2.2 is that water is underpriced in certain applications, particularly in agricultural and municipal uses.

Note: By 2004, a consortium of financing sources including the World Bank, the United States, Japan, Libya, and the European Union provided grants and loans to improve the efficiency of the Amman water distribution network, increase flow to Amman via the King Abdullah Canal, new wells and collector system in and pipeline from the Disi Aquifer to Amman to address short and intermediate term water needs (SPG, 2004).

ECONOMIC ANALYSIS

The economic analysis that Schiffler conducts employs four "depletion paths" for the Zarqa Basin and a hydroeconomic model to evaluate each path for comparison. Schiffler then evaluates the economics of transfers from irrigated agriculture to municipal and industrial use of groundwater. The approach is defined by a series of equations and a model that is implemented through a spreadsheet (not provided as a documented example in the text), which will be generally described here.

Equations: The equations used in the model provide the relationships among the groundwater system, the pumping of groundwater, and the water economy of the agricultural, municipal, and industrial sectors. The equations are shown here in that order:

A decline in the *groundwater table* is calculated as (p. 56)

$$\Delta H/\Delta t = (R - W - W_{\mathrm{n}})/(A * S)$$

EXHIBIT CS2.1 PRICES OF ALTERNATIVE WATER SOURCES IN JORDAN

Alternative	Cost per Unit
Truck delivered water	Jordanian dinar (JD) 2/m^3 (1996; p. 269) [equivalent to1996 US\$ 2.82/m^3 or US\$ 8.00/100 ft^3]; assumed 1998–2000 US\$ 3.00/m^3 (World Bank, 2004)[a] [equivalent to 2000]
Municipal water (Amman)	JD 0.5/m^3 (1992; average household rate); JD 0.6/m^3 (1992; highest increasing block rate); assumed approximate year 2000 US\$ 0.38/m^3, about 1/3 of total delivered cost (World Bank, 2004)
Irrigation water	1995 US\$ 0.025/m^3, about 1/2 of operation and maintenance costs of previous 10 years (World Bank, 2004)
Jordan/Yarmouk Rivers dams and pipeline (proposed/defunct)	JD 0.717/m^3 (1992) (wholesale cost)
(Southern) Disi Aquifer wellfield and pipeline (proposed)	JD 0.654/m^3 (1992) (wholesale cost)
Seawater desalinization with pipeline from Red Sea to Amman (evaluated by Schiffler, pp. 225–226)	JD 1.5/m^3 (1991) (wholesale cost)

[a] Exchange rates for the Jordanian dinar (JD) to the United States dollar (USD or \$) as of January 1 of each year are as follows:

Year	JD to	USD (\$)	Year	JD to	USD (\$)	Year	JD to	USD (\$)
1992	1	Not available	1996	1	1.41243	2000	1	1.41243
1993	1	Not available	1997	1	1.40944	2001	1	1.41243
1994	1	1.42146	1998	1	1.41143	2002	1	1.42086
1995	1	1.42857	1999	1	1.41044	2003	1	1.4184

Sources:

1. Schiffler, M., *The Economics of Groundwater Management in Arid Countries: Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, Portland, OR, 1998, 394.
2. World Bank, From Scarcity to Security: Averting a Water Crisis in the Middle East and North Africa, World Bank Group, Website URL: http://lnweb18.worldbank.org/mna/mena.nsf/0/, 2004.
3. The Currency Site, URL: http://www.oanda.com/convert/classic (accessed September 18, 2004).

where

A = area of the aquifer (km^2)
S = storage coefficient of the aquifer
R = natural recharge (million m^3, MCM)
W = withdrawal from the aquifer (million m^3, MCM)
W_n = natural discharge in springs (million m^3, MCM)
H = groundwater level (m)
S = ground level (m)

Pumping costs are calculated as (p. 58)

$$C_P = [(H * a)/e] * \text{EC} + (\text{RC} * H) + \text{PC}$$

where

C_P = pumping cost
H = groundwater level (m)
a = kilowatt-hours (kWh) required to raise one m^3 one meter (0.0027 kWh)
e = pumping efficiency (0.54 assumed)
EC = energy costs per kWh
RC = repair cost per meter of groundwater level depth
PC = groundwater production (abstraction) charge (if any)

The depletion paths described later are evaluated using the typical *net present value* equation (pp. 57–58):

$$\text{NPV} = \sum_{j=1}^{n} (\text{TVP}_j - C_j)\big/(1+i)^j + \cdots + (\text{TVP}_n - C_n)\big/(1+i)^n$$

where

NPV = net present value
TVP = total value product (value added) of all activities based on water use from a given groundwater stock, calculated by multiplying quantities by prices of different outputs
C = sum of costs including nonwater factor and variable labor costs, cost of capital and land, and opportunity cost of family labor
i = discount rate
j = the different time periods, 1 through n
n = the last time period
TVP – C = average water profit (or water rent)

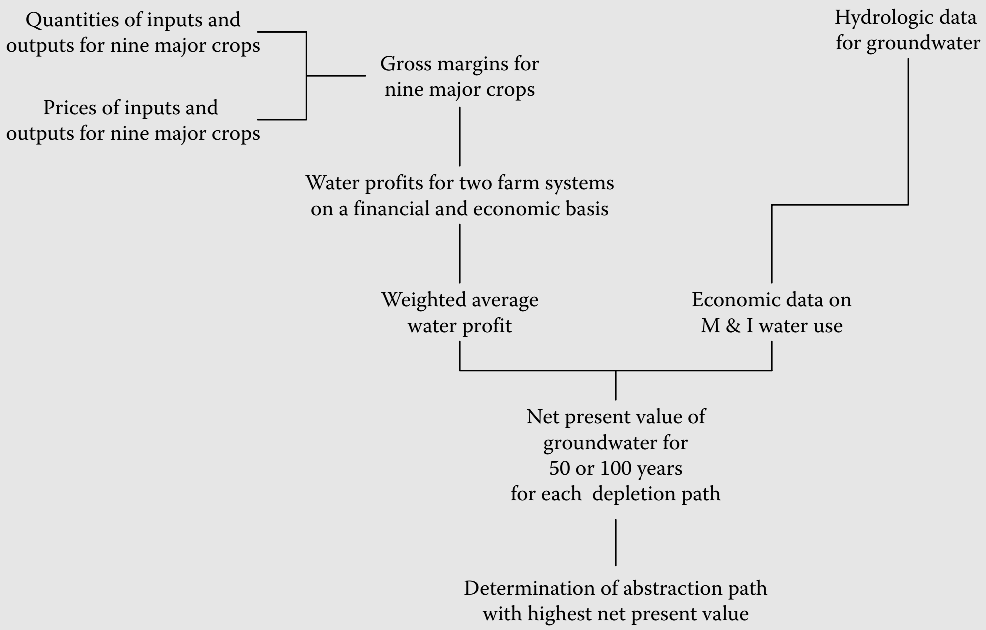
On inspection of the equations, it is evident that they are linked by common variables. The groundwater level, H, appears in both the groundwater table and pumping cost equations. Cost, C, appears in both the pumping cost and net present value equations. These calculations with data (presented by Schiffler in appendices in his book) are applied to four depletion paths described in Exhibit CS2.3 for either 50 or 100 years and evaluated through a "hydroeconomic" model.

Model: Schiffler's hydroeconomic model relates quantities and prices of inputs and outputs for nine major crops, water profits for two farm systems, and hydrologic data to abstraction paths and net present value (NPV) for the path with the highest NPV. The hydroeconomic model appears in Exhibit CS2.2.

Assumptions: Major assumptions used in modeling the net present value of the depletion paths are as follows:
General Assumptions

1. Other depletion paths are possible but not conducted (p. 232), considering the paths chosen to be extremes and intermediate conditions between the extremes.
2. A groundwater depletion rate greater than that of the then-current one (year 1994) is not viable (p. 232).
3. The "two farms" defined as a "fruit farm" and a "vegetable farm" are representative of agriculture in the Zarqa Basin (discussed below) (p. 231).

EXHIBIT CS2.2 HYDROECONOMIC MODEL FOR EVALUATING GROUNDWATER DEPLETION IN THE ZARQA BASIN, JORDAN



Source: Adapted from Schiffler, M., *Economics of Groundwater Management in Arid Countries; Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, Portland, OR, 1998, 59, Figure 6. With permission.

EXHIBIT CS2.3 GROUNDWATER DEPLETION PATHS

Schiffler (pp. 57, 232) describes the four depletion paths as follows to consider rate and management of depletion of the Zarqa Aquifer in his evaluation.

Path	General Description	Model Description
1. Uncontrolled depletion	Open-access aquifer; after depletion, groundwater withdrawal constrained to natural recharge	Withdrawal at high (then) current rates until exhausted, then limited to rate of natural recharge
2. Controlled depletion	Exclusive groundwater property rights; withdrawal reduced linearly over 20 years to safe yield and then constrained to natural recharge	Withdrawal is half of Path 1, doubling the time to exhaustion then limited to rate of natural recharge
3. No depletion	Withdrawal constrained to natural recharge	Withdrawal limited to rate of natural recharge and aquifer stays in equilibrium
4. Depletion in the distant future	Withdrawal constrained to safe yield, then depleted in remaining years	Future withdrawal constrained to recharge until the remaining 20 years at which time it is depleted for municipal and industrial purposes

Hydrologic Assumptions (pp. 233–236)

4. Average meteorological conditions will apply over the 50 or 100 year timeframes evaluated.
5. The model applies to all aquifers in the Zarqa Basin, even though many aquifers exist in the interbedded strata at varying depths.
6. The total stock of groundwater in the Zarqa Basin is 1700 MCM (p. 234).
7. Since extensive groundwater production can result in salinity concentrations sufficiently high to make the water unpotable and unuseful for irrigation, only 50% of the total stock is usable for irrigation and drinking.
8. The hydrogeologic matrix of the Zarqa Basin has a storage coefficient of 3%; the lower this coefficient, the greater the drop in the groundwater table for a specific volume of water produced.
9. The coefficient for return flow (water returning to the aquifer after use for irrigation) is zero since the use of drip irrigation is extensive in the basin and wastewater does not contribute substantially to groundwater recharge.
10. The groundwater table throughout the basin is below the level that would allow springs to flow because of groundwater mining.
11. For all depletion paths except 4, municipal and industrial use does not change; if decreases in groundwater consumption are modeled, they are from less agricultural water use.

Economic Assumptions (pp. 236–239)

12. Prices are for 1994.
13. If less water is available for irrigation, farmers base their water use on the crop to be planted and reduce their irrigable land area, thereby maintaining high-quality, marketable output.
14. Even though a unit of water applied to different crops may have a range of yields and resultant values (termed “water productivity,” i.e., JD/m^3/year), and because of fluctuations in crop prices, weather, pests, and demand factors, farmers will cultivate a range of crops, rather than eliminate the one with lowest value (reflecting water’s value at the margin) at a particular time. Therefore, marginal returns on crops are the same as average returns on crops.
15. Considering the range of energy costs for pumping, the average cost used is normalized to a unit volume of one cubic meter (m^3) over a vertical rise of 100 m. For diesel-fueled pumping, the average cost is JD 0.035/m^3/100 m. For electric pumps, the average pumping cost is JD 0.010/m^3/100 m. Energy costs include only operation, not capital or other sunk costs. (Pumping costs are based on Schiffler’s field survey in 1996.)

Evaluation Steps (p. 231): The evaluation steps reflect the model components as shown in Exhibit CS2.2:

1. Economic Assessment of “Water Productivity” Results (JD/m^3/year) for Irrigated Crops
   a. Determine the quantities of inputs and outputs
   b. Determine the prices of inputs and outputs
   c. Calculate values of inputs and outputs
   d. Calculate gross margins/m^3 of irrigation water for each crop

The nine *major crops evaluated* include: wheat, olives, grapes, apples, peaches, tomatoes, watermelon, greenhouse cucumber, and squash (pp. 383–385). The analysis assumes two “average” farms, one growing vegetables and the other fruits (p. 231).

Inputs to the model are: seed, fertilizer (manure, nitrogen, phosphate, potash, compound), chemicals, hired machinery (land preparation, sowing/planting, husbandry, harvesting), labor requirements (land preparation, sowing/planting, husbandry, harvesting), and water use. Tables in appendices to the book show quantities of inputs for a given amount of production (output) for each crop (pp. 383–385).

Economic and financial data and calculations in the model include: area planted, financial gross margin, effective rate of protection (considering shadow price of crop), economic gross margin, land rent, depreciation, interest, living allowance, financial profit, economic profit, water use, and fixed investment (well and pump; drip irrigation system; land preparation; water, labor, and fertilizer while fruit trees mature; and greenhouse for vegetables) (pp. 386–387). Financial water profit is calculated at market prices. Economic profit incorporates shadow prices of inputs and outputs (except for water), utilizing the effective rate of protection (considering adjustments to price set by other conventions, such as by the government through tariffs, price controls, subsidies, and other methods affecting a nation's trade (p. 45)) as it applies to some crops. Shadow prices for the outputs may be lower (or possibly higher depending on the factor or crop) than the market price.

2. Weighting Water Productivities of Fruits and Vegetables
   This step applies a weighting factor relating the significance (supply) of fruits and vegetables to market demand for them, 45% and 55%, respectively (an assumption), and then applies these percentages to the financial and economic water productivities by farm type (fruit or vegetable) to calculate average financial and economic productivities of water for these two farm types.
3. Hydrologic Data Specification
   - a Hydrologic data include: total stock, reserve stock, usable stock, total withdrawal, industrial withdrawal, municipal, agricultural withdrawal, natural recharge, storage coefficient, and area of the aquifer.
   - b. Economic data are: electricity tariff, water withdrawal charge, industrial water productivity, municipal willingness-to-pay, and annual rate of increase in water productivity.
4. Hydroeconomic Model Application to Each Depletion Path
   - a. Apply the hydrologic and economic data to the model for 50 years, including depth to groundwater table and calculation of change in stock of groundwater.
   - b. Incorporate pumping cost data to obtain net financial and economic water productivity and value-added results for the agricultural and industrial sectors, and municipal benefits.
   - c. Calculate the net present value of water produced and value of the groundwater stock for each depletion path at a range of discount rates (0%, 2%, 5%, and 10%).

The model is applied to the depletion paths as described and then to additional scenarios for a sensitivity analysis relating to water transfers between sectors and changes in shadow prices, with each scenario being evaluated for 50 and 100 years in JD. The scenarios (pp. 242–246) are as follows with the first number being for 50 years and the second for 100 years:

1 and 5—The original depletion paths: net present value (NPV) of the income stream from all uses

2 and 6—NPV of the income stream from all uses, no sectoral change, higher agricultural shadow price (real rate of increase in agricultural water productivity of 2%/year, municipal willingness-to-pay remains constant, assuming inexpensive new supplies equal new demand)

3 and 7—NPV of the income stream from all uses, sectoral change (transfers of water from agricultural to municipal/industrial use), higher municipal shadow price (assumed to be 3%–4%/year)

4 and 8—NPV of the income stream from all uses, sectoral change (transfers of water from agricultural to municipal/industrial use), higher agricultural shadow price

RESULTS

The results of the hydroeconomic model analysis of depletion of the Zarqa Basin aquifers are heavily dependent on the timing of groundwater use and the discount rate. Tables CS2.1 through CS2.3 (taken directly from Schiffler, 1998, pp. 240–242) present the net present value of groundwater use over 50 years for different aggregations of use. Table CS2.1 portrays outcomes over a range of discount rates and depletion paths for *agricultural* groundwater use only. Table CS2.2 gives the results of the model for *municipal* groundwater use only. Table CS2.3 combines these results in one table.

Table CS2.1 shows that when only evaluating agricultural irrigation, the largest use of groundwater in the Zarqa Basin, with no change in the shadow price, the preferred path considering monetary valuing of the outcome is Path 1, rapid depletion of the aquifer. In Path 1, substantial irrigated agricultural production occurs every year. In the condition with a zero discount rate (0%) that does not give time preference to the present over the future, rapid depletion is most favorable in terms of highest net present value. Path 3 (and 4) shows the result if irrigated agriculture relied solely on renewable water from recharge and would be expected to have a lower value, since less production results in every year. The average value of stored groundwater for agricultural purposes only (850 MCM) in the basin is 1991 JD 0.22/m^3.

Table CS2.2 presents the results for only the municipal and industrial use of groundwater in the Zarqa Basin. Municipal use is the second largest use, followed by industrial use (see Exhibit CS2.1 above).

TABLE CS2.1
Net Present Value of the Income Stream from Agricultural Groundwater Use over 50 Years (Millions of JD)

Abstraction Path/Discount Rate (%)	Path 1: Rapid Depletion	Path 2: Slow Depletion	Path 3: No Depletion	Path 4: Future Depletion	Path with Highest NPV
0	188	188	86	86	1
2	145	142	54	54	1
5	109	104	31	31	1
10	78	72	17	17	1

Source: Adapted from Schiffler, M., *Economics of Groundwater Management in Arid Countries; Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, Portland, OR, 1998, 240, Table 30. With permission.

TABLE CS2.2
Net Present Value of the Income Stream from Municipal Groundwater Use over 50 Years (Millions of JD)

Abstraction Path/ Discount Rate (%)	Paths 1–3	Path 4: Future Depletion	Path with Highest NPV
0	6474	8483	4
2	3904	4816	4
5	2145	2440	4
10	1093	1144	4

Source: Adapted from Schiffler, M., *Economics of Groundwater Management in Arid Countries; Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, Portland, OR, 1998, 241, Table 31. With permission.

The model for this table assumes in Path 4 a shift to municipal and industrial uses for the last 20 years of the 50 year horizon. In Paths 1–3, municipal and industrial use is held constant. In Path 4, municipal and industrial use is allowed to expand in the future in response to expected population increase and its associated demands. Path 4 also incorporates a growing scarcity of groundwater in the future and, therefore, its greater opportunity cost will cause the shadow price to increase. Clearly, Path 4 in Table CS2.3 has the larger net present value for groundwater reflecting the greater shadow price in municipal use of two or more times that of irrigated agriculture initially, increasing at about 2%/year and with municipal use ballooning to use all groundwater in the last 20 years. The model indicates that the average value of the groundwater then in storage was 1994 JD 1.35.

Table CS2.3 combines the results of Tables CS2.1 and CS2.2 to show the effect of agricultural and municipal use over the 50 years in the various paths and discount rates. This result suggests that in considering the combined competing demands on groundwater in the Zarqa Basin, depletion in the more distant future for higher value municipal use of the aquifers is economically preferable at lower discount rates to rapid depletion predominantly for high demand, lower value agriculture, as expressed in Path 1. Only at the 10% discount rate is irrigated agricultural use, extending current trends, more favorable, and then by less than 1% of the value over Path 4. This outcome at high discount rates results from the heavy discounting of higher future values in municipal use. Interestingly, Schiffler notes that "the value of total deposits at Jordanian banks was JD 2694 in 1994" (p. 242). Assuming that the Zarqa Basin held 850 MCM of usable groundwater stock in 1994 at a value at least between JD 1110 and JD 1170, the value of all groundwater stocks in Jordan was conservatively 9–12 times its bank deposit value, indicating the need for prudent stewardship of this resource (p. 242).

The sensitivity analysis reinforced the effects of timing and discount rates on the outcomes. The net present value of all the modeled quantities increased as the timeframe extended. Notably, the effect of extending the time of analysis out to 100 years was that Path 1, rapid depletion, was more propitious at a 5% discount rate in every scenario than the future depletion of Path 4. This follows because the high value municipal use is further in the future than before in the 50-year horizon and therefore discounted over a longer timeframe (p. 245).

Other significant conclusions include (pp. 246–248):

- High discount rates promote rapid depletion, whereas low discount rates favor depletion in the future.
- "The assumption of higher agricultural and lower municipal shadow prices of water decreases the NPV and makes more rapid depletion slightly more attractive" because prices for municipal water are greater than for agricultural water (p. 247).

TABLE CS2.3
Net Present Value of the Income Stream from All Groundwater Uses Over 50 Years [Scenario 1] (Millions of JD)

Abstraction Path/Discount Rate (%)	Path 1: Rapid Depletion	Path 2: Slow Depletion	Path 3: No Depletion	Path 4: Future Depletion	Path with Highest NPV
0	6662	6662	6500	8569	4
2	4049	4046	3958	4870	4
5	2254	2249	2176	2471	4
10	1171	1165	1110	1161	1

Source: Adapted from Schiffler, M., *Economics of Groundwater Management in Arid Countries; Theory, International Experience and a Case Study of Jordan*, Frank Cass Publishers, Portland, OR, 1998, 242, Table 32. With permission.

- Transfers of water from irrigated agriculture to municipal use raise the NPV, pointing marginally to a preference to forestalling depletion to a future time.
- Lengthening the period of evaluation even reduced the NPV of the future depletion path at rates for which it had a favorable result.
- If the real growth rate of 2%, realized in industrial economies, could be applied routinely for critical resource management in which the natural asset must be relied on by future generations, then in 3/4 of the scenarios modeled, depletion of groundwater in the future with higher value municipal uses expanding and even predominating is economically more desirable than rapid depletion (p. 248).

Schiffler concludes that "(s)low depletion (Path 2) and no depletion (Path 3) are never optimal in any of the circumstances analyzed …. For these reasons, it is advisable not to deplete groundwater stocks for present agricultural uses, but rather to conserve then for future M&I uses …" (p. 248).

DISCUSSION

The economic evaluation of Jordan's groundwater circumstances by Schiffler is thoroughly documented. Importantly, the analysis shows the close link between hydrologic assumptions and the economic results, indicating the essential need for multidisciplinary analysis of groundwater issues. The reader is encouraged to obtain it for detailed study. Prices used in the model are well developed tying them to economic theory. Schiffler also examines groundwater policy development and the prospects for alternative approaches in an economic context that also incorporates contributions from other relevant disciplines.

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Case Study 3: Groundwater Contaminant Remediation Economics

BACKGROUND

Remediation of contaminated hazardous waste sites is an environmental millstone, economic problem, a financial challenge, and an emotional nightmare to those who have to live on or near one. Clearly, the economic system did not incorporate proper waste processing in the cost of products manufactured and did not value the natural capital represented in environmental resources to ensure their appropriate use in accommodating wastes. Southeast Rockford, Illinois is one of those places. Action is taking place to remedy the condition of the area.

The Southeast Rockford Groundwater Contamination Superfund Project site encompasses about 7.8 km^2 in the city of Rockford in northern Illinois. It was placed on the U.S. National Priorities List of uncontrolled hazardous waste sites in 1989 because private wells and at least one municipal well were contaminated with chlorinated industrial solvents. Land use at the site comprises predominantly residential areas with a population of 52,000 within 1.6 km of it as well as smaller scattered industrial/commercial developments.

The site (also referred to as "Source Area 7") is a former unregulated disposal area evidently used for both household and industrial waste. Early aerial photographs of the site show evidence of waste disposal and excavation from 1959 to 1970. The area, located north of Balsam Lane in Rockford, now contains a field, wooded areas, and Ekberg Park. The depth of contamination varies from 1.2 m below ground surface to at least 8.8 m. The Illinois Environmental Protection Agency (IEPA) estimates that there are approximately 202,607 m^3 of highly contaminated soil beneath the ground surface.

IEPA soil borings show sands, silts, and clay to bedrock. Bedrock varies between 10.7 and 41.1 m below ground surface. The water table varies from 11 m below ground surface south of the park to 4 m in the park and 0.6 m near the creek. The groundwater flows to the northwest.

The soil is a continuing source of the contaminants to groundwater as precipitation percolates through the soil and mobilizes the contaminants for migration to the water table and saturated zone. Residential wells tested at the site had five solvents at elevated levels in their groundwater: trichloroethene (428 parts per billion, ppb), tetrachloroethene (545 ppb), 1,1,1-trichloroethane (TCA, 991 ppb), *cis*-1,2-dichloroethene (1233 ppb), and vinyl chloride (114 ppb). High levels of similar compounds also have been identified at four other source areas of groundwater contamination in southeast Rockford. Localized high concentrations of benzene, toluene, ethylbenzene, and xylene further complicate the groundwater quality condition.

The United States Environmental Protection Agency (USEPA) performed an initial time-critical action in late 1991 by connecting 283 residents on contaminated private wells to the municipal water supply. USEPA also installed a granular activated carbon treatment unit on Rockford Municipal Well #35. IEPA undertook a second action to address less significant groundwater contamination in other residential wells. In this action, 264 homes received municipal water service connections by late 1992.

In 1995, IEPA set cleanup goals for the contaminated aquifer to be accomplished over a period of many years through natural attenuation and remedial action. Additionally, this action calls for connecting homes and businesses whose water wells either recently (as of 1995) exceeded health standards or were predicted to exceed them within the next 70 years. The City of Rockford began implementing the final groundwater remedy in early 1998 through an agreement with the Illinois EPA and the USEPA. By June 1999, the city installed over 2804 m of ductile iron water mains and connected an additional 262 homes and businesses to municipal water service. Also, nine additional groundwater-monitoring wells were installed to supplement the existing monitoring network. Since 1999, the City of Rockford has implemented a groundwater-monitoring program and reported sampling results on aquifer quality to the USEPA and IEPA. Such monitoring is to continue until cleanup goals are attained (IEPA, 2001a,b; USEPA, 2004a).

INITIAL GROUNDWATER MONITORING RESULTS AND PUBLIC HEALTH CONCERNS

Well sampling in 1990 indicated that

- 31 wells had no detected contamination
- 25 wells had contaminants at levels that violated the USEPA public water supply standards
- 60 wells had small amounts of contaminants at levels that did not violate USEPA public water supply standards
- One well had one contaminant for which there is no standard
- Lead was the only metal detected at levels violating public water supply standards
- Further monitoring in 1993 continued to find high levels of solvents in the groundwater with TCA up to 8000 ppb. The drinking water standard in the United States for TCA is 200 ppb.

The public health concern about the chemical concentrations is that some violate USEPA standards for public water supplies and may pose a health risk for people who consume the water for a lifetime. Many of the industrial solvents detected may affect the liver, kidneys, and central nervous system, some being classified by the USEPA as probable cancer-causing agents in humans. Vinyl chloride, which was detected in three wells, is classified by the USEPA as a known cancer-causing agent in humans.

ALTERNATIVE EMERGENCY AND REMEDIAL ACTIONS

The USEPA and IEPA addressed actions on two levels: (1) alternatives to providing safe drinking water as soon as possible on an emergency basis to residents and businesses affected by contaminated groundwater and (2) remedial response to remove contamination from the groundwater and restore use of that portion of the aquifer.

Safe Water Supply Alternatives Considered. USEPA and IEPA considered four alternatives for supplying safe water to the residents:

ALTERNATIVE 1—HOOKUPS TO THE ROCKFORD PUBLIC WATER SUPPLY

Connecting affected houses to the Rockford water supply would provide residents with a permanent source of safe drinking water. USEPA and IEPA would pay for the extension of the water main, for the service connection from the street to the house, for the water meter, and for plugging private wells. The residents would be responsible for the monthly water bill to the City of Rockford. This alternative also includes the treatment of Municipal Well #35 with a granular activated carbon treatment facility. This facility would remove volatile organic compounds detected in the well to allow the city to use this well during peak demand. Cost of Alternative 1: $5,820,000.

ALTERNATIVE 2—NEW RESIDENTIAL WATER WELLS

This alternative involves the construction of new deeper water wells at each of the affected residences. This alternative is based on the assumption that the deeper water supply is not contaminated. USEPA and IEPA would pay for the construction of the new well and plugging the old contaminated well at each residence. Cost of Alternative 2: $6,970,000.

ALTERNATIVE 3—POINT OF ENTRY WATER TREATMENT DEVICES

This alternative involves the installation of individual treatment units at affected residences. The treatment system would be designed to remove VOCs from the water before it was distributed in the house. Cost of Alternative 3: $18,250,000.

ALTERNATIVE 4—NO ACTION

United States federal law requires that the "no action" alternative be considered. "No action" means that no action would be taken to provide alternative water. Cost of Alternative 4: $0.

Agency (or "Institutional") Evaluation of Safe Water Alternatives. IEPA and USEPA chose Alternative 1 (hookups to the Rockford public water supply) as the method for providing safe water to residents with well water that violates public water supply standards and meets the criteria described below. In the opinion of IEPA and USEPA, this alternative is most satisfactory because it is a cost-effective method of providing a permanent source of safe water for residents whose wells meet the criteria of (1) being within the boundaries of the contamination zone or the buffer zone, (2) being a source of drinking water for humans, and (3) the water from the wells cannot be "sold" for commercial purposes.

The IEPA and the USEPA rejected the other alternatives for the following reasons:

- Alternative 2 (new residential wells) was rejected because the groundwater quality at greater depths is unknown and cannot be guaranteed to provide safe water to residents in the future.
- Alternative 3 (point of entry water treatment devices) was rejected because of cost and the ongoing expense and commitment required to maintain the water filters.
- Alternative 4 (no action) was rejected because it did not protect human health.

IEPA continued to sample wells in the vicinity of the site to determine if other residences or businesses should be considered for inclusion in the selected alternative to provide safe water (IEPA, 1991).

Long-Term Remedial Alternatives Considered: The IEPA and USEPA evaluated several remedial alternatives to clean up contamination of soil and groundwater. The United States federal law, the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or "Superfund") specifies the following nine criteria for evaluation of remedies: (1) Overall protection of human health and the environment, (2) compliance with relevant state and federal law, (3) long-term effectiveness and permanence, (4) reduction of toxicity mobility or volume of contaminants through treatment, (5) short-term effectiveness, (6) implementability, (7) cost, (8) state acceptance, and (9) community acceptance. The remedy has several purposes including:

- To stop ongoing contamination of the groundwater by Area 7 waste, thus protecting the water resource for further generations;
- To ensure that VOCs in soil gas do not move into basements of nearby residences;

- To protect people from ingestion of produce grown in contaminated soil in the park;
- To reduce the potential for people to come into direct contact with contaminated soil and free product beneath the ground surfaces; and
- To comply with the 1995 Record of Decision for the project that required groundwater contamination sources be controlled.

The remediation goals for the site are cleanup objectives that must be reached before the remedy will be considered complete. The soil goal is based on State of Illinois guidelines to allow residential use of the area and to protect groundwater from further contamination. The leachate goal is achievement of U.S. federal drinking water standards at the groundwater management zone (GMZ) boundary of the site. The groundwater beyond the GMZ boundary is being treated by natural attenuation, which is the remedy chosen for area-wide groundwater in 1995.

The IEPA conducted a feasibility study of alternative remedies and prepared a proposed plan for controlling the contamination in Source Area 7 of the Southeast Rockford Groundwater

TABLE CS3.1
Soil Remedial Alternatives for Source Area 7

Alternative No.: Name	Summary Description	Time	Cost Estimate (2001 US$)
1. (SCS-7A): No Action	No action	80–90 years	None
2. (SCS-7B): Limited Action	Institutional controls would be placed on the property restricting use and access to the property until remediation goals are met.	80–90 years	$275,000
3. (SCS-7C): Ex Situ Biological Treatment	1. Soil excavation. An estimated 43,580 m^3 of soil, waste, and free product would be excavated and dewatered 2. Treatment of vapors from enclosure 3. Dewatering 4. On-site biological treatment of excavated material 5. Leachate collection	Biological treatment of soil would take approximately 5 years. Leachate would meet remediation goals in 15–25 years	$18,218,000
4. (SCS-7D): Excavation, On-site Treatment by Low Temperature Thermal Desorption (LTTD)	1. Institutional controls 2. Soil excavation 3. Dewatering 4. Low-temperature thermal desorption 5. Air monitoring 6. Treated soil returned to excavation hole	Treatment of soil by the LTTD would take approximately 8 months. The leachate would meet goals in 10–20 years	$15,209,000
5. (SCS-7E): Soil Vapor Extraction [Selected alternative]	1. Same as SCS-7B plus the following: 2. Soil vapor extraction 3. Air sparging injection well system 4. Catalytic oxidation 5. Air monitoring	15–25 years	$5,624,000

TABLE CS3.2
Groundwater/Leachate Alternatives for Source Area 7 (See Notes for Cost Calculation Details)

Alternative No.: Name	Summary Description	Time	Cost Estimate (2001 US$)
1. (SCL-7A): No Action	1. Institutional controls—A restriction would be placed on the property limiting use and access to the property until remediation goals are met. 2. Groundwater monitoring—Groundwater would be monitored through a system of nine monitoring wells until drinking water standards are met at the GMZ boundary.	80–90 years	$347,000
2. (SCL-7B): Limited Actions, MultiPhase Extraction, Leachate Containment [Selected Alternative]	1. Same as SCL-7A plus the following: 2. Multiphase extraction 3. Leachate containment 4. Air stripping 5. Catalytic oxidation unit 6. Air monitoring 7. Water monitoring 8. Leachate discharge	30–40 years	
3. (SCL-7C) Reactive barrier wall/Leachate Monitoring	1. Same as alternative SCL-7A plus: 2. Reactive barrier wall (subsurface wall of permeable iron filings constructed downgradient of the GMZ boundary to intercept groundwater and resulting in a chemical reaction breaking down VOCs into harmless compounds	1–10 years; wall to be maintained for approximately 80–90 years	

1. Capital costs for construction items do not include oversight fees.
2. Replacement costs include construction and oversight capital costs.
3. Capital costs represent the present worth of the given alternative.
4. Sampling and analysis costs are based on a 7% discount rate over a 30 year projection for the multiphase extraction system (based on Resource Conservation and Recovery Act (RCRA) Closure Guidelines).
5. Present worth of replacement costs is based on a 7% annual discount rate and replacement of monitoring wells and leachate containment system (including central pump station, extraction wells, piping, pumps, and air stripping unit) every 15 years (twice over 30-year projection).

Contamination Superfund project. Fact sheets describing the alternatives and proposed plans for the other three major source areas are available from the IEPA website at http://www.epa.state.il.us/community-relations/fact-sheets/southeast-rockford/. More detailed description of selected alternatives can be found in the 1995 Record of Decision at http://www.epa.state.il.us/community-relations/fact-sheets/southeast-rockford/record-of-decision.pdf.

While the Southeast Rockford Groundwater Contamination Superfund project is complex, it is not the most challenging groundwater contamination site, nor the best known. However, it presents a reasonable depth of information for consideration in the context of economic analysis of groundwater contamination remediation. First, a brief description of the soil remedial alternatives are presented, followed by the groundwater alternatives. Estimated costs include both capital costs and operation and maintenance expenses and are given in 2001 US$.

The estimated cost of remediating contamination of soil and groundwater in Source Area 7 is $8,261,000. The total cost of the Southeast Rockford Groundwater Superfund Project for remediation of all four contaminant source areas is estimated in 2001 to be $22,812,500 (IEPA, 2001b).

ECONOMIC ANALYSIS

Typically, emergency and remedial actions at abandoned, uncontrolled hazardous waste sites are approached in an institutional economics context by considering cost effectiveness. Cost-effectiveness can compare the relative efficiency of different approaches that serve the same objective(s). In the case of the Southeast Rockford Groundwater Superfund Project, cost-effectiveness can be considered both for the emergency safe water supply and for the long-term remediation of groundwater. The benefits of remediating groundwater contamination are not evaluated, and therefore are assumed to be widely accepted. They may include provision of safe water to communities now and in the future thereby avoiding health costs, reduced environmental effects on flora and fauna, and beneficial use of a resource that might be considered unavailable owing to degraded quality.

SAFE WATER SUPPLY

The four alternatives for supplying safe water to residents with contaminated wells were (1) hookups to the Rockford Public Water Supply, (2) new residential water wells, (3) point of entry water treatment devices, and (4) no action. Based on personal knowledge of the author, a fifth alternative was considered early in the project development, that of providing bottled or trucked water. To compare these alternatives in a cost-effective framework, their objectives should all be the same. In this case, the objectives are not the same and perhaps should be reconsidered; however, an alternative was selected by the project sponsors and has already been implemented: Alternative 1, connecting to the City of Rockford public water supply.

In providing water to residents of this area, depending on the water purpose or use being addressed, exposure to the contaminants in this groundwater can be variably affected:

1. Provision of water to drink and cook relates to ingestion of the water.
2. Provision of water for bathing affects both dermal and inhalation contacts.
3. Provision of water for washing and domestic waste removal relates to some dermal and inhalation contacts.
4. Provision of water for other purposes, such as car washing or lawn and garden watering relates to some dermal and inhalation contacts.

An assessment of alternatives to exposure outcomes gives the following:

Alternative 1—Hookups to the Rockford Public Water Supply—provides water for all purposes and affects all routes of contact.

Alternative 2—New Residential Water Wells—provides water for all purposes and affects all routes of contact.

These two alternatives are similar in their water provision objectives. Their costs can be compared in a cost-effectiveness framework.

Alternative 3—Point of Entry Water Treatment Devices—If the point of entry device is installed in the typical manner, it will be placed on the primary faucet used to obtain water for drinking and cooking.

Alternative 3 is not comparable with Alternatives 1 and 2 in terms of water use or public health (contaminant exposure) objectives served. If this alternative were implemented in an atypical manner, which resulted in point of entry devices being installed on all faucets and spigots inside and outside of the house, then it would be comparable, and more expensive, also.

Alternative 4—No Action—Clearly, this alternative does not serve to improve water quality conditions for any water use.

The fifth alternative not included in this final set of published alternatives is actually bottled water and, separately, trucked water. Bottled water would address purpose (1), above, for drinking and potentially for cooking. Trucked water, depending on its implementation, could affect purpose (1) only, purposes (1), (2), and (3), or all the purposes. Trucked water requires a storage container at a height above the points of use to allow gravity flow or at ground storage with a pump to lift the water into the house. The bottled water alternative is more similar to Alternative 3 in that the water use purposes are also similar. The trucked water alternative would need to be clearly defined in its implementation before it could be compared.

The safe water supply alternatives, then, basically fall into two groups: (1) alternatives affecting all water uses and all paths of contaminant exposure and (2) those affecting single primary use and path of exposure. Categorized in this way by "common objectives served," they can be evaluated in a cost-effectiveness framework. Assuming that all the expenditures are estimated in the same monetary units and have been discounted to the same year, the evaluation in this case is straightforward. The connection to municipal water clearly meets all the objectives for $1,150,000 less than the alternative for new wells. While Alternative 3, point-of-use devices, is obviously more expensive than Alternatives 1 and 2, it could not be compared with them through cost-effectiveness evaluation since it addresses a different objective set. If Alternative 3 were less costly than the other alternatives, the only way it could be compared would be to determine the relative proportion of all water uses purpose (1)—drinking and cooking—was at that time and add to it the cost of options that would separately serve the other objectives, perhaps trucked water implemented in certain configurations and depending on its quality.

LONG-TERM REMEDIAL ACTION

Long-term remedial action includes treatment of both soil and groundwater leachate.

Soil

The No Action alternative imposes costs on future generations because the soil will be a continuing source of contaminants. The No Action alternative is not responsive to any of the nine criteria to be considered under law. Institutional controls, Alternative 2, effectively remove from certain uses large areas of land for a specified period of time. The costs identified are only those of administrative activities. These costs should have included the opportunity cost foregone by not being able to use these lands for other productive purposes. [This latter point is exactly the focus of the Brownfields law and projects.] Thus, potentially significant costs were not considered in the way the cost comparison was set up. It only addressed the cost to the government-directed activity to clean up the soil contamination. The comparative analysis did not address the cost at the community level, but only at the project level. Since the City of Rockford is a major manufacturing center, the economic evaluation could also have projected economic effects at a state or regional level; however, this type of evaluation may be considered beyond the statutorily required criteria.

The other three soil remedial alternatives basically focus on similar objectives of active contaminant removal or reduction to allow use of the land and groundwater by future users. Clearly, Alternative 5 is more cost effective in addressing the site's soil contamination by $9,585,000 less than Alternative 4 and $12,594,000 less than Alternative 3. However, Alternative 5 may still have costs associated with it that may be dealt with in Alternative 3. These costs are associated with the release of contaminants to air, transferring the chemical residuals from groundwater to the atmosphere. While these costs may be minimal for one site, the long-term cumulative effect from such releases at many sites is not considered. Thus, the accounting scale is significant in developing information on costs for decision making.

Groundwater/Leachate

The remedial alternatives for groundwater/leachate are evaluated relative to their contribution toward nine statutorily required criteria or objectives (listed above) that must be balanced in selecting the one that will be implemented to control a site's contamination and exposure of future population in using the groundwater. Based on relative current dollars, the institutional control alternative (SCL-7A) seems to be the most cost effective. However, it does not adequately balance short-term and long-term effectiveness criteria. Importantly, Remedial Alternative 1 neither addresses sufficiently near-term mitigation of public health and environmental effects nor meets drinking water standards, two significant criteria. Concerning these latter criteria, Alternative 1 places costs on future generations to deal with the impact of the contamination. In effect, the Institutional Controls remove from use the contaminated groundwater with the same result as exploitive depletion in water-scarce regions. The groundwater zone affected effectively expands as the contamination migrates over time, albeit becoming less concentrated. The long-term health and environmental effects of these contaminants at low concentration and mixtures are not known and so the social costs cannot be calculated, at least not easily.

Remedial Alternatives SCL-7B and SCL-7C appear to address the same criteria in similar ways, but they have different external effects, the costs of which are not evaluated in the alternative selection process. While SCL-7C results in harmless breakdown products, Alternative SCL-7B shifts some contamination from groundwater to air. Additionally, this alternative produces groundwater to be treated, possibly lowering the water table and local groundwater flow, while discharging the treated water to a nearby stream. The government's Record of Decision suggests that this is a relatively minor effect. The cumulative effects of many such decisions are not known or evaluated in economic or quantitative terms. One net effect may be the permanent or long-term loss of groundwater that may not be available for other uses. Thus, the opportunity cost of the groundwater lost should be evaluated for SCL-7B to benefits and costs of the added water to the stream to determine a more complete economic analytical result for decision purposes. Methods for determining such values for groundwater appear elsewhere in the text and include evaluation of commodity value and contingent valuation, among others.

The decision did consider off-site effects on the stream that receives groundwater discharge. The risks to aquatic life were considered along with other impacts of site contamination. No economic data were associated with these effects, nor was any quantification of effects reported. Indicators of relative stream health were neither applied at the time of the decision to proceed with remediation, nor were compared with other similar streams that were not associated with hazardous waste sites done to provide a level of ecological accounting.

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Illinois Environmental Protection Agency (IEPA). 2001a. Source Area 7 Remedial Investigation Results; Southeast Rockford Groundwater Contamination Superfund Project; February 2001. Web site URL: http://www.epa.state.il.us/community-relations/fact-sheets/southeast-rockford/southeast-rockford-9b.html (accessed April 15, 2004).

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Case Study 4: Wellhead Protection: Benefits and Costs

BACKGROUND

Wellhead protection is an approach to preventing contamination of groundwater that supplies public wells started in Europe in the 1960s and 1970s and has been part of European Union legal directives for many years. The concept comprises several steps that have now also been defined in law in the United States (Safe Drinking Water Act, Section 1428), which include the following basic measures:

1. Define the zone of principal recharge to existing and future wells
2. Identify potential sources of contamination within the zone
3. Specify and implement management measures to control the potential sources of contamination

While simple in concept, this approach is challenging to carry out, since it involves defining a protection area around wells and the participation of existing land users in that area whose practices may be incompatible with preventing contamination of groundwater. The concept of wellhead protection is also complementary to the current understanding that once groundwater is found to be degraded, it is difficult, time-intensive and costly, and perhaps nearly impossible in some hydrogeologic settings, to treat and restore it to its previous quality in the foreseeable future. A conceptual wellhead protection area is depicted in Exhibit CS4.1.

In an economics context, wellhead protection posed a challenge to demonstrate that its benefits outweighed its costs. Basically, the issue was to measure the benefits of preventing an adverse outcome: contamination of the local groundwater supply. The U.S. Environmental Protection Agency addressed this issue in a study it conducted in 1995 (USEPA, 1996). The approach taken for this evaluation was to estimate resource benefits through costs avoided by preventing contamination of the groundwater source, referred to as “avoided-cost benefits.” The premise underlying the avoided-cost approach is that communities faced with a contaminated groundwater supply will respond and incur costs of treating or remediating the groundwater or install new wells in a different location that has safe water. Other possible costs of contamination include damages measured as reduced agricultural production and increased manufacturing costs. The expected value of these costs may be determined by applying the probability of contamination.

Estimating the costs of implementing wellhead protection is also part of this evaluation. This step involved quantifying the costs of developing and implementing a wellhead protection program (WHPP). A key factor is the probability that wellhead protection will prevent contamination.

Through literature search, documentation review, and interviews, the study chose five communities and one pair of communities in the same region that had experienced recent contamination of their groundwater source *and* had decided to implement a WHPP. This approach avoided concern that one community’s contamination problem could not be compared with another community’s prevention plan. USEPA prepared case histories of these communities, including water system description, hydrology of the area, management factors, groundwater contamination and response, and wellhead protection activities. For the readily quantifiable factors, USEPA collected cost data during 1994 and 1995. The communities represent a range of sizes (populations from 700 to 60,000) and geography (Maine to Louisiana to Washington State).

Several interpretive factors affect one's perspective of the results. The study was not statistically designed. The communities were selected because they had both experienced contamination of their water supply and planned or implemented wellhead protection, and, thus, were unique in that regard. The accounting unit is the community, rather than a state or nation. The evaluation assumes the probabilities of both contamination of groundwater sources and success of wellhead protection to be 100%. This is an overestimate of these probabilities for most communities. The analysis did not quantify the probability of contamination to weight the results collected. The opportunity costs of volunteers' time in two communities were included in the evaluation. Nearly all costs included in the case studies were those that were easily available from local, state, or federal documentation. Where possible, business and private sector costs are included if they were readily available. Some remedial costs were not included because of lack of documentation: health-related costs, lost production of people and industries, interruption of fire protection, loss of economic development opportunities, and loss of property value and tax revenue. Prevention costs not addressed are changes in processes, activities, or facilities beyond that planned or required by law. Some of the costs of both remedial response to contamination and wellhead protection were projected at the time of the analysis. Based on these premises and assumptions, one of the cities in the case studies will be presented in greater detail: Middletown, Ohio.

CASE STUDY: MIDDLETOWN, OHIO (ALL MONETARY UNITS ARE IN 1994 U.S. DOLLARS)

Contamination Response

The industrial area of southwest Ohio is the location of Middletown, which has a range of land uses from residential to heavy industrial supporting a population of 60,000 people. In the mid-1980s, the Middletown public water system's sampling program found volatile organic chemicals in its wells and immediately closed three of them. The State of Ohio Environmental Protection Agency determined that a manufacturer of printing plates, AEP Flexo, Inc., was the source, spilling and improperly disposing of perchloroethylene (PCE, also referred to as tetrachloroethylene), a cleaning and degreasing solvent and known carcinogen (ATSDR, 1997). The company, under a consent agreement with the state, has investigated and is remediating the contamination. The City of Middletown spent $732,000 by September 1995 in responding to the contamination, including

- Field investigation: $342,000
- Plugging one well: $51,000
- Installation of monitoring wells: $114,000
- Contamination-related improvements to remaining wells: $204,000
- Quarterly VOC monitoring of 13 wells: $16,128
- Litigation: $5100
- Anticipated costs between 1995 and 2005 to
    - abandon two more wells: $70,093
    - construct two new wells: $122,159
- Air stripping the contaminants from groundwater
    - Air strippers: $280,374
    - Electricity: $210,707
    - Periodic media replacement: $14,047

The State of Ohio oversight costs were $45,861 at that time, which the company was to reimburse. For the purposes of the economic analysis, it was assumed that the company had similar contamination investigation costs to the city, $342,000. Additionally, the city projected expenditures from

1995 to 2005 of between $192,000 and $697,000 to supply safe drinking water to residents, depending on implementation of air strippers for remediation.

Other intangible costs that were not monetized but identified include those of an adjacent business owner under whose property the contaminant plume extended that he would not be able to sell his property. Similar real concerns are documented elsewhere (see, for example, the case of groundwater contamination in Legler, New Jersey, reported in Edelstein, 2004, pp. 99–100).

WELLHEAD PROTECTION

The City of Middletown decided in 1991 to implement a WHPP, partly in response to the contamination of its water supply wells and as a result of receiving a state wellhead protection demonstration grant of $12,000. The city, through staff and technical consultants, delineated the wellhead protection areas (WHPAs) of its wells, identified 80 potential and 3 actual contaminant sources, and prioritized the potential sources based on risks to the wells. Based on the area's hydrologeology and groundwater use, the consultant also identified areas for groundwater monitoring. By the end of 1993, Middletown completed its proposed wellhead protection plan that included rating all land parcels based on the amount and types of chemicals used and stored, land owner adoption of engineering controls and risk management measures to maintain site rating if chemical use and storage continued, a risk reduction fund to provide financial assistance to businesses implementing contaminant prevention measures, and groundwater monitoring. By 2005, Middletown projects spending for its WHPP of $1.3 million, funded through a $0.50 monthly connection fee for all consumers and a 5% surcharge on industrial use. Projected costs *through 2005* include

Basic wellhead protection

- Delineation and contaminant source identification: $45,000
- Management Plan: $11,220
- Contaminant Source Administration and Inspection: $239,072

Special wellhead protection (beyond requirements typical of other communities' basic approach)

- Public school education program on groundwater protection: $25,500
- Monitoring in WHPAs: $245,472
- Spill response/risk management to remediate contamination and provide loans to business to conduct best management practices: $811,248

Intangible costs could not be determined. Businesses must have chemical contaminant structures. Other requirements of the city's WHPP plan are restatements of basic federal and state regulatory requirements that already exist.

In Summary Assuming that all 13 city wells could become contaminated if not protected, the Middletown benefit–cost analysis was reported as

- Contamination costs (for 3 wells): $970,342–$1,475,470
- Wellhead protection (for 13 wells)
  - Basic costs: $295,892
  - Special protection costs: $1,082,220
- Contamination costs per well: $323,447–$491,823
- Basic wellhead protection costs per well: $22,761
- Potential per well contamination to basic prevention costs ratio: 14–22: 1
- Potential per well contamination to basic "plus" special prevention costs ratio: 3–5: 1

These results suggest that significant benefits in the form of avoided contamination costs derive from wellhead protection as a groundwater contaminant prevention approach for water supply.

The study did a similar analysis for five other cities and towns in the United States implementing wellhead protection with the following results. Additionally, it included a sensitivity analysis, which assumed that the wells had a 50% probability of contamination *and* that the contaminant remediation costs were half of those estimated for the contaminated wells. Table CS4.1 presents these findings.

Other results are notable. The table implies and the report notes that contamination remedial costs are not proportional to community size: Gilbert, Louisiana, population 700 and the smallest community in the study, had estimated remedial costs nearly as high as Middletown, Ohio, population 60,000, the largest community in the study. For the six communities, groundwater remediation was funded from a range of sources. The average percentages for the communities combined were: community, 50%; state, 38%; federal, 12%, and private, <0.5%. For the wellhead protection costs of their basic protection programs, the six communities funded 84% themselves; states funded 6%, Federal programs 4%, and private sources 7%. The range of benefit to cost ratios is large, suggesting that further analysis based on community size and other factors might be useful in further understanding this spread of avoided costs and protection costs. Even including added special protection activities, such as detailed delineations and monitoring, the overall ratio of per well avoided-cost benefits to protection costs is 14:1, suggesting that protection efforts may yield significant future savings, in this analysis by an order of magnitude. These overall results, if assumed to be representative, also indicate that water consumers pay a larger share of protection costs than for remedial costs.

As a comparative measure, the study briefly considered the value of the contaminated groundwater to the community as a commodity. The value of groundwater if uncontaminated and supplied to the 12 wells affected in the study was determined by using the communities' prices of water, reflecting the consumers' willingness to pay. In the case of Middletown, Ohio, for the period February 1988 to May 2005, the volume of groundwater not pumped from the contaminated wells was estimated to be 169,974,517,702 L. The unit price in 1994 $US was $0.42/1,000 L giving a value for the groundwater not produced because of contamination of $71,844,000. The unit price varied at the time of the study (1994) from $0.36 (Dartmouth, Massachusetts) to $0.87 (Norway, Maine)

TABLE CS4.1
Ratios of per Well Avoided-Cost Benefits to Wellhead Protection Costs Assuming All Wells May Become Contaminated (100% Probability of Contamination)

Community	Population	No. of Protected Wells	With Basic Protection	With Special Protection	Sensitivity Analysis: Assuming 50% Probability of Contamination and 50% of Contamination Costs/Basic Protection Costs
Gilbert, LA	700	2	200:1	200:1	50:1
Norway, ME	4000	1	5:1	4:1	1:1
Tumwater, WA	13,000	13	26:1	11:1	7:1
Lancaster Co., PA	20,000	11	178:1	104:1	44:1
Dartmouth, MA	24,000	7	12:1	4:1	3:1
Middletown, OH	60,000	13	22:1	5:1	5:1
Total		47	42:1	14:1	10:1

per cubic meter. The total estimated value of the groundwater that was not produced over approximately an 18-year period (on average) because of contamination for the six communities combined was $111,016,000. On a per well basis, this averages to $9,251.333. The per well cost of remediation for the six communities combined estimated over approximately the same timeframe was $916,667, an order of magnitude less than the value of the groundwater. The per well cost of basic wellhead protection for the six communities combined is $34,702 and including special protection, $105,059.

DISCUSSION

The challenges with this analysis are several. First, because it is not statistically based, it is difficult to extrapolate its results nationally. Therefore, it may not be representative. However, it did consider a range of water system sizes, which is useful in understanding the problems along that range of size, such as what is unique or similar. Second, several assumptions must be accepted, most significantly that wellhead protection activities will yield total prevention from contamination. In actuality, wellhead protection is like an insurance program in which you reduce the probability of contamination occurring. Mishan briefly discusses the insurance aspect of willingness to pay a premium for a particular monetary outcome related to loss of life (Mishan, 1982, pp. 324–325). While he indicates that the insurance premium is an indication of concern, it does not reflect, in the case of wellhead protection, the value a community sets on water.

Not all costs of remediation were estimated at the time of the study. For Middletown, private costs included only represented investigation. The company may have incurred other costs. Adjacent property owners' costs and changes in property values and resulting tax revenues were not evaluated. For many sites, initial cost estimates are considerably less than final costs because of unanticipated circumstances. It is not clear whether health and other social costs evolved over time.

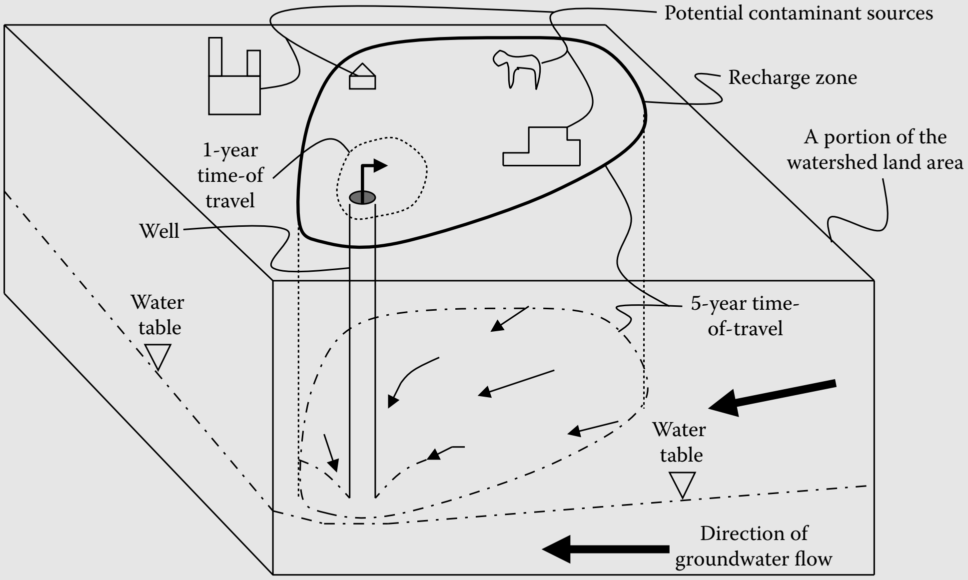
Likewise, not all wellhead protection costs could be estimated. As noted, changes in property values and tax revenues were not assessed. Within the same community, the net effect of these changes may have been negligible and simply exchanged within its boundaries. A full accounting of administrative costs may yield a different result in retrospect.

How should the relationship, if it can be assumed to be representative, of protection costs to remediation costs to water value be viewed? The price of groundwater delivered by a public water system reflects many costs. At the time of the study (1994), approximately 84 contaminants were required to be tested for in the United States and, if found, treated. The price should also reflect the costs of distribution as well as overall operation and maintenance of the system. The relationship for these communities taken as a group suggests that the relative ratio of protection costs to remedial costs to water value on a per well basis is 1:10:100. The important aspect of this relationship is the protection cost to remedial cost ratio. It suggests that if water consumers pay for the protection and remedial costs, rather than taxpayers (which is not the case for the majority of remedial costs in this study), then water supply costs would only rise by 1% for protection to insure that costs do not increase by 10% for remediation if a well is unprotected and becomes contaminated.

A further consideration relative to the assumptions about wellhead protection and the costs of remediation evaluated in this case study is that the range of contaminants possibly affecting these wells may have been large. The contaminants that a WHPP may potentially prevent reaching the wells at harmful levels could include pesticides, inorganic chemicals, and microorganisms. Since these potential contaminants were not included in the analysis, the use of the remedial costs for the volatile organic chemicals found may then underestimate the possible larger avoided costs to the city for contaminants that could have threatened the well field if other types of contaminant sources were in the vicinity, assuming effective wellhead protection.

EXHIBIT CS4.1 CONCEPTUAL WELLHEAD PROTECTION AREA

Based on flow rates in the aquifer, the area of the designated time-of-travel (TOT) of groundwater flow determined to be protective, such as 5 years (or other timeframe depending on treatment capability and contaminants of concern) is projected to the land surface to delineate the recharge zone of the well and its source protection area contributing groundwater to the well for the purposes of wellhead protection. Potential contaminant sources within the wellhead protection area are managed or located so as not to affect groundwater quality adversely.



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Case Study 5: Economic Assessment of a National Regulation—Waste Disposal Wells

INTRODUCTION

The Underground Injection Control (UIC) Program, established under the Safe Drinking Water Act (SDWA) in the United States, provides protection for underground sources of drinking water by setting standards and controls that govern disposal of liquid wastes through wells into the subsurface environment. The UIC program established five classes of injection wells described previously and listed again here:

Beneath lowermost underground source of drinking water

Class I—for hazardous wastes, industrial non-hazardous liquids, or municipal wastewater
Class II—for brines and oil and gas production fluids
Class III—for fluids associated with solution mining

Into or above underground source of drinking water

Class IV—for hazardous and radioactive wastes (these wells are banned)
Class V—for other non-hazardous fluids in shallow wells (typically)

The rule for which this case study assesses the economics addresses two categories of high-risk wells in Class V: motor vehicle waste disposal wells and large-capacity cesspools. The United States EPA has estimated that as many as 800,000 Class V wells exist in the United States; of these, an estimated 21,692 are motor vehicle waste disposal wells and 9,583 are large capacity cesspools (p. 10). The definitions of these wells are

> Motor vehicle waste disposal wells: "These are drywells or septic tank and leachfield combinations that receive or have received fluids from vehicular repair or maintenance activities, such as an auto body repair shop, automotive repair shop, new and used car dealership, specialty repair shop (e.g., transmission and muffler repair shop), or any facility that does any vehicular repair work. Fluids disposed in these wells may contain organic and inorganic chemicals in concentrations that exceed the maximum contaminant levels (MCLs) established by the primary drinking water regulations (see 40 CFR Part 142). These fluids also may include waste petroleum products and may contain contaminants, such as heavy metals and volatile organic compounds, which pose risks to human health" (p. 7).
>
> Large-capacity cesspools: "Cesspools are drywells that receive untreated sanitary waste, and which sometimes have an open bottom and/or perforated sides. The UIC requirements do not apply to single-family residential cesspools nor to nonresidential cesspools that receive solely sanitary waste and have the capacity to serve fewer than 20 persons a day" (p. 7).

This case study will focus on motor vehicle waste disposal wells and the regulatory and transaction costs in its implementation. Exhibit CS5.1 describes in general terms the regulation of Class V motor vehicle waste disposal wells in the United States to protect underground sources of drinking water.

EXHIBIT CS5.1 REGULATION OF INJECTION WELLS AND MOTOR VEHICLE WASTE DISPOSAL WELLS IN THE UNITED STATES

What is underground injection?
Underground injection is the technology of placing fluids underground, in porous formations of rocks, through wells or other similar conveyance systems. While rocks such as sandstone, shale, limestone appear to be solid, they can contain significant voids or pores that allow water and other fluids to fill and move through them. Man-made or produced fluids (liquids, gases, or slurries) can move into the pores of rocks by the use of pumps or by gravity. The fluids may be water, wastewater, or water mixed with chemicals.

What is a Class V injection well?
Class V injection wells are typically shallow disposal systems that are used to place a variety of fluids below the land surface. Injection wells are regulated by EPA and the states through the UIC program to protect underground sources of drinking water from contamination.

Why are Class V injection wells of concern?
Class V wells are a concern because they pose a risk to underground sources of drinking water. Eighty-nine percent of America's public water systems use groundwater as a drinking water source.

- EPA estimates that there are more than 600,000 Class V injection wells currently in the United States. Class V injection wells are located in every state, especially in unsewered areas where the population is also likely to depend on groundwater for its drinking water source. There are many types of Class V wells including motor vehicle waste disposal wells, large capacity cesspools, storm water drainage wells, aquifer remediation wells, and large capacity septic systems. The fluids released by certain types of these wells have a high potential to contain elevated concentrations of contaminants that may endanger drinking water.

Are Class V injection wells currently regulated?
Class V injection wells are currently regulated by the UIC program, under the authority of the SDWA. Under the existing federal regulations, Class V injection wells are "authorized by rule" (40 CFR 144). This means that Class V injection wells do not require a permit if they do not endanger underground sources of drinking water and they comply with other UIC program requirements.

These program requirements include (1) submitting basic information about Class V injection wells to EPA or the state primacy agency and (2) constructing, operating, and closing Class V injection wells in a manner that protects underground sources of drinking water. EPA or a state primacy agency may ask for additional information or require a permit to ensure that groundwater quality is adequately protected. Further, many UIC primacy state programs have additional prohibitions or permitting requirements for certain types of Class V injection wells.

What are the new regulatory requirements?
These new requirements protect public health and the environment by eliminating or reducing injection of wastes from large capacity cesspools and motor vehicle waste disposal wells.

EXHIBIT CS5.1 (continued) REGULATION OF INJECTION WELLS AND MOTOR VEHICLE WASTE DISPOSAL WELLS IN THE UNITED STATES

Motor vehicle waste disposal wells

- New wells are prohibited nationwide as of April 2000.
- Existing wells in regulated areas will be phased out (details below), but owners and operators can seek a waiver and obtain a permit. Permits must set out minimum requirements including (1) meeting MCLs and other health-based standards at the point of injection, (2) monitoring for injectate and sludge, and (3) implementing best management practices (BMP), such as recycling and waste minimization.

Where are existing motor vehicle waste disposal wells being regulated?

The requirements for existing motor vehicle waste disposal wells are being linked with State Source Water Assessment Programs. States are conducting source water assessments as required by the 1996 Amendments to the SDWA. The Amendments require states to establish Source Water Assessment Programs that, when complete, will (1) delineate areas in the state in which one or more public drinking water systems have sources of drinking water and (2) identify, to the extent practical, the origins of regulated and certain unregulated contaminants in the delineated area to determine the susceptibility of drinking water systems to such contaminants.

The new requirements will apply in groundwater protection areas, as identified by the state's assessment for community and nontransient noncommunity water systems that use groundwater.

The requirements will also apply in other areas that states identify as sensitive groundwater areas. These areas are critical to protecting existing and future drinking water sources because hydrogeologic conditions would allow contaminants to readily migrate to drinking water sources.

What are the compliance schedules for owners and operators in groundwater protection areas and other sensitive groundwater areas?

The new requirements for existing motor vehicle waste disposal wells will be phased-in over approximately seven years. The first wells to be affected will be those located in groundwater protection areas.

Motor vehicle waste disposal wells in groundwater protection areas

Owners and operators in groundwater protection areas must close their well or obtain a permit within one year of completion of the state's groundwater protection assessment. States could grant a one year extension under certain conditions.

States must complete the groundwater protection assessments by January 1, 2004. If they do not, three things could occur:

The rule would apply statewide, and owners and operators would have until January 1, 2005, to close their wells or obtain a permit.

States could apply to EPA for a one year extension to complete their assessments. Owners and operators would have one year from the completion of the groundwater protection assessment to close their well or obtain a permit.

If states get an extension and fail to complete their assessments, the rule would apply statewide and owners and operators would have until January 1, 2006, to close their wells or obtain a permit.

(*continued*)

EXHIBIT CS5.1 (continued) REGULATION OF INJECTION WELLS AND MOTOR VEHICLE WASTE DISPOSAL WELLS IN THE UNITED STATES

Motor vehicle waste disposal wells in other sensitive groundwater areas
States must designate other sensitive groundwater areas by January 1, 2004. Owners and operators of existing wells in these sensitive groundwater areas have until January 1, 2007, to comply with the requirements.

Sources:

1. U.S. Environmental Protection Agency (USEPA), What is the UIC program? 2004, URL: http://www.epa.gov/safewater/uic/whatis.html (accessed October 11, 2004).
2. EPA, UIC Class V Wells Fact Sheet, 2004, URL: http://www.epa.gov/safewater/uic/c5fin-fs.html (accessed October 11, 2004).

For motor vehicle waste disposal wells, the regulatory process considered the following options (pp. 8–9):

1a. Banning motor vehicle waste disposal wells within groundwater protection areas
1b. Banning motor vehicle waste disposal wells within groundwater protection areas, but allowing owners and operators of individual wells in such areas to seek a waiver to keep operating by applying for a permit
2a. Banning motor vehicle waste disposal wells within groundwater protection areas and other sensitive groundwater areas
2b. Banning motor vehicle waste disposal wells within groundwater protection areas and other sensitive groundwater areas, but allowing owners and operators of individual wells in either kind of area to seek a waiver to keep operating by applying for a permit
3a. Banning motor vehicle waste disposal wells statewide
3b. Banning motor vehicle waste disposal wells statewide, but allowing owners and operators of individual wells in such areas to seek a waiver to keep operating by applying for a permit

This case study will focus on motor vehicle waste disposal wells and the costing methodology to arrive at a national cost estimate for implementing the regulation. The regulation has two basic options as presented above that must have cost estimates prepared for the national estimate derived from average costs per facility: (1) ban motor vehicle waste disposal wells and (2) ban such wells, but allow owners and operators to apply for a permit to operate the wells under a waiver to the ban.

To develop costs, projections must be made using the best available information. Detailed information is presented in the report summarized here. To make projections, reasonable assumptions must be developed and applied to the regulatory process. The major assumptions by basic regulatory options are (pp. 19–22)

Ban motor vehicle waste disposal wells—owners/operators will

- Close all motor vehicle waste disposal wells
- Implement BMPs to reduce volume and toxicity of wastewater
- Close the well (plugging or permanent seal)
- Send wastewater to a publicly owned treatment works (POTWs), an industrial/commercial wastewater treatment facility, or to a recycler
- Conduct soil sampling

- Remediate site in 35% of facilities projected to have contamination, including further sampling and appropriate disposal of wastes at an off-site disposal facility
    - 1/3 of remedial sites will have soil categorized as hazardous and require hazardous waste thermal treatment
    - 1/3 of remedial sites will have soil that can be disposed at nonhazardous thermal treatment facilities
    - 1/3 of remedial sites will be able to use nonhazardous landfills for their contaminated soil

Ban motor vehicle waste disposal wells, but allow waiver permits—owners/operators will

- Implement BMPs to reduce volume and toxicity of wastewater
- Sample injectate to determine whether it meets the MCL for regulated contaminants in drinking water
- If injectate complies with MCLs, seek a permit for continued well use for wastewater disposal, periodic sampling of injectate and sludge, and proper sludge disposal
- If injectate does not comply with MCLs, close the well and follow steps above of banning wells (without a waiver permit)

COST ASSUMPTIONS AND ESTIMATES

As in most studies of cost for policy implementation, assumptions must be made to estimate and project costs over the time horizon of the activity to be conducted. The economic assessment for motor vehicle waste disposal wells uses the following assumptions and cost estimates.

Overall (pp. 19–22)

- Average quantity of injectate can be estimated from the available information
- Injectate characterization and its chemical concentrations are based on historical data
- Distance of the injection facility to treatment works and sewer lines are based on current understanding of access to these facilities generally
- Volume of soil contaminated can be estimated based on available information of the results of past practices
- Extent of well closure under the waiver permit option can be estimated from industry experience
- Waste streams can be categorized as one of 12 modeled waste streams considering rate of flow; quantities of organics, oils, and greases; and occurrence of metals
- Waste streams and BMPs can be assigned to industrial classifications (in the United States, to four-digit standard industrial classification (SIC) codes) to coincide with expected (average) industry response to the regulation
- Under the Ban Option (pp. 22–25),
    - 100% of motor vehicle waste disposal wells close
    - All owners/operators of these wells will test soil around them for contamination
    - 35% of owners/operators will find contamination and remediate, disposing the soil at a hazardous waste thermal treatment facility, a nonhazardous waste thermal treatment facility, or a nonhazardous waste facility, with each facility type receiving one-third of the disposed soil, and retesting soil at the contamination site to determine that remediation was effective (see Exhibit CS5.2)
- Under the *ban with waiver permit option*, based on available information (pp. 25–26),

- 100% of motor vehicle facilities with waste disposal wells will apply BMPs
- 72.5% of the motor vehicle facilities will meet MCLs after applying BMPs and request a permit to continue to operate, while 27.5% would be closed because they could not meet MCLs
- Monitoring of injectate would occur quarterly for 3 years and then annually
- Liquids from sludge previously disposed in wells would be monitored annually, with two-thirds of sludge liquids not meeting MCLs and necessitating sludge disposal
- For wells closed (27.5% of facilities), owners/operators will incur closure costs to seal well to prevent future use for disposal, with 35% of these wells having soil around them requiring remediation, with one-third of the wastes going to each of the disposal/treatment facility types (either hazardous waste thermal treatment, nonhazardous waste thermal treatment, or nonhazardous waste landfill)

Waste Stream Characterization (pp. 26–27)

- Of the 12 waste stream types modeled, automotive service-related facilities are divided into service-related facilities with low flow rates of 2000 gallons/year and dealerships with high flow rates of 20,000 gallons/year

Best Management Practices (pp. 28–29)

- BMPs will improve the quality of the injectate to meet MCLs and decrease the volume of wastewater to be disposed
- BMPs can be categorized as (1) good housekeeping, (2) parts washing, or (3) solvent recovery, and more than one may be applied at a site depending on the waste streams:
  - Good housekeeping includes spill collection devices, improved handling practices, and labeling and inventory controls with capital costs of $1727 and O&M costs of $1267 per facility (p. 29).
  - Most motor vehicle service-related facilities will utilize both good housekeeping and parts washing, with the latter BMP having capital costs of $7484 and O&M costs of $1686 per facility.
  - Aircraft services will generate wastes of organic solvents, with solvent recovery having capital costs of $26,966 and O&M costs of $4,606 per facility.
- BMPs are assumed to be applied to reduce the wastewater flow off-site by 50% based on the following expected practices that result in
  - Good housekeeping BMPs, 10%–40% flow reduction
  - Parts washing and solvent recovery, 40%–80% flow reduction
  - Process modification, 50% flow reduction
- Highly concentrated wastes will be disposed of as hazardous wastes. Use of Class V wells for hazardous waste disposal is illegal; however, "(b)ased on past experience about 13% of motor vehicle waste disposal wells are assumed to inject some hazardous waste." Additionally, some facility managers may decide to concentrate their waste thereby decreasing the quantity for "more cost-effective" disposal in hazardous waste treatment off-site (p. 35).

Injectate and Sludge Monitoring (pp. 29–31)

- No injectate and sludge monitoring would occur under the "Ban" option.
- The option to ban with waiver permits to operate would necessitate monitoring (including sampling, analysis, and recordkeeping) the injectate and sludge liquids to determine whether they are in compliance with MCLs on the schedule described above.

  - Organic constituents monitoring costs: initial and annual monitoring of $493/well
  - Organic and metal constituents monitoring costs: initial and annual monitoring of $647/well
  - Monitoring costs of organic constituents with oil and grease: initial and annual monitoring of $586/well
  - Quarterly injectate compliance monitoring for first 3 years has costs of $1658–$2272/well
  - Annual sludge sampling cost: $1192/facility

Sludge Disposal (p. 31)

- If sludge monitoring finds concentrations exceeding MCLs, the sludge disposal cost estimate per well is $737.

Permit Applications (p. 31)

- Labor to prepare and apply one time for a permit to continue operating a motor vehicle waste disposal well that meets MCLs is estimated to be $1300.

Well Closure (pp. 31–33)

- Owners/operators must notify the state of decision to close a motor vehicle waste disposal well with an estimated cost of $41/well.
- Well closure costs are for "pipe flushing, pipe plugging, wastewater disposal, and well backfilling" with an average cost per well used for organic wastes is estimated to be $1293. When solvent recovery is involved, filling pipes with grout increase closure costs per well to $3480. Soil testing must also be done for closed wells with an annualized cost to owners/operators of $365 (p. 32).
- An expected 10% of facility owners/operators will hire outside contractors to assist in complying with requirements with an average cost for such facilities of $2713.

Off-Site Treatment and Disposal (pp. 33–36)

1. Disposal and treatment types include
   a. Waste exchange (reuse and recycling)
      - All waste streams with high organic content are candidates.
      - Impractical for wastes with low organic concentrations.
   b. Hazardous waste treatment
      - High concentration wastes are characterized as hazardous for treatment purposes.
   c. Nonhazardous waste treatment
      - Low organic concentration wastes are treated as nonhazardous.
   d. Publicly owned treatment works
      - Do not treat wastewater with high concentrations of both organic and metal wastes.
   e. If more than one waste management alternative can be utilized, owners/operators will use them in equal ratios, but 50% of wastes are assumed to go to waste exchanges with the remainder going in equal quantities to the other options if more than two alternatives are available.
2. For waste streams requiring off-site disposal,
   a. Transportation distances and associated costs applied were
      - 40.2 km for a POTW at $1.61/km/m^3$
      - 80.5 km for a nonhazardous waste facility at $1.61/km/m^3$
      - 321.9 km for a hazardous waste facility at $0.66/km/m^3$

b. No pretreatment or segregation are assumed and estimated off-site disposal costs were
  - \$0.49/m^3 at a POTW
  - \$0.41/L at a nonhazardous waste facility
  - \$0.55/L at a hazardous waste facility

Soil Sampling and Remediation

1. For wells required to close, owners/operators must test soil samples at an estimated cost of \$3871 per well. If contaminated, which is assumed at 35% of wells to be closed, soil must be excavated and properly disposed.
  a. Average facility will need to remediate 30.6 m^3 of soil (50.8 metric tons).
  b. Average excavation cost of \$1680 (assuming average cost per metric ton of \$33) per facility.
  c. Soil from two-thirds of the 35% of closed wells will be considered nonhazardous waste for treatment purposes with the remainder going to hazardous waste facilities.
  d. Nonhazardous waste soils have associated costs of
    - \$392 per facility for transportation
    - \$33/metric ton for disposal at a landfill for 50% of the 67% that involve nonhazardous soils
    - \$55/metric ton for disposal at a nonhazardous waste thermal treatment facility for the remaining half of the 67% that have nonhazardous soils
  e. Hazardous waste soils have estimated costs of
    - \$2698/facility at \$58/metric ton
    - \$386/metric ton for thermal treatment

Other Administrative Costs

1. Owners/operators will incur costs of \$164 once to read the regulations, contact the enforcement agency concerning whether their wells are in groundwater protection areas or sensitive groundwater areas, and for recordkeeping.

COST ESTIMATES

Cost estimates were developed based on costs of equipment, operation and maintenance, and labor time for the activities that owners and operators of injection wells would take in responding to the regulation for each waste stream and BMP. "The analysis … calculates an average annual capital cost, assuming that capital costs are annualized using a 7 percent interest rate and a 20-year payback period for each well owner." (p. 37) Since each SIC (industrial) category is assumed to have at least two waste streams, "the analysis … calculates the weighted average facility costs in each SIC category … [which] produces the weighted average capital and O&M costs that are applied to all facilities within" each SIC category. (p. 38) Details of these costs are available from "Economic Analysis for the Proposed Revision to Underground Injection Control Regulations for Class V Injection Wells," Volume 2 (Draft) (USEPA, 1998). Exhibit CS5.2 provides a waste stream characterization, associated flow rate and a relative indication of the occurrence of organic and metal contaminants in the waste stream. The summarized capital and operation and maintenance costs by activity are provided in Exhibit CS5.3 for best management practices associated with the respective industrial process.

Several other processes and assumptions are noted in the description of this economic assessment of costs. First, a listing of the major steps in deriving costs for motor vehicle waste disposal wells is given, followed by additional assumptions in the costing of the decision process and alternatives treatments.

EXHIBIT CS5.2 WASTE STREAM CHARACTERIZATION OF MOTOR VEHICLE WASTE DISPOSAL WELLS

		Waste Characterization		
		Organics		
Group Label	Annual Flow Rate	Low	High	Metals
A	Low	X	—	—
B	Low	—	X	—
C	Low	X	—	X
D	Low	—	X	X
E1	Low	X[a]	—	—
E2	Low	—	X[a]	—
F1	High	X[a]	—	—
F2	High	—	X[a]	—
G	High	X	—	—
H	High	—	X	—
I	High	X	—	X
J	High	—	X	X

Source: U.S. Environmental Protection Agency (USEPA), Underground injection control Regulations for Class V injection wells, revision; Final rule, 40 CFR Parts 9, 144, 145, and 146. Federal Register, Vol. 64, No. 234. December 7, 1999, p. 27.

[a] These waste streams, which best represent motor vehicle waste fluids, are likely to contain oil and grease in addition to other organics.

Major Steps in Deriving Costs

1. An inventory of motor vehicle disposal wells by state
2. Estimations of the number of wells within and outside of groundwater protection areas and potentially in sensitive groundwater areas
3. Sampling and monitoring cost estimates by waste stream, including
   a. Contracted field sampling labor
   b. Contacting laboratory and supervising sampling
   c. Decontamination and disposal of materials
   d. Laboratory analysis of oil, grease, VOCs, and metals
   e. Reporting and recordkeeping

   Notably, waste streams A, B, G, and H had the lowest compliance costs (onetime annual $494; quarterly over year, $1658) and C, D, I, and J had the highest costs ($647; quarterly over year, $2272).
4. On-site treatment cost estimates (as a percentage of on-site treatment capital costs) by waste stream, including

EXHIBIT CS5.3 WASTE STREAM CHARACTERIZATION AND BEST MANAGEMENT PRACTICE BY SIC CODE

SIC Code	Brief Industrial Description	Flow Rate/ Waste Category	Best Management Practice (BMP) Process Description	
			Capital	Operation & Maintenance
BMP Category 1: Good Housekeeping				
5531	Auto and home supply stores	A, G	1. Install collection devices 2. Improve handling process Total capital costs = $1,727	1. Labels/inventory 2. Keep floor clean 3. Improve handling process Total O&M costs = $1,267
9111	Executive offices	A, G		
BMP Category 2: Parts Washing				
4142	Bus charter service, except local	E1, E2	1. Install collection devices 2. Recycle wastes in on-site solvent units 3. Improve handling process Total capital Costs = $7484	1. Labels/inventory 2. Recycle wastes in on-site solvent units 3. Keep floor clean 3. Improve handling process Total O&M costs = $1686
4212	Local trucking, without storage	E1, E2		
4213	Trucking, except local	E1, E2		
5015	Motor vehicle parts, used	F1, F2		
5511	Motor vehicle dealers (new and used)	F1, F2		
5521	Motor vehicle dealers (used only)	F1, F2		
5541	Gasoline service stations	E1, E2		
7514	Passenger car rental	E1, E2		
7515	Passenger car leasing	F1, F2		
7532	Top, body and upholstery repair shops and paint shops	E1, E2		
7533	Auto exhaust system repair shops	E1, E2		
7537	Automotive transmission repair shops	E1, E2		
7538	General automotive repair shops	E1, E2		
7539	Automotive repair shops, NEC	E1, E2		
7549	Automotive services, except repair and carwashes	A, B, G, H		

(*continued*)

EXHIBIT CS5.3 (continued) WASTE STREAM CHARACTERIZATION AND BEST MANAGEMENT PRACTICE BY SIC CODE

SIC Code	Brief Industrial Description	Flow Rate/ Waste Category	Best Management Practice (BMP) Process Description: Capital	Best Management Practice (BMP) Process Description: Operation & Maintenance
BMP Category 3: Solvent Recovery Unit				
4581	Airports, flying fields, and airport terminal services	C, D, I, J	1. Install collection devices 2. Keep floors clean 3. Mechanical devices for material removal 4. Improve handling process 5. Install built-in distillation unit 6. Operate distillation unit Total capital costs = $26,966	1. Labels/Inventory 2. Keep floor clean 3. Improve handling process 4. Prewashing 5. Maintain and calibrate equipment 6. Inspect and repair gaskets 7. Inspect air relief valves 8. Inspect baffle assembly bi-weekly Total O&M costs = $4606

- a. Permitting, administration, and legal fees (5% of capital costs)
- b. Contractor's overhead and profit (15%)
- c. Engineering design (10%)
- d. Contingencies (10%)
- e. Operation and maintenance costs (5% of capital costs), including annual monitoring to establish compliance

For on-site treatment capital costs, the lowest was waste stream A (low-flow, low concentration of organic waste) at $17,000, while the highest cost was waste stream J (high-flow, high concentration of organic and metal wastes) at $95,300 per well.

Labor, materials, and power comprise the main operation and maintenance (O&M) costs. "The labor cost is assumed to be a function of the treatment system, hours of operation, maintenance calls, system complexity, number of changeouts (e.g., replacement of pre- and post-filters, granulated activated carbon, [GAC] filters, and ion exchange column), and sludge production rate. Treatment system materials include filters, GAC units, coagulant, acid/base, and ion exchange resin" (p. G-1). The range in O&M costs per well was $2,600–$21,900, respectively, for waste streams A and F2.

5. For off-site disposal/treatment, the following costs were included in the calculations:
   - a. Soil and sludge monitoring
   - b. Excavation of contaminated soil
   - c. Disposal or treatment of contaminated soil and/or sludge at one or combination of a hazardous waste thermal treatment facility, a nonhazardous waste thermal treatment facility, or a nonhazardous waste facility, as well as a waste exchange if the sludge had properties that allowed it to be reused or recycled, including labor, capital, and O&M costs
   - d. Administrative costs

NATIONAL COST OF THE REGULATION

To calculate the number of motor vehicle waste disposal wells that fall within groundwater protection areas, EPA assumed that States will delineate groundwater protection areas by using areas of one-half mile radius around water supply wells for groundwater community water systems and of one-quarter mile radius around water supply wells for groundwater nontransient noncommunity water systems. (The economic assessment estimated the universe of motor vehicle waste disposal wells in the United States to be 21,692 [p. B-3]). The number of affected motor vehicle wells is now estimated to range from 3035 to 9903 (compared with 7045 estimated for the proposed rule). This range is based on the amount of land area that States may delineate as sensitive. The estimated average annual cost per facility to owners and operators of motor vehicle waste disposal wells is between $4,450 and $11,000 depending on the waste streams generated by the facility (USEPA, 1999, p. 68559). Thus, the national estimated average annual cost of the regulation of motor vehicle waste disposal wells is from $13,505,750 (= 3,035 wells × $4,450/well), assuming the least number of wells and lowest costs of operation, remediation, and closure, to $108,933,000 (= 9,903 wells × $11,000/well), assuming the largest number of wells being affected with the highest costs.

DISCUSSION

National costs must be offset by equal or greater benefits for a regulation to be determined as economically viable and effective. In the case of regulation of motor vehicle waste disposal wells, the benefits of regulation were the cost savings, which were never estimated, from avoiding extensive, potentially long-lasting, and expensive contamination of nearly every significant community water system and noncommunity nontransient water system relying on groundwater and having a nearby motor vehicle waste disposal well at a service station or airport. In the United States, these costs ($4,450–$11,000 annualized cost per motor vehicle waste disposal well over 20 years in 1998 $US) could be compared with the avoided costs of groundwater remediation to provide safe water in the case studies on wellhead protection at community water systems, which ranged from approximately $323,000 to $4 million (net present value in 1996 $US) per well affected by contamination.

REFERENCES

EPA. 2004. UIC Class V Wells Fact Sheet. URL: http://www.epa.gov/safewater/uic/c5fin-fs.html (accessed October 11, 2004)

U.S. Environmental Protection Agency (USEPA). 1998. Economic analysis for the proposed revision to underground injection control regulations for Class V injection wells, Vol. 2 (Draft). May 12, 1998. 77 pp.

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U.S. Environmental Protection Agency (USEPA). 2004. What is the underground injection control program? URL: http://www.epa.gov/safewater/uic/whatis.html (accessed October 11, 2004).

Case Study 6: Contingent Valuation of Municipal Water Supply

BACKGROUND

The World Bank conducted several studies of willingness to pay for water by families in a number of countries, one of them being in Brazil (the focus of this case study), which used contingent valuation as its technique for valuing water. Underlying the survey is the goal to provide fundamental access to water for poor populations, while maintaining a financially viable local water system. The project examined the values placed on water by 200 families in three communities: Ceará, Minas Gerais, and Paraná, which rely on groundwater for their water supply. Within these communities, families were categorized into the following groups:

A1—already connected to distribution line of available central water system (Ceará, Minas Gerais, and Paraná)
A2—chose not to connect to distribution line of available central water system (Ceará and Paraná)
B1—no distribution line available but to be offered connection at prevailing price (Paraná)
B2—no distribution line available but to be offered connection at price to be established (Paraná)
B3—neither connection nor price yet established (Ceará and Paraná)

OTHER INFORMATION ABOUT THE SURVEY

Established price in communities with central water system and distribution line: 41 cruzados.

Socioeconomic characteristics collected: income, assets, employment, education, family size, current level of water service, distance from house to water service, dependability of water source, and residents' view of current water quality.

Basic question to respondents: At a price of X cruzados per month, would they obtain their water from the distribution line or from another source?

Response Choices: Bid prices offered ranged from 50 to 200 cruzados for families already with service; 0 to 40 cruzados for families with distribution line nearby but not connected; 10 to 200 cruzados for families without distribution lines; 0 to 10 cruzados for families without distribution line but having public taps nearby; and 15 to 100 cruzados for families without distribution line but desiring connection to one.

All A1, A2, B1, and B2 communities had choices in the survey of either connection to the distribution line or access to a public tap. The B3 communities also had a third choice of an alternate unimproved source. These choices were to provide the opportunity to determine response to range of personal strategies for acquiring water.

Analysis of results: The data were analyzed through regression analysis with the output indicating the following:

- The price elasticity of a private connection was −0.47, meaning that a 2% increase in charges for receiving water from a private connection results in a 1% reduction in use of the private connections.

- A rise in the price of using public taps decreases the families relying on them, but the decrease is minimal.
- Where perceived water quality or service is not dependable, if the price for private connection rises, a substantial number of families would choose to obtain free water from public taps.
- The average willingness to pay for an improved water source at the time of the survey (assumed 1987) was 100 cruzados. In areas without distribution lines, the lower bound on maximum willingness to pay was 74 cruzados where a price was established for future service and 56 cruzados where no price was previously set. These bid prices are considered lower bound because of the possibility that the respondents might be trying to indirectly communicate through the survey an interest in receiving improved service at a lower cost since they do not yet have service.
- Assuming a very small marginal cost associated with installing public taps and the low cross-price elasticity of private connections and public taps (0.04), the analysis supports the concept of placing public taps near poor areas of the community without concern that use of private connections will decline.
- Higher-income families in these communities benefit from the private connections (the difference in their willingness to pay and the current charge). Poorer families benefit from free public taps.
- The results suggest that rural communities can operate financially viable water systems and ensure equitable water availability to poor families through subsidizing free public taps.

DISCUSSION

This study highlights both value and equity concerns particularly relevant in a time of increasing demand for groundwater. Policy makers will need to continue to weigh these factors in setting rates for water supply. It is not obvious how these results would apply in an area that is depleting its aquifer. This may be a fruitful subject for future research.

REFERENCE

Briscoe, J., Furtado de Castro, P., Griffin, C., North, J., and Olsen, O. 1990. Toward equitable and sustainable rural water supplies: A contingent valuation study in Brazil. The International Bank for Reconstruction and Development, The World Bank. *The World Bank Economic Review*, 4(2), 115–134.

Case Study 7: Determining Water Rates

Determining a water rate, which is the price a consumer pays for water delivered by a water utility to his or her residence or company, is well documented for a range of methods (NRRI, 1990). A water utility may be publicly owned or privately owned. Ownership makes a difference, since the water rate for privately owned utility includes a return on equity (ROE), a payment expressed as a percent that is made to shareholders who provided capital for the utility. Water utilities typically do not sell water in competitive markets, so they are treated as monopolies. As a result, their water rates are set by a unit of government, a municipality, or other local government in the case of most publicly owned utilities, or by a state utility commission in the United States in the case of privately owned utilities. A water rate may be treated as a value of water in the uses to which the rate applies. The utility presents its expenditures, which are in turn recognized as needing a revenue stream to be paid by consumers based on rates applied to projected amounts of water purchased. For the purposes of this discussion, a simple approach will be described, followed by a case example. Water rates are determined based on the expenses of the water utility, which generally include the following expenditures in Exhibit CS7.1:

The simple cost-of-service approach that relies on a specified rate of return (ROE) on the utility's capital investment follows from this basic equation (NRRI, 1990, p. 40):

$$\text{RR} = \text{O\&M} + D + T + r(\text{RB})$$

where

RR = annual revenue requirement

O&M = annual operation and maintenance expenses

D = annual depreciation expense (representing the change in the value of the utility's property from last year to the current year, usually set by law or the regulatory agency)

T = annual taxes (sales and income)

r = rate of return

RB = rate base (adjusted for accumulated depreciation)

(Rate base is the value of a water utility's property used in computing an authorized return under the applicable laws and/or regulatory policies of the agency setting rates for the utility. [NRRI, 1990, p. 193])

The revenue requirement, RR, is used then in setting water rates, usually by customer category (such as residential, commercial, agricultural irrigation) and/or by time of year (such as winter and summer). A range of rate-setting techniques are available and were summarized previously.

If a water utility used marginal cost to set its price for a unit of water, it might use the simple marginal cost formula (NRRI, 1990, p. 82):

$$\text{SMC}_t = \frac{(R_t - R_{t-1}) + I_t}{(Q_t - Q_{t-1})}$$

EXHIBIT CS7.1 REVENUE REQUIREMENTS FOR A WATER UTILITY

EXPENDITURE COMPONENTS

Operation and maintenance expense
Source of supply (for groundwater, operation and maintenance of wells)

- Pumping:
  - Power
  - Others
- Treatment:
  - Chemicals
  - Others
- Transmission and distribution:
  - Distribution reservoirs
  - Transmission mains
  - Meters
  - Distribution mains
  - Services
  - Fire hydrants
  - Others
- Customer billing and collecting:
  - Meter reading
  - Billing and collecting
  - Others
- Administrative and general:
  - Fringe benefits
  - Others

Debt service requirements (payment of principal and interest on loans)
For privately owned utilities: ROE of shareholders
Payment in lieu of taxes for publicly owned utilities or taxes for privately owned utilities
Annual requirements for replacements, extensions, and improvements
Sum of expenditures equals total revenue requirements

Source: Modified from NRRI, 1990, p. 41

where
t = the year for which the calculation is being made
R = operating and maintenance expenditures
I = capital investment becoming operational
Q = water output

This formulation of marginal cost may result in substantial differences in the marginal cost from year to year because it does not spread the capital investment over the time it is used. A second formulation that takes into account marginal capital cost is (NRRI, 1990, pp. 82–83)

$$\begin{aligned} \mathrm{MC}_t &= \mathrm{SRMC}_1 + \mathrm{MCC}_1 \\ &= \frac{(R_t - R_{t-1}) + rI_t}{(Q_t - Q_{t-1})} \end{aligned}$$

where

$SRMC_1$ = short-run marginal cost
MCC_1 = marginal capital cost [capital expenditure increments]
r = the capital recovery factor or the annual payment that would repay a unit loan over the economic life, n years, of the capital expenditure with compound interest of I on the unpaid balance; that is,

$$r = \frac{i(1+i)^n}{(1+i)^n - 1}$$

This second formulation reflects only the costs in the respective years under evaluation. A third formulation considers investment costs over a longer planning horizon and is referred to as the average marginal cost method (AMC) or average incremental cost (AIC). It is represented as (NRRI, 1990, pp. 84–87)

$$\text{AIC} = \frac{\text{Present worth of the least-cost investment stream}}{\begin{array}{l}\text{Present worth of the incremental output stream}\\ \text{resulting from the capacity investment}\end{array}}$$

This method for calculating allows for varying investments over the planning horizon and focuses on short-run allocation efficiency by utilizing the least-cost investment stream. Other methods and approaches may also be used in particular circumstances to set water rates.

Whatever approach is used to determine water supply costs or required revenues, the amount must be divided by the appropriate water volume, which is itself a matter of deliberation, such as full capacity (considering peak or design capacity), historic trends projected, or some other appropriate measure. This calculation would result in a unit price to the customer. Water rates are just one measure that is used to estimate the value of water.

Additionally, factors affecting the cost of capital are significant in determining water rates. In the example below, these factors are shown in some detail. The cost of capital is usually considered to have two main components: cost of debt (basically, the interest rate for borrowing funds) and the ROE (the ROE required by investors, if the utility is privately owned). The cost of debt is typically derived from market interest requirements above the 30 year U.S. Treasury Bond rate in the United States. The ROE is the product of the combined effect of market rates expected by investors for the category of utility and the risk premium (RP) rate reflecting the operating conditions of the particular utility. A comparison of discounted cash flow (DCF) rates for similar utilities can provide an average market return. Relative to RPs, in the example summarized below, the Public Utility Commission of California noted generally that:

"Risk factors consist of financial, business and regulatory risk. Financial risk is tied to the utility's capital structure. The proportion of its debt to permanent capital determines the level of financial risk that a utility faces. As a utility's debt ration increases, a higher return on equity may be needed to compensate for that increased risk.

Business risk pertains to uncertainties resulting from competition and the economy. That is, a utility that has the most variability in operating results has the most business risk. An increase in business risk can be caused by a variety of events that include poor management, and greater fixed costs in relationship to sales volume.

Regulatory risks pertain to the impact on risks that investors may face from future regulatory actions that we, and other regulatory agencies, might take. These risks are assessed to determine whether there is a need to increase or decrease a ROE to compensate investors for added or reduced risks" (CPUC, 2004, 55–56).

An RP is a return required by investors over and above that of market rates (FitzGerald, 1997, 6) that reflects specific factors affecting the entity being invested in, expressed in equation form as

$$\text{Cost of equity capital} = \text{Risk-free rate} + \text{Equity RP}$$

(modified from FitzGerald, 1997, 7)

The Commission then noted that
"Ultimately, the choice of factors used to measure an appropriate return on investor's equity is a matter of judgement" (CPUC, 2004, 57).

A specific example is presented to describe the factors incorporated in the water rate setting for one location, Fontana, California, and environs. Other jurisdictions may consider other factors than described below.

WATER RATE EXAMPLE: FONTANA, CALIFORNIA*

The California Public Utilities Commission (CPUC) sets water rates for investor-owned water utilities in California. The San Gabriel Valley Water Company's (SGVWC) Fontana Division (FD), a groundwater supplier, serves 37,000 customers in portions of Fontana, Rancho Cucamonga, Rialto, and vicinity, in San Bernardino County, California, and requested a decision on a water rate increase in November 2002. The Commission drafted a decision in March and then revised it in May 2004 (the copy of the final decision different from the last draft was not available). The Commission evaluated a range of factors relevant to the deliberation, including

- Forecast average residential customer usage is 32,100 cubic feet per year (908,971 L/year)
- Nearly unable to provide water for peak demand in the summer of 2003
- Four years of reduced rainfall
- Groundwater table levels dropping
- Perchlorate contamination of groundwater resulted in closure of seven water supply wells and loss of 30% of peak summer capacity
- No final plan exists for recovering well closure and replacement costs from polluters
- Demand is growing in excess of 1000 new connections each year
- Interconnection to neighboring water supplier is for emergency purposes only and not for ongoing water supply

Unaccounted for water averages 6.8% per year.

Reclaimed water is available from the city but no distribution system is in place to supply it to potential users.

During the process of considering these issues, the state Commission received comments from the public, including Fontana City and School District, companies, individuals, and an office representing ratepayers. From the Commission record, it appears that most of these persons and representatives did not favor a rate increase for SGVWC/FD.

The Commission examined operating and maintenance costs; plant, equipment, and materials (components of the utility's rate base); and the utility's cost of capital. The city, local school system, and ratepayers commented on the request and did not support the increased water rate.

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* *Source:* Public Utilities Commission of the State of California (CPUC), In the Matter of the Application of San Gabriel Valley Water Company (U337W) for Authority to Increase Rates Charged for Water Services in its Fontana Water Company Division, Alternate Draft Proposed Decision of ALJ Patrick, Agenda ID #3568. Application 02-11-044, May 13, 2004, 74 p.

Operating and maintenance costs, which the Commission considered, included

1. Supply cost expenses
    a. Unmetered and unaccounted for water
    b. Reclaimed water
    c. Water purchases from neighboring water district
    d. Water costs
    e. Purchased power costs
    f. Chemicals expense
    g. Treatment plant reimbursements
    h. Labor costs for new positions
2. Other expenses
    a. Materials and supplies
    b. Transportation
    c. Outside services other than legal
    d. Outside legal services
        i Non-perchlorate related
        ii Perchlorate related
    e. Utilities and rents
    f. Employee pensions and benefits
    g. Regulatory Commission
    h. Labor costs for administrative and general purposes

Total O&M expenses were not reported in the decision, but are available in appended documents for viewing at the state Commission offices.

The portion of the Commission's decision dealing with components of the rate base had more detailed and complete financial information published with it. These components covered plant, equipment, operating systems, vehicles and structures, as well as other items. Components of the rate base are as described in Exhibit CS7.2.

EXHIBIT CS7.2 SAN GABRIEL VALLEY WATER COMPANY, FONTANA DIVISION (CALIFORNIA), RATE BASE

To substantiate the rationale for increasing water rates, the SGVWC, FD, had to identify the additional capital items that justified its request. The Commission approved items are briefly listed below, with cost information if available in the decision document without appendices.

Plant additions

1. Wellhead treatment facilities and surface water treatment
    - Upgrades to existing treatment plant: $3.0 million
    - Seven wellhead treatment plants to remove perchlorate: $1.75 million each
2. Wells to meet peak summer demand
    - Three new wells in 2003
    - One new well in 2004
3. New reservoirs
    - Six new reservoirs to be constructed in 2003 and 2004 costing $4.55 million
4. Booster stations
    - Booster stations needed at 5 sites to move water to zones requiring higher pressure, costing $395,000

(*continued*)

EXHIBIT CS7.2 (continued) SAN GABRIEL VALLEY WATER COMPANY, FONTANA DIVISION (CALIFORNIA), RATE BASE

5. SCADA system
    - Supervisory control and data acquisition system (SCADA) to monitor and manage wells, pumps, treatment, and water flow needed for operating 34 wells and 5 pressure zones, proposed to cost $1.2 million
6. Security equipment
    - Protective devices and equipment needed to avert malevolent acts to the water supply in alignment with government and industry measures to cost $1 million
7. Emergency generators
    - Four emergency generators to operate wells, pumps, and treatment plants when electrical power is interrupted, costing $400,000
8. Water treatment and distribution mains
    - Water transmission and distribution mains proposed to cost $7,470,000
9. Vehicles
    - Transportation equipment for replacing used vehicles and for expanded staff to cost $270,000 per year
10. Tools and equipment
    - For 2003, tools and equipment costs of $125,000, and in 2004, $5,000
11. New building
    - Land purchase for future new administrative building, cost not specified in the decision document

Materials and supplies

- SGVWC/FD estimates for materials and supplies were accepted by the state Commission but not published in the decision document

Construction work in progress

- SGVWC/FD estimates for construction work in progress were accepted by the state Commission but not published in the decision document

Fontana Union Water Company Stock

- SGVWC holds stock in the amount of $747,800 in Fontana Union Water Company, which is its primary water supplier

Working cash

- Funds permanently committed for operating expenses and maintaining open bank accounts in the amount of $631,000 in 2003 and $739,000 in 2004

Plant sales/condemnation proceeds

- Net plant sales and condemnation proceeds of $2,320,909 that resulted from governmental taking through condemnation and damages from contamination of its groundwater source by other parties

Cost of capital

1. Capital structure
    - The state Commission determined that the capital structure for SGVWC should be divided between 40% debt and 60% equity to allow this small Class A water utility to sell bonds with reasonable terms and finance planned and unanticipated needs in a way to support public demands

EXHIBIT CS7.2 (continued) SAN GABRIEL VALLEY WATER COMPANY, FONTANA DIVISION (CALIFORNIA), RATE BASE

2. Effective cost of long-term debt
    - The state Commission found that the costs of new long-term debt issues for SGVWC should be based on the 30 year U.S. Treasury Bond rate plus 246 basis points, resulting in Commission-adopted costs for the utility of 8.04% for 2004 and 8.82% for 2006. The average embedded costs of debt are then 8.38%, 8.36%, and 8.35% for the years 2003–2005, respectively (no calculations provided in the decision document).
3. Equity cost
    - Since the utility investors are entitled to a reasonable rate of return on its property used to provide water, the Commission considered ROE estimates derived from both DCF and RP rates. The Commission evaluated DCF rates of return on equity (also referred to as DCF growth rates) from seven similar utilities and RPs based on 5 and 10 year returns on 10 and 30 year U.S. Treasury Bonds.
    - Risk factors cited by SGVWC in addition to those noted above were (CPUC, 2004, 60)
        - "Contamination of its water supplies, including uncertainty as to the availability of its wells"
        - "Increased investment needs"
        - "Ongoing and future costs of defending lawsuits alleging tort liability"
        - "Further risks to San Gabriel's earnings due to the erratic availability of surface water supplies"
        - "The lack of financing flexibility for a closely held company like San Gabriel"
        - "The asymmetric treatment of water supply costs under the new balancing account rules adopted by the Commission"
    - The Commission determined that the ROE would be 10.10% for the years 2003–2005.
    - The Commission approved a weighted cost of capital, including both debt and equity, for the utility of 9.41% and 9.40% for years 2003–2005 as shown in the following table (CPUC, 2004, 62):

Year: Capital Category	Capital Ratio (%)	Cost Factor (%)	Weighted Cost of Capital (%)
2003: Long-term debt	40	8.38	3.35
Common equity	60	10.10	6.06
Total	100		9.41
2004: Long-term debt	40	8.36	3.34
Common equity	60	10.10	6.06
Total	100		9.40
2005: Long-term debt	40	8.35	3.34
Common equity	60	10.10	6.06
Total	100		9.40

REVENUE RECOVERY ISSUES

1. Balancing and memorandum accounts
    - The Commission approved SGVWC to recover through amortization of costs for uncollected balances as a surcharge or surcredit of the following costs "calculated using… Year 2004 sales, with interest on the balances continuing to accrue at the 90 day commercial paper rate" for a period of 12 months (CPUC, 2004, 63):

Balancing and Memorandum Account	Balance	Date of Balance	$/100 ft^3
Water production	($1,329,744)	December 2002	($0.0678)
Purchased power	$2,990,913	December 2002	$0.1526
Water quality litigation	$1,027,047	July 2003	$0.0520
DOHS/EPA compliance	$32,413	December 2001	$0.0017
Total	$2,720,629		$0.1385

2. Continued need for the full cost balancing account
    - The Commission considered approving continued future "full cost balancing accounts" for water production and purchased power because of the highly variable water supply mix and associated power demands.
3. Requested water quality memorandum account
    - SGVWC requested establishment of a water quality memorandum account to record costs of treating contaminated groundwater and proceeds from polluters or the government, which would be used in turn to reduce consumers' water rates.
4. Proposed low-income rate program
    - SGVWC also asked for approval to organize and conduct a program to subsidize water rates for qualifying low-income customers.

The draft decision covers other aspects of the Commission's authority over the utility, which will not be summarized here.

The June 2004 water rates for SGVWC were a flat $0.38 per cubic meter, with a $10.36 m charge for most residential and small water users (SGVWC, 2004).

DISCUSSION

In its deliberation over the rate increase for SGVWC, the state Commission did not consider willingness to pay. From comments received, it may appear on the surface that the locality's interests were not willing to pay more for groundwater, in spite of the significant problems of water availability and contamination. From the record, it is clear that depletion rates were not considered, nor were an increasing block rate or seasonal rate, to reflect times of relative groundwater scarcity. The Commission did address an equity issue in the matter of subsidized rates for low-income consumers. The Commission took a strict "cost of service" approach in establishing a water rate for Fontana.

REFERENCES

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National Regulatory Research Institute (NRRI). 1990. *Cost Allocation and Rate Design for Water Utilities*. NRRI, Columbus, OH, 210 pp.

Public Utilities Commission of the State of California (CPUC). 2004. In the matter of the application of San Gabriel Valley Water Company (U337W) for authority to increase rates charged for water services in its Fontana Water Company Division. Alternate draft proposed decision of ALJ Patrick. Agenda ID #3568. Application 02-11-044. May 13, 2004. 74 pp.

San Gabriel Valley Water Company (SGVWC). 2004. Schedule No. F0–1, Fontana Water Company, General Metered Service. URL: www.sgvwater.com/tariff/1457-w.pdf (accessed July 16, 2004).

Case Study 8: Groundwater Valuation in Rural Settings

BENEFITS OF PROTECTING GROUNDWATER IN FOUR GEOGRAPHIC REGIONS*

Crutchfield et al. were interested in estimating the benefits of protecting groundwater from agricultural pesticides that might be a risk to rural families through high concentrations in their drinking water. The researchers identified three studies that gathered data on a range of, but not the same, factors, such as age, income, education, awareness of contamination, causes of contamination, risk perception, motives for establishing benefits, and willingness to pay for preventing contamination of their drinking water. These studies had similar objectives of estimating benefits from groundwater protection. The surveys also asked how much the respondents would be willing to pay for that protection. They paired these surveys with other information available on farm costs and returns from U.S. Department of Agriculture data used a proxy for income and data on groundwater impairment from the U.S. Geological Survey. Drawing on the regression equations of the earlier studies, the Crutchfield team developed a new regression analysis that could relate the previous respondents' answers to income and actual contamination in their areas in Washington, Indiana, Nebraska, and Pennsylvania–Maryland. The range of estimated willingness to pay for groundwater protection was \$197–\$730 million. Willingness to pay related well to environmental impairment in the area and to information about contamination.

HEDONIC PRICING: MARKET VALUE OF GROUNDWATER BASED ON CROP VALUE†

The Ogallala (or High Plains) Aquifer is a vast subsurface water body underlaying 450,658 km^2 of portions of South Dakota, Kansas, Nebraska, Wyoming, Colorado, Oklahoma, Texas, and New Mexico. The aquifer contains 4.317 km^3 of groundwater. The Ogallala does not receive much recharge and is ostensibly a nonrenewable stock resource. Because of the increasing cost of pumping from an aquifer with a declining water table, farming was converting from irrigated agriculture to dryland production. A New Mexico State University study calculated the value of groundwater in the aquifer as the difference between crop production sales of irrigated and dryland farming. The data set contained information from more than 7200 sales of irrigated and dryland farms, with the difference being a water value. Dividing the farm sales value by its area and then further dividing by the aquifer thickness gives the water value in hectare–meters. Derivation of in-storage water values assumed average depths to water in the northern, central, and southern Ogallala to be 30.48, 30.48, and 45.72 m, respectively, with associated pumping costs of \$0.005/m^3 in northern and central areas and \$0.007/m^3 in the southern area. Subtracting the pumping costs from the average water value differences in each of the areas resulted in groundwater values of \$0.03/m^3 in the northern and central areas and \$0.009 in the south (assumed 1990 US\$).

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* Crutchfield, et al. (1995).

† Abstracted from Torell, et al. (1990).

CONTINGENT VALUATION OF OPTION PRICE AND VALUE FOR GROUNDWATER IN CAPE COD*

Cape Cod's groundwater resource is the designated sole source of its residents' drinking water. Nitrate levels in this aquifer were rising during the 1980s and 1990s raising questions about groundwater protection. A contingent valuation survey of 1000 persons on Cape Cod focused on the benefits associated with potable groundwater, including a cost-effective water supply for residential use and protecting the resource for future generation's use. Health risk was not a factor in the survey, since it was assumed that the water supplier would take steps to make the drinking water safe. The objective of the survey was to determine the option price and value of residents to protect the groundwater resource. Option price is defined as the sum of the expected value of consumer surplus and option value. In this survey, option value is the bequest value that future generations have safe groundwater. In addition to questions about income, respondents were asked questions about (1) the year of expected future contamination, (2) the probability of nitrate contamination without a regional plan for groundwater management, (3) the probability of contamination with a plan, (4) the price of bottled water, and (5) the annual payment they would be willing to make to prevent contamination of the aquifer. Of those persons randomly selected for the survey, 58.5% responded.

The results indicated that the option value of a protected aquifer serving Cape Cod ranged from \$5 million (assumed 1986 US\$), assuming that nonrespondents had no value for the resource, to \$25 million, assuming that nonrespondents had similar characteristics as the respondents (\$8.1–\$40.4 million in 2001 US\$). This outcome suggests that individuals are willing to pay significantly to protect groundwater for future generation's use. Other results indicate that (1) option price increases linearly with income, (2) the more certain the water supply in the future, the greater the option price, (3) the option value for this survey is 1% or less of the option price when related to the increase in water supply probability, (4) since option prices may be related to personal expectations about resource availability, worse case scenarios most likely overstate benefits of preventing contamination of groundwater, (5) estimation of benefits and costs relative to groundwater resource issues are site specific, considering variations across the country in subsurface conditions, socioeconomic factors, future demand, and individual perspectives about bequests for future generations.

REFERENCES

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* Abstracted from Edwards (1988).

Case Study 9: Wetland Benefits Evaluation*

INTRODUCTION

At the convergence of the Hadejia and Jama'are Rivers in northeastern Nigeria, wetlands provide groundwater recharge as well as a range of economic services. The floodplain is seasonally inundated with water standing on the plain to allow crops requiring such circumstances to grow, as well as providing recharge to a regional aquifer shared by neighboring Niger. The economic and environmental significance of the wetland affect as many as 2 million people locally through the benefits of agriculture, grazing lands, fuel wood, and fishing, and regionally from dry-season grazing, agricultural surpluses, groundwater recharge, and "insurance" resources during droughts. The wetland also provides habitat and offers scientific, educational, and tourism benefits (p. ii).

While much of the floodplain may be dry a substantial portion of the year, the seasonal flooding inundates as much as 700–900 km^2 (270–374 square miles) (p. 1). However, prior to 1964, wetlands existed over 2000–3000 km^2 of the basin. Because of upstream reservoir projects to provide irrigation water, flooding has reduced the wetland area. During the drought of 1984, less than 300 km^2 were flooded (p. 3). The rivers flow through and converge in an area of sand dunes with a height of 10–30 m (32.8–98.4 feet) (p. 2). Precipitation and resulting streamflow are highly variable with 80% of runoff typically generated in August and September. In the basin, rainfall ranges from 500 mm (19.7 in.) in the northeast to 1300 mm (51.2 in.) in the southwest. Because of this seasonal rainfall, agriculture has developed into dryland (locally referred to as *tudu*) farming on more well-drained soils and wetland (called *fadama*) cropping along with grazing and fishing (p. 2). Rain-fed *tudu* crops consist mainly of millet and sorghum, as well as some cotton and groundnuts. The inundated *fadama* farming is primarily rice. Flooded wetlands also provide for significant fishing as well as fuel wood and grasslands for grazing for nomadic pastorialists, who increase the population by as much as 5% during the grazing season in the wetlands (pp. 3–4). Additionally, during the dry season, palm leaves are harvested for a variety of products, including stew and soup ingredients, rope and baskets sold regionally, and bees pollenating the trees and other vegetation produce honey marketed in the area.

The Hadejia–Jama'are floodplain wetlands also provide groundwater recharge and wildlife habitat. These wetlands significantly recharge the Chad Formation aquifers supplying groundwater to Kano and Borno states in Nigeria as well as users in Niger. While the regional groundwater storage under the floodplain was fairly stable during nondrought years, it contracted by 5 trillion m^3 during the 1980s because of drought and resultant decreased inundation and from upstream reservoir development (p. 5). Most groundwater recharge occurs when the floodplain is inundated (p. 7). Groundwater has been accessible by shallow wells using simple buckets and watering points considerable distances from the river (p. 6). Wildlife surveys in the floodplain have found Palaeoarctic and Afro-tropical bird species that migrate through the area, offering potential benefits for research, study, and tourism (pp. 21–22).

In the uplands area of the basin, several reservoir projects have been built or are planned to provide irrigation water to agricultural interests outside the wetland area. The Tiga Dam on the Kano River and the Challawa Gorge Dam on a tributary of the Hadejia River already supply irrigation water to

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* Abstracted from Barbier et al. (1991).

farms. Another reservoir would send water from above the wetlands by way of channels to an area downstream of the wetlands for irrigated agriculture. The dams control water release to the rivers and reduce the inundation of the wetland. The reservoirs also lose water to evaporation and some groundwater recharge and the upland irrigated crops to evapotranspiration, reducing water available downstream for the wetlands and their groundwater recharge (pp. 6–7).

BENEFITS EVALUATION

The evaluation of the Hadejia–Jama'are floodplain wetland benefits first considers the benefits of upstream reservoir development and irrigation and then compares these to the services of the wetlands downstream. At the conceptual level, the direct benefits (from upland irrigated agriculture), B^{D}, less the direct costs (such as the construction costs for dams and water channels), C^{D}, equal the direct net benefits of the reservoir projects:

$$\mathrm{NB}^{\mathrm{D}} = B^{\mathrm{D}} - C^{\mathrm{D}} \tag{1W}$$

The upstream water diversion results in less streamflow supplying the wetlands and their agricultural, timber, and fishing products, groundwater production, and wildlife. Some of these products and services with direct use values can no longer be provided and are lost to the economy. Recreation and tourism (from bird-watching) could also be counted as direct benefits if quantified. Furthermore, nonuse values may accrue and could be accounted for if they are also quantified, such as ecological functions of wetlands and groundwater recharge. "Existence values" may derive from some people's satisfaction in simply knowing that a unique habitat exists in the Hadejia–Jama'are floodplain. Other people may have "bequest values" for protecting and maintaining the habitat for the enjoyment and use of future generations. Still others may obtain "option value" through reserving the floodplain wetlands as they are as "insurance" to mitigate any future loss from not having them available for whatever benefit they could provide, especially if those benefits are anticipated to be significant but now unknown and if the forfeit cannot be reversed. These wetland benefits, B^{W}, less costs in obtaining them, C^{W}, equal the direct net benefits of the wetland:

$$\mathrm{NB}^{\mathrm{W}} = B^{\mathrm{W}} - C^{\mathrm{W}} \tag{2W}$$

[The authors of the paper did not show the step above in Equation 2W. They assumed that the cost of obtaining the benefits of the wetlands as 0 (zero), that is, they occur naturally or are negligible.]

The actual net benefits of the irrigation reservoir project (NB^{P}) are $\mathrm{NB}^{\mathrm{D}} - \mathrm{NB}^{\mathrm{W}}$. The development project may be accepted if

$$\mathrm{NB}^{\mathrm{P}} = \mathrm{NB}^{\mathrm{D}} - \mathrm{NB}^{\mathrm{W}} > 0 \text{ (p. 8)} \tag{3W}$$

Since the wetland benefits are evident, inaction to quantify the loss of wetland benefits will most likely result in a larger value for NB^{P} than would be expected, equivalent to assigning no opportunity cost for floodwater diversion from the wetlands (p. 8).

DISCUSSION

The framework for evaluating wetland benefits in this case study considers different use values for the outputs and benefits. The purpose of evaluating direct use, indirect use, and nonuse benefits focuses on estimating a community's or group's willingness to pay (WTP) for them. Within an economy established under open competition for inputs and outputs, prices in the market will be taken to measure WTP for goods and services. As noted in other case studies, in developing countries, two issues occur in evaluating WTP for the services of wetlands:

1. In some developing countries, prices are affected by government policy to protect the economy and promote national development through setting rates of exchange, subsidizing native production, taxing imports, and other steps. To conduct economic analyses in such instances, "shadow prices" are frequently applied, which "are actual prices "adjusted" to eliminate any distortions caused by policies or market imperfections so as to reflect true WTP. [In this case, since] we are ultimately concerned with the opportunity cost to society of allowing water to continue flowing into the floodplain compared to its diversion for other development uses, then actual prices should be adjusted to reflect economic values" (pp. 10–11).
2. Many goods and services of wetlands are captured by prices in any way. This circumstance applies to the results of natural processes (e.g., groundwater recharge from streams), produce gathered from vegetation on unmanaged open public lands (e.g., palm leaves) in developing countries and "nonuse" values. While valuation methods for these goods and services include travel cost, contingent valuation, and hedonic pricing techniques, their use in distant or isolated settings in developing countries may be tenuous. Other approaches that are not associated directly with WTP but may be used to estimate these values are
    - Indirect substitute
    - Indirect opportunity cost
    - Relocation cost
    - Damage cost avoided

Care should be taken in using these methods since situations and conditions may be very different from those in which the original measurement was done.

An added concern about extrapolating the existing utilization of wetlands is whether the use is sustainable. Current use may exceed the long-term capability of the resource to provide a product or service indefinitely. Such practice should be accounted for in calculating the value of the resource and its services so as not to overestimate benefits. The authors suggest employing an "alternative sustainability scenario" to address this concern, showing when depletion may occur and values would drop to zero. Another way to deal with this issue is to analyze an "environmental compensating project" to the alternatives considered. Such a project would mitigate the effects of the project causing resource damage or adverse effect (p. 12). This approach might be incorporated when renewable resources are affected, which could be the case in wetlands.

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Case Study 10: Groundwater Sustainability to Balance Urban and Agricultural Needs*

BACKGROUND

The North China Plain is a productive agricultural and industrial area in northeast China encompassing 320,000 km^2 and 200 million people over eastern Asia's largest alluvial plain. Irrigated agriculture is the largest water user. Based on the Falkenmark water stress index of 1000 m^3 of water needed per person, the region receives only 1/3 of the water required to support its population from precipitation (500 mm annually), mostly coming in the wet summer months. The area is prone to droughts with nearly 1/3 of the last 500 years having drought. After the drought of 1965, large expansion of wells occurred with 1.2 million existing wells currently. Groundwater level decline exceeds 1 m/year in much of the plain.

This case study focuses on the urban area of Shijazhuang and the surrounding seven counties, an area of 4000 km^2 and approximately 5 million people situated over alluvial deposits of discontinuous strata of gravel, sand, and clay, arranged in a shallow aquifer and a deeper aquifer with more clay and silt and bottom depth of 300–370 m. Most groundwater recharge is derived from precipitation, flow from the mountains to the west, and agricultural return flow. Evaporation of groundwater is negligible with water table declines of 10–50 m since the 1960s. The greatest drawdown occurs in the cone of depression's center of over 50 m. Groundwater flow responds mainly to precipitation and pumping. The South–North Water Transfer is being constructed to bring river water to the North China Plain. Most of the water would be used for irrigation. The implementation of this project also reduces the demand on the aquifer.

HYDROGEOLOGIC MODEL

Scientists applied the MODFLOW computer model of the U.S. Geological Survey to the available groundwater levels data from 1959 to 2004. Groundwater levels data were available from the Hydrogeology and Engineering Geology Survey of Hebei Province with more detailed data for every 3 months for the period 1991–2004. With the model having 17,550 cells in its grid, the research team established a reasonable convergence of the modeled and actual groundwater elevations. Hydraulic conductivity ranged from 20 to 180 m/day. Specific yield for the unconfined aquifer was fixed at 0.1. Based on soil profiles, recharge rates ranged from 5 to 105 cm/year. Irrigation return flow was estimated to be 15%. Results demonstrated that since the 1980s, groundwater is being depleted at a much faster rate, which is unsustainable.

ANALYSIS

The analysis focused on both institutional and economic aspects of current groundwater use. One institutional finding was that no relation exists between groundwater availability and authorization of water production permits. The economic analysis examined optimizing multiobjective models

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* Abstracted from Liu et al. (2008).

that (1) maximized total volume pumped with a minimum hydraulic head maintained in the area and (2) minimized pumping cost across the area while providing a particular volume of water supply.

RESULTS

The results of optimizing the first model showed nearly 500 million m^3 may represent the extent of overexploitation annually. The second model which minimized pumping cost showed that after 60 iterations of the optimization procedure, 19,000,000 Yuan is the cost savings from reduced power consumption, down from 32,000,000 Yuan annually. Conversion of land use from agriculture to urban reduces groundwater use and water level decline. Over the planning horizon out to 2055, water levels could rise between 3 and 15 m.

DISCUSSION

The annual savings include only pumping savings. Other socioeconomic factors should also be considered in establishing sustainable groundwater use. Conversion of land from agriculture to urban, while reducing groundwater use, also reduces crop production, which has internal and international implications for food supply.

Sustainability analysis should include examination of alternatives, which may include alternative sources of water, a measure of the opportunity cost of the resource supply. Objectives should be consistent to allow comparison, such as water needed to maintain agricultural production or water to supply a specified population. Analysis should also consider effects on other resources and their sustainability as well as whether ecosystem objectives should be addressed. Thus, water sustainability is related to other long-term resource use.

REFERENCE

Liu, J., Zheng, C., Zheng, L., and Lei, Y. 2008. *Ground Water*, 46(6) (November–December), 897–909.

Case Study 11: Balancing Ecosystem, Water Use, and Pricing

BACKGROUND

The Edwards Aquifer, a fractured limestone formation underlying 20,720 km^2 in southcentral Texas, is the habitat to 14 threatened and endangered species and other aquatic life and provides water to 1.7 million people, 1.3 million of which live in the city of San Antonio. The city's population continues to grow at nearly 2% per year. The 13,986 km^2 drainage area transmits water to the 3,237 km^2 recharge zone. The State of Texas established the Edwards Aquifer Authority to oversee the balance of human and endangered species needs for its groundwater. The aquifer maintains over 200 springs, which also support endangered species.

In 2002 and 2003, the San Antonio Water System had to acquire an additional 3500 acre-feet of water per year through contracts and also involved well installation, pumping, treatment, storage, and distribution of this water from the Trinity Aquifer, adjacent to the Edwards Aquifer, at a commodity cost of approximately \$0.355/m^3 (contracted as \$425/1233.481 m^3) per year. In 2004, SAWS also implemented an aquifer storage and recovery facility at a cost of \$255 million, which included 29 injection and recovery wells, capacity for 61,674,450 m^3 of excess Edwards Aquifer water, 113,562 m^3/day treatment capacity, and 64.4 km of pipeline. An average residential water rate (excluding wastewater treatment charges) in San Antonio is \$0.90/m^3 (in the United States the average cost in 2008 was \$0.74/m^3; in Germany, \$2.36/m^3 in 2007*).

ECOSYSTEM BALANCE AND CONSERVATION

The Edwards Aquifer must be managed to balance ecosystem and water supply needs. The ecosystem objective established through the Edwards Aquifer Authority is to maintain the aquifer level at an elevation of no less than 192 m above sea level to support habitat and spring discharge for endangered species and other wildlife. While the city's water customer base increased by 30% from 1982 to 2007, its pumping of the aquifer remained relatively stable. To accomplish this balancing, SAWS implemented a water conservation program that obtained a reduction in per capita water use of 49% over that period, from 852 to 435 L/capita/day. In this way, the city actually used conservation of groundwater as a source of supply for its growing water demand. The city established a water conservation program, which serves as a source of water, since more water does not have to be acquired, treated, and distributed. The program includes

- Commercial programs for
  Facility retrofitting, which the water system funds
  Efficient toilets

Source: San Antonio Water System, Conservation, 2008, http://www.saws.org/conservation/ (accessed December 22, 2008); Edwards Aquifer Authority, The Edwards Aquifer, 2008, http://www.edwardsaquifer.org/ (accessed December 22, 2008); City of San Antonio, Texas, San Antonio Trends, Challenges and Opportunities (presentation), 2008, http://www.sanantonio.gov/planning/powerpoint/Growth_Trends_092506.pps#1 (accessed December 22, 2008).

* Reuters, Average U.S. Water Costs Increase by 7.3%, September 24, 2008, URL: http://www.reuters.com/article/pressRelease/idUS163067+24-Sep-2008+MW20080924 (accessed January 10, 2009); Schleich, J. and Thomas H., Determinants of Residential Water Demand in Germany, Working Paper, Sustainability and Innovation, No. S 3/2007, 2007, URL: http://www.isi.fraunhofer.de/publ/downloads/isi07a05/residential-water-demand-in-germany.pdf (accessed January 10, 2009).

  - Industry certification of water use for food service, schools, high-volume washing, and hotels
  - Audits
  - Awards for water saving
- Residential programs for
  - Efficient toilets
  - Rebates
  - Hot water on demand
  - Low-income assistance
  - Garden irrigation advice
  - Irrigation system checks
  - High user targets
  - Education

Additionally, water use regulations cover water waste, timing of irrigation, drought restrictions, evaporative processes, high-volume users, irrigation system reviews, reclaiming water on-site, and grass and soil selection.

With all these efforts, SAWS achieved its water use reduction goals established in 1993 for 2008 seven years early. Many of the savings are for conservation devices for both industry and residential application for which SAWS pays because the expenses to achieve the water use reductions are less than acquiring water rights and producing the additional water.

A HYPOTHETICAL CASE: DOES WATER CONSERVATION PAY?

While a specific economic analysis of San Antonio's decision to pursue conservation is not readily available, we can make assumptions about San Antonio's circumstances for a hypothetical and reasonable analysis of water conservation versus purchasing groundwater as commodity. We will assume that some portion of the city's analysis prior to its 1982 conservation practices considered water use in the technologies of showers and toilets in the city to develop this hypothetical case. This analysis only relies on two water conservation devices: high efficiency toilets and conservation showerheads. Assumptions for the analysis include

San Antonio population in 2008: approximately 1,300,000
Average number of people per family: 4 (assumed across city to simplify analysis)
Cost of 1,233.481 m^3 of groundwater: $425 (based on contracted price)
Municipal bond rating: AAA (highest municipal bond rating)
AAA bond rating yield: 4%
High-efficiency toilet and showerhead installation capital cost for large volume order: $100
High-efficiency toilet and showerhead installation time: 1 h
Funding source for conservation devices: City of San Antonio
Water savings for family of four annually for high-efficiency toilet: 33.16 m^3/year
Water savings for family of four annually for conservation showerhead: 33.16 m^3/year
Contract plumbing rate: $20/h
Planning horizon: 10 years

RESULTS

PURCHASE GROUNDWATER COMMODITY

- Additional water needed with no conservation: 21,554,353 m^3/year
- $7,426,450/year for groundwater purchase under a 10 year contract
- Does not include treatment plant and transmission line operation and maintenance

High-Efficiency Toilet and Showerhead, Including Labor for Installation

- Water conserved: 21,554,353 m^3/year
- Capital cost of: \$39,000,000
- Financed over 10 years at 4%: \$4,808,346/year
- Assumes no operation and maintenance cost over a 10 year planning horizon

Cost–Benefit Comparison

Avoided costs to the city as a benefit of not purchasing groundwater: \$7,426,450/year
(Discounted cash flow for 10 years at 4% = \$60,235,162)
Incurred cost of conservation toilets and showerheads: \$4,808,346/year
(Current cost of conservation devices = \$39,000,000)
Cost:benefit ratio: 1:1.54, or costs are 64.7% of benefits

Basically, the water conservation savings are the difference between the lower investment and operation and maintenance costs over some period of time when compared with the higher cost water right plus added capital investment for facilities to process and deliver the water and the operation and maintenance costs of the additional facilities for greater water supply needed.

DISCUSSION

A key point is that operation and maintenance costs are not considered in this analysis. Inclusion of O&M costs could push the benefits of conservation even higher. Additionally, evaluation over a longer period of time such as 20 years would make conservation even more attractive, since toilets and showerheads typically have a long life if maintained properly.

The analysis above assumes that all conservation devices are installed in the first year and the water savings occur immediately in that year and then in each subsequent year. In a more reasonable scenario, if the installation occurs over 3 years (beginning in year "0"), a schedule of expenditures on the devices and the associated water savings and their value can be created to which a discounted cash flow analysis would be applied. The following table applies the discounted cash flow formula to the cost of the conservation devices with one-third of them installed in each of the first 3 years of the example. The analysis assumes that the cost of the devices is incurred in a year (e.g., year "0") before the benefits of water savings are accumulated in the following year (e.g., year "1").

Year	Cost of Conservation Devices (\$)	Water Conserved (m^3)	Contract Price of Water Saved (\$)	Discounted Cost (@ 4%) of Conservation Devices (\$)	Discounted Price (@ 4%) of Water Saved (\$)
0	13,000,000	0	0	13,000,000	0
1	13,000,000	7,184,783	2,475,524	12,500,000	2,380,312
2	13,000,000	14,369,566	4,951,050	12,019,230	4,577,524
3	0	21,554,350	7,426,575	0	6,602,198
4	0	21,554,350	7,426,575	0	6,348,267
5	0	21,554,350	7,426,575	0	6,104,103
6	0	21,554,350	7,426,575	0	5,869,330
7	0	21,554,350	7,426,575	0	5,643,586
8	0	21,554,350	7,426,575	0	5,426,525
9	0	21,554,350	7,426,575	0	5,217,813
10	0	21,554,350	7,426,575	0	5,017,128
Total discounted cash flow net present value summations				\$37,519,230	\$53,186,786

In this simplified analysis, the cost to benefit ratio is 1:1.42 over the 10 years of the analysis. Given the long useful life of such conservation devices, as more years might be added to the analysis, the ratio of benefits to costs would be even greater.

What are the major points resulting from this analysis?

1. Considering a sustainability objective of reducing water throughput per capita with a growing population:
   Water conservation throughput < conventional technology throughput
2. Relative to an ecosystem balancing objective:
   Water levels in aquifer > 192 m with conservation program
3. From an economic decision standpoint:
   Monetary benefits of avoiding groundwater purchase > monetary costs of conservation by a substantial amount

CONCLUSION

Proceed with application of water conservation technology.

Note that we have not been able to assign a monetary value to achieving the ecosystem balancing objective of maintaining safe adequate water levels in the aquifer for both human use and species diversity. If this value could be priced, it would most likely only make the net present value of water conservation still larger.

This analysis does show how shifting of costs and benefits over time changes the outcome of the discounted cash flow and cost–benefit ratio. Since the benefits were not incurred immediately and shifted to future years with the staged deployment of the conservation devices, the net present value of the benefits is smaller, reflecting the effect of both the time shift and the discounting of the benefits.

Most importantly, this case study reinforces that given a specific ecosystem objective and human water need, groundwater use can be managed to address both requirements in a sustainable manner.

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Environmental Engineering

Groundwater Economics

Charles A. Job

From the western United States to the Indian subcontinent, water issues have always been economic issues. Considered ubiquitous under the continents, groundwater varies considerably in depth, quality, accessibility, and availability. A unified discussion of groundwater and its economic importance, **Groundwater Economics** explores economic evaluation and cost–benefit analysis for the use, protection, remediation, and conservation of groundwater.

The book reviews the major economic uses of and demand for groundwater, provides an ecosystem context for resource withdrawals, discusses the application of economics to groundwater policy and decisions, and explores the economics of groundwater sustainability. It examines the legal basis for use and access, and then addresses drinking water, irrigation, and waste disposal. The author considers micro- and macro-economic factors, cost–benefit tools, sustainability, transboundary considerations, climate change and policy evaluation, ease of policy implementation, and societal acceptance. He synthesizes key points into practical steps for future application, describing ways to evaluate the economics of groundwater use in the context of the larger ecosystem and the natural capital it provides.

The comprehensive approach taken by this book addresses a full range of groundwater topics building on other supporting disciplines, rather than focusing solely on how to evaluate the economics of remediation of contaminated sites or of a single resource use. This multidisciplinary course is a more current way to address this complex issue, compared to the single-discipline approach that addresses the physical groundwater resource on the one hand and economics on the other. This unified approach presents an array of tools and factors for the evaluation of the economics of proposals for future groundwater use in relation to the ecosystem and its sustainability.

CRC Press
Taylor & Francis Group
an informa business
www.crcpress.com

6000 Broken Sound Parkway, NW
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2 Park Square, Milton Park
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K10444
ISBN: 978-1-4398-0900-6
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