Developments in Agricultural Engineering 13

Microirrigation for Crop Production

Design, Operation, and Management

Freddie R. Lamm
James E. Ayars
Francis S. Nakayama
(Editors)

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Edited by

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PREFACE

Microirrigation, the slow and targeted application of irrigation water to prescribed soil volumes has became synonymous with modern and efficient irrigation practices that conserve precious water resources and maximize plant performance. Microirrigation technology and application have grown steadily during the past 20 years. Today, nearly 3.2 million ha are irrigated by some type of microirrigation system including surface drip, subsurface drip, bubbler, or microsprinkler. Initially, microirrigation was used almost exclusively for high-valued crops based on profitability per unit area such as trees and vines. In recent years, producers have begun using microirrigation on field crops such as tomato and cotton. Improvements in the reliability, durability, and longevity of system components and materials and the introduction of innovative designs have reduced the cost of microirrigation to levels that enable small-scale producers in both industrialized and developing countries to use microirrigation. Continuing research and development have improved emitter design, system design and installation, water filtration and treatment, and system and crop management since the publication of the first edition of this book, *Trickle Irrigation for Crop Production.* Also, improved reliability of computers and data acquisition and processing has widened the application of automated control to microirrigation and led to broad acceptance in both large and small commercial field operations.

The primary goal in producing this book revision is to provide information describing the remarkable advances achieved in microirrigation since 1986, when the first edition of the book was published. The first edition has served primarily as a reference book and as a text book for instructional use. We have crafted this new edition with the goal of serving both as a text and reference book for irrigation professionals. The book is divided into three sections, I. Microirrigation Theory and Design Principles, II. Operation and Maintenance Principles, and III. System Type and Management Principles. Chapters One through Six introduce the topic of microirrigation with a focus on fundamental information and theories related to water and salinity management followed by the procedures for basic hydraulic design and a discussion of system economics. Chapters Seven through Eleven provide detailed descriptions of system automation and chemigation principles, application of recycled or reclaimed wastewater, and system maintenance. The final section of the book, Chapters Twelve through Fifteen, covers the design and management considerations for the four major types of microirrigation, surface drip, subsurface drip, bubbler and microsprinkler. The information presented should enable irrigation professionals to design, maintain, and manage microirrigation systems.

We acknowledge the significant contributions of the authors of the first edition of this book to the field of microirrigation. Some of the current chapters include original authors from the first edition, whereas other chapters required recruiting new authors. The first edition was developed under the auspices of the USDA-RRF Western Regional Research Committee, W-128, *Trickle Irrigation to Improve Crop Production and Water Management.* Although this revision is not a formal product of the current USDA-RRF Western Regional Research Committee, W-1128, *Reducing Barriers to Adoption of Microirrigation,* it should be noted that several of the current committee members are contributing to this edition.

We thank our families and also those of the authors for their patience and cooperation during the long preparation process of this book. We also especially thank Ms. Vicki Brown, Kansas State University, for her meticulous work in finalizing the manuscript for printing.

May 2006 Freddie R. Lamm, James E. Ayars, and Francis S. Nakayama

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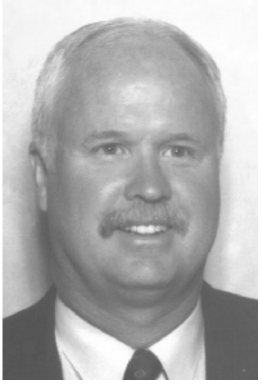

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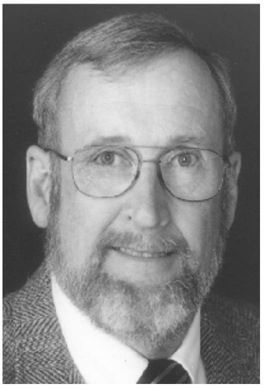

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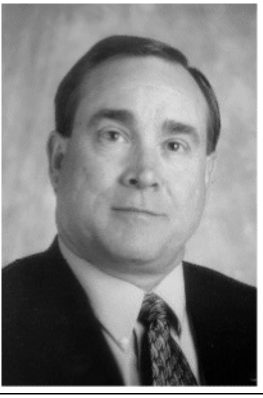

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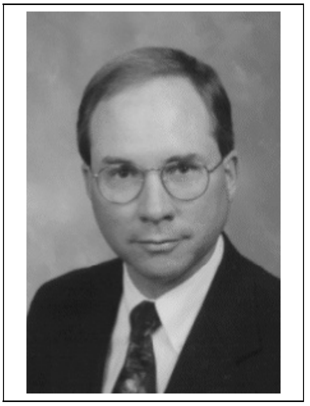

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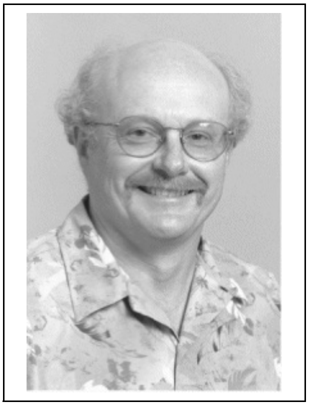

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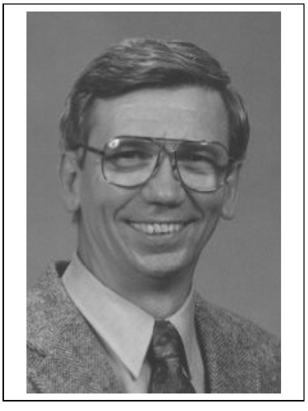

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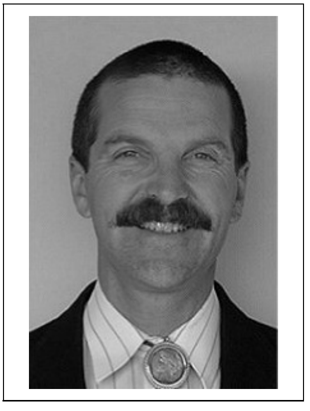

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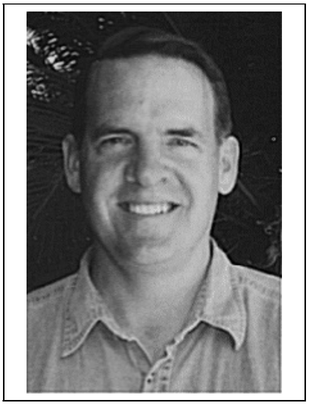

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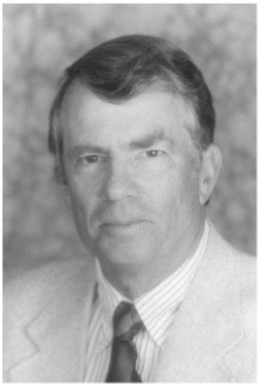

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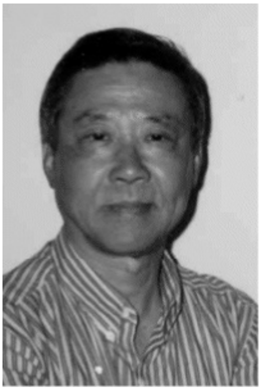

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Microirrigation for Crop Production
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1. INTRODUCTION

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"Whiskey is for drinking, water is for fighting." Attributed to Mark Twain

DALE A. BUCKS
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"Water is a scarce resource that must be conserved and protected."

FREDDIE R. LAMM
Kansas State University, Colby, Kansas, USA
"Water, water, everywhere is no proper way to irrigate."

FRANCIS S. NAKAYAMA
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"Water, like fire, is a good servant, but a bad master."

1.1. DEFINITION

Microirrigation is the slow application of water on, above, or below the soil by surface drip, subsurface drip, bubbler, and microsprinkler systems. Water is applied as discrete or continuous drips, tiny streams, or miniature spray through emitters or applicators placed along a water delivery line adjacent to the plant row (ASAE, 2001). In some parts of the world, microirrigation is called localized irrigation to emphasize that only part of the soil volume is wetted. Thus, with the localized aspect, there are implications concerning evaporation, transpiration, deep percolation, soil water, nutrient, and salinity distributions with respect to crop spatial position and root distributions (Pizarro, 1987). The shape or design of the emitter reduces the operating pressure from the supply line, and a small volume of water is discharged at the emission point. Water flows from the emission points through the soil by capillarity and gravity. Microirrigation is usually characterized by the following features: (1) water is applied at low rate; (2) water is applied over long periods; (3) water is applied at frequent intervals; (4) water is applied near or into the root zone; (5) water is applied by a low-pressure delivery system; and (6) water is routinely used to transport fertilizers and other agricultural chemicals.

Rapid advances in microirrigation systems and practices have occurred since the publication of the first edition of this book (Nakayama and Bucks, 1986). Microirrigation, as with other irrigation methods, cannot be used for all agricultural crops, land situations, or user objectives. However, for certain cropping systems and situations, it does offer many unique agronomic, agrotechnical, and economic advantages compared with other irrigation technologies presently used.

1.2. HISTORY AND CURRENT STATUS

Historical and archaeological findings show that irrigation has played a major role in the development of ancient civilizations. The oldest irrigation-based civilizations developed along the Nile, Tigris, Euphrates, Indus, and Yellow Rivers (Gelbrud, 1985; Postel, 1999). Gravity irrigation began along the Nile about 6,000 B.C. and still continues to be the dominant irrigation method. Irrigation methodology resisted change until the 20th century when pressurized systems with sprinklers became available. Microirrigation, a new and innovative approach evolved from subirrigation where irrigation water is supplied to the plant by raising the water table up to the root zone.

1.2.1. Early History Worldwide

Although simple in its concept, the widespread use of microirrigation was not practical until very recently because of the availability of suitable, economical materials to construct the equipment. Beginning in 1860, researchers experimented with a combination irrigation and drainage system using clay pipes. These subirrigation and drainage tiles lasted for more than 20 years, in which irrigation water was pumped into the underground drainage system. One of the earliest patents (No. 146,572) for microirrigation in the United States was granted to Nehemiah Clark in 1874 (Clark, 1874). This early system allowed water emission through the joints of the pipeline. The end of one pipe was slightly smaller than the beginning of the next that allowed the water emission while still protecting the joints from clogging. The first research on subsurface microirrigation where water was applied to the root zone without raising the water table was conducted in the United States at Colorado State University in 1913 by House (1918), who concluded that it was too expensive for practical use.

Microirrigation has been a multinational development. An important breakthrough was made around 1920 in Germany when perforated pipe was introduced. In the United States, porous pipe or canvas was used for subsurface irrigation at Michigan State University (Robey, 1934). Thereafter, research and development centered around using perforated and porous pipes made of various materials to determine whether water flow from these pipes into the soil could be controlled by the soil water potential rather than by the water pressure in the system. At the same time, subirrigation experiments in Germany, the Union of Soviet Socialist Republics, and France led to water application through closely-spaced channels to raise the groundwater level close to the root zone. Various other forms of subirrigation were also used in other countries including the United States, the Netherlands, and the United Kingdom.

With the continuing improvements in plastics, first developed during World War II, plastic pipe for irrigation became feasible. In the late 1940s, microirrigation systems based on plastic pipe were used to irrigate greenhouse plants in the United Kingdom. About the same time, Dorter (1962) and others in Germany began extensive work on subsurface irrigation (called underground irrigation at this time) with plastic pipe. Over 100 papers were published on the concept of underground irrigation. Publications on the modern-day surface drip system began to appear from Israel in 1963 and the United States in 1964. Research and development from both countries actually started earlier. Additional patents for microirrigation components began to appear in the 1950s and 1960s. A low pressure device which resembles what is currently referred to as a microsprinkler was patented in the United States by Ludwig Blass in 1956 (No. 2,752,201) entitled “Methods and Means for the Irrigation of Land” (Fig. 1.1a.). These microsprinklers were constructed of machined aluminum and would not be economical for large scale markets (Blass, 1956). The first U. S. patent (No. 3,420,064) of a surface drip irrigation emitter was awarded to Ischajahu Blass and Symcha Blass (No family relationship to Ludwig Blass) in 1969 (Blass and Blass, 1969) entitled “Irrigation Dripper Unit and Pipe System” (Fig. 1.1b.). The U.S. patent was based on an earlier patent (No. 25,197) awarded in Israel in 1966 to Symcha Blass. Blass, an engineer from Israel, has been often quoted describing greater vigor of a large tree near a leaking faucet over other trees in the area as the basis for developing the dripper. The concept of surface drip irrigation spread from Israel in the 1960s to Australia, North America, and South Africa, and eventually throughout the world. Patents related to microirrigation and techniques continue to be issued by the U. S. patent office and throughout the world.

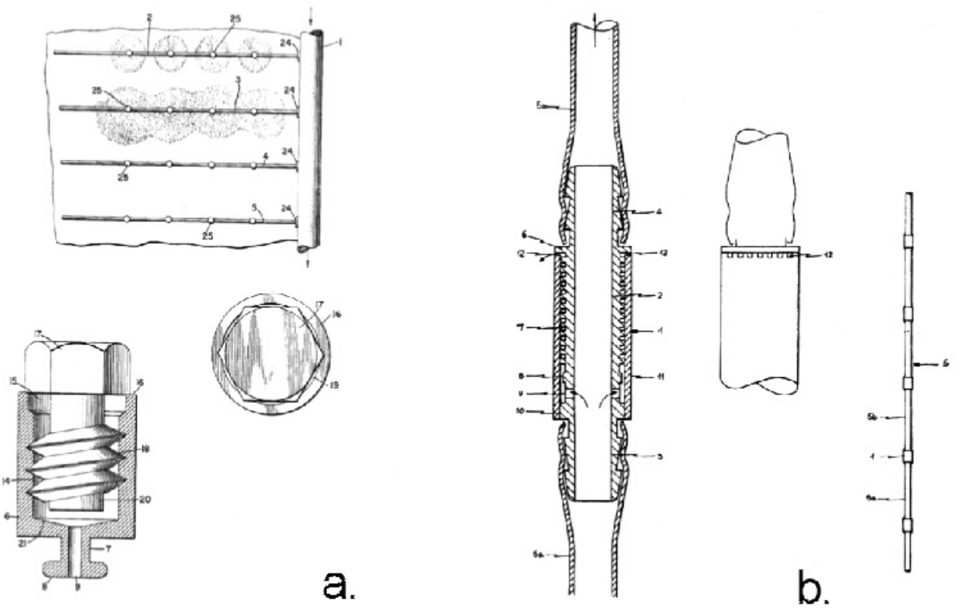

Figure 1.1. Early microirrigation components patented in the United States during the 1950s and 60s. Fig 1.1a. Patent No. 2,752,201. Methods and Means for the Irrigation of Land, L. Blass; Fig 1,1b. Patent No. 3,420,064. Irrigation Dripper Unit and Pipe System, I. and S. Blass.

The First International Drip Irrigation Congress in 1971 held in Tel Aviv, Israel, had 24 papers. The Second International Drip Irrigation Congress in San Diego, California, USA in 1974 had 83 presentations with over 1000 registrants from 26 countries. The Third Congress met in 1985 at Fresno, California USA, had 157 papers contributing to its theme Drip/Trickle Irrigation in Action. It was co-sponsored by the American Society of Agricultural Engineers (ASAE) and the Irrigation Association (IA), signaling a coming of age for microirrigation as an accepted method of irrigation. Continued progress in microirrigation was demonstrated at the Fourth Congress (October 23-28, 1988) in Aubury-Wodonga, Australia featuring 89 presentations. The Fifth International Microirrigation Congress met in Orlando, Florida, USA on April 2-6, 1995 and was again sponsored by ASAE in cooperation with IA and the Florida Irrigation Society (FIS) with the support of 11 additional technical organizations. The Fifth International Microirrigation Congress truly was an international forum featuring 156 technical presentations representing 313 authors from 28 countries throughout the world. The most recent Microirrigation Congress in Capetown, South Africa in 2000 placed a strong emphasis on the emerging use of microirrigation in the developing world. An important part of the Sixth Congress dealt with empowering women to meet family food needs and provide additional income through use of microirrigation.

1.2.2. Early History in United States

In the mid 1950s, a small irrigation manufacturing firm (Chapin Watermatics) in Watertown, New York, began to supply polyethylene tubing (called spaghetti tubing) to water plants and flowers grown in greenhouses. By the early 1960s, plastic-pipe drip irrigation systems were extensively used in greenhouse research and most commercial enterprises. Norman Smith, a cooperative extension agent from New York and Richard Chapin of Chapin Watermatics are credited with conducting the early pioneering work with plastic film mulch and surface drip irrigation for row crop production at the Old Westbury Gardens, Westbury Long Island, New York in 1963 (Fig. 1.2). This site was commemorated with a historic plaque by the American Society for Plasticulture (ASP) in 1993.

Figure 1.2. The first use of surface drip irrigation and plastic mulch on a cantaloupe field in the United States (New York) in 1963. Pictured is Norman Smith, Nassau County Cooperative Extension Agent, New York. Photo courtesy of G. Giacomelli, Arizona State University.

The first field experiment in the United States with a subsurface drip irrigation system was established on a lemon orchard at Pomona, California in 1963 and on an orange orchard near Riverside, California in 1964 (Davis, 1974). The first research and demonstration study on a private grower's trees was in an avocado orchard in San Diego, California in 1969. About the same time trials were started using drip irrigation and plastic mulch on strawberries and tomatoes also in and around San Diego (Davis and Bucks, 1983).

1.2.3. Current Irrigated Area

Irrigated land development has kept pace with the world population since about 1800. In 1977, the Food and Agriculture unit of the United Nations Organization estimated that the total global irrigated area was 223 million ha. This increased to about 262 million ha by 1996. The 2000 irrigation survey conducted by Irrigation Journal (2001) indicated 25.5 million irrigated ha in the United States. Of this area, about 12.7 million ha (49.9 %) were irrigated by sprinkler irrigation, 11.5 million ha (45.1 %) by gravity irrigation, and 1.3 million ha (4.9 %) by microirrigation.

The Working Group on Microirrigation of the International Commission on Irrigation and Drainage (ICID) has conducted surveys on the extent of microirrigation periodically since 1981. These surveys (Table 1.1), summarized by Reinders (2000), indicate that microirrigation has increased from 0.4 million to 3.2 million ha during the1981 to 2000 period.

The ICID surveys (Bucks, 1995) indicated that the main reasons for choosing microirrigation were as follows: (1) water and labor were expensive; (2) water supply was limited; (3) water supply was saline (although periodic leaching was still required); (4) the use of other irrigation methods was difficult (example, hillside orchards); (5) landscaping or greenhouse irrigation was required; and (6) chemigation was possible.

In the United States, the states of California, Florida, Washington, Texas, Hawaii, Georgia, and Michigan account for approximately 91% of the microirrigated land area (Fig. 1.3.) Although the current cropped area using microirrigation is a small fraction of the total irrigated area, many of the high-value crops that require intensive production practices are grown with this irrigation method. In addition, conversion of marginal lands to microirrigation is increasing.

1.2.4. Principal Crops Utilizing Microirrigation

Whereas almost all crops can be suitable for microirrigation, the practice is primarily concentrated only on high-value perennial crops, tree and vine crops, fruits, vegetables and ornamentals. However, there is growing interest in applying microirrigation to lower-valued field crops, such as cotton and corn through the use of multi-year subsurface drip irrigation. Application of microirrigation for landscaping, greenhouses, and nurseries has also increased tremendously and includes ornamental trees and shrubs, ground covers on highway roadsides and residential properties. While the emphasis in this book will be on systems designed for production agriculture, the design and management principles are applicable across all types of microirrigation scenarios.

Table 1.1. Extent of microirrigation, ha, in selected countries and the world during the period 1981 to 2000. After Reinders (2000)

Country	1981	1986	1991	2000	
United States	185,300	392,000	606,000	1,050,000	
India	20	0	55,000	260,000	
Australia	20,050	58,758	147,011	258,000	*
Spain	0	112,500	160,000	230,000	
South Africa	44,000	102,250	144,000	220,000	
Israel	81,700	126,810	104,302	161,000	
France	22,000	0	50,953	140,000	
Mexico	2,000	12,684	60,000	105,000	*
Egypt	0	68,450	68,450	104,000	
Japan	0	1,400	57,098	100,000	*
Italy	10,300	21,700	78,600	80,000	
Thailand	0	3,660	45,150	72,000	*
Colombia	0	0	29,500	52,000	*
Jordan	1,020	12,000	12,000	38,300	
Brazil	2,000	20,150	20,150	35,000	*
China	8,040	10,000	19,000	34,000	
Cyprus	6,000	10,000	25,000	25,000	
Portugal	0	23,565	23,565	25,000	
Chinese Taipei	0	10,005	10,005	18,000	*
Morocco	3,600	5,825	9,766	17,000	*
Other	50,560	38,821	100,737	177,000	*
World	436,590	1,030,578	1,826,287	3,201,300	

* Areas for these countries adjusted from 1991 figures according to the average percentage increase of other countries that had provided updated information to ICID.

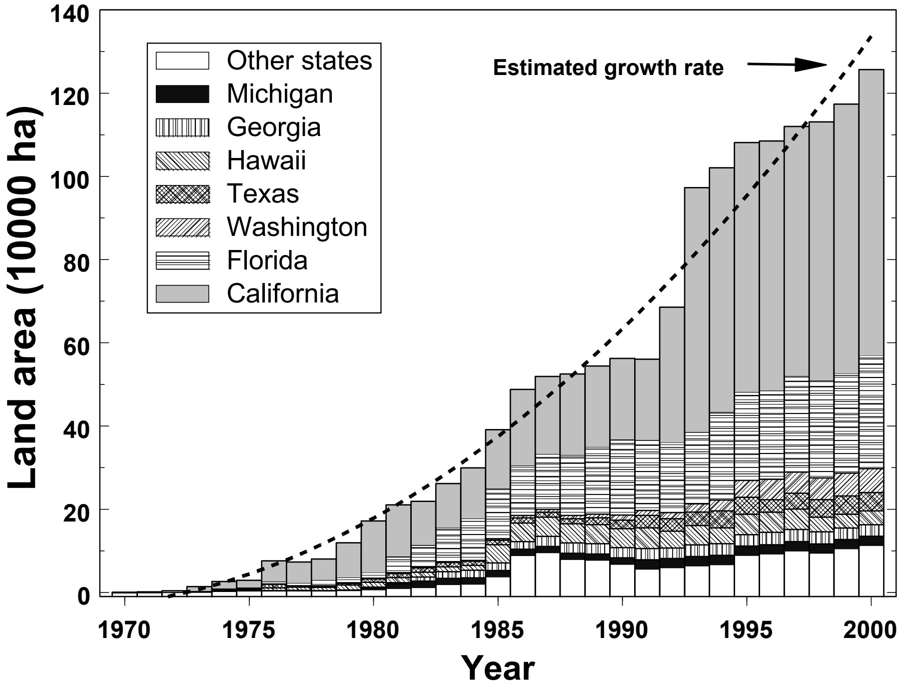

Figure 1.3. Microirrigation land area and distribution in the United States from 1970 through 2000. Based on surveys conducted by Irrigation Journal.

1.2.5. Trends

An intensive survey of the trends in microirrigation is impractical, but some indication of what is occurring in research and application is evidenced by the types of sessions and papers presented at the Microirrigation Congresses over the years. The initial Congresses focused on the physical aspects of the systems (hydraulic design, uniformity), the components (filters, emitters), and applications to crops. As many of the initial problems were solved in manufacturing and quality products became available, the emphasis in research moved towards system management. This included both water and fertilizer management. Microirrigation systems were initially installed on high-value crops primarily in developed countries with minor applications in developing countries. As the industry matured, interest has increased in microirrigation to lower-value field crops and in devising low cost systems for use in developing countries. The Sixth International Microirrigation Congress in South Africa had sessions related to applications in the developing world and encouraging women to use microirrigation to meet family food needs and increase income. As the microirrigation industry continues to develop, the economics of microirrigation is getting more attention to in efforts to reduce overall system costs.

1.2.6. Economics

The high cost of installation, operation, and maintenance of microirrigation systems remains a major constraint to microirrigation expansion. Only crops with the highest returns are generally considered for implementation of microirrigation. A complete discussion of the economics of microirrigation is provided in Chapter 6. A detailed breakdown of the costs for individual components is not provided because these are variable and are not applicable over a wide range of time and regions.

In the 1991 ICID survey (Bucks, 1995), nearly all the countries indicated that microirrigation systems used in vegetable and field crops and in greenhouses would be more expensive than the same systems used on tree crops. In Japan, system costs for flowers and vegetables were as high as $16,000/ha. However, many of the countries indicated that an average installation cost for microirrigation systems was $2,000 to $4,000/ha. Estimates of operation and maintenance costs ranged from $100 to $800/ha-year. This large range was attributed to variable labor costs, a large variation in crop types, and differences in the age of the microirrigation systems.

1.2.7. Expansion in Developing Countries

Polak et al. (1997) projected that reducing the cost of microirrigation from $2,500 to $250 per ha would more than double its global adoption. Application was projected to be particularly appropriate in water short areas of India and sub-Saharan Africa and in the hilly regions of the Himalayas. They indicated that the inability to break large farms into small parcels is the most important barrier to the adoption of expensive technology, which favors the large farmers. Improvements in pumping technology (man-powered treadle pumps) enabled small farmers to take advantage of microirrigation. International Development Enterprises has developed portable drip systems and has installed about 880 systems in India and 470 in Nepal (Hoffman, 1985; Postel, 1999; Keller and Keller, 2003).

Richard Chapin (Chapin Watermatics) working through his Living Waters Foundation (Postel, 1999) described a drip irrigation and plastic mulch combination system that was distributed in Africa. The initial design that used a 190 L barrel for a reservoir proved unacceptable to the farmers. Instead, a 19 L reservoir (bucket) placed at a lower height has gained acceptance. The system with a combination of drip irrigation and mulch was easy to install, was very effective in production, and represented an economic alternative for market garden production. Basic aspects of all of these systems designed for developing countries is their ease of use and relatively low cost (Fig. 1.4.).

1.3. GENERAL PRINCIPLES

Many commercial companies and government agencies have invested large sums of money and time to foster the advancement of microirrigation. However, as with any new technology, microirrigation had few supporters in its conception, and initially had many unanticipated design and management problems. Extensive research throughout the world has solved most of the early problems and the rate of acceptance of the technology has increased. The user must recognize that microirrigation has advantages and disadvantages. To maximize efficiency, the system must be tailored to specific field and water conditions before success can be achieved. This includes proper design, installation, maintenance, and management. Design considerations are highlighted in this chapter and in detail in Chapter 5. In addition, detailed design procedures will be discussed in Chapters 12, 13, 14, and 15 for specific types of microirrigation systems. The advantages and disadvantages of microirrigation in general are noted in the following sections and are discussed in detail in Chapters 12, 13, 14, and 15 for specific types of microirrigation systems.

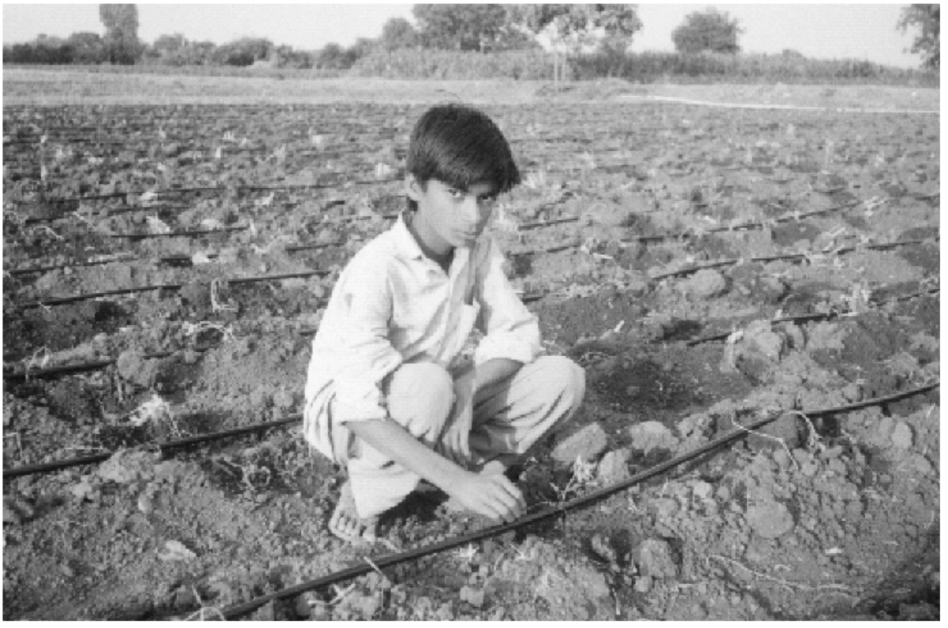

Figure 1.4. Young irrigator in Maharashtra, India inspecting tomato transplants under low-cost microirrigation system installed and operated by him. Photo taken in November 2002, and is courtesy of Jack Keller, International Development Enterprises.

1.3.1. Advantages

Numerous reports (Goldberg et al., 1976; Shoji, 1977; Howell et al., 1981; Bucks et al., 1982; Davis and Bucks, 1983) have summarized potential advantages of drip compared with other irrigation methods. The more important benefits are highlighted in the following sections.

1.3.1.1. Increased water use efficiency

Water use efficiency is defined as the ratio of the total dry matter or harvested (economic) portion of the crop produced per unit of water consumed. Significant improvements in yield have been documented with microirrigation without significant increases in the consumed water leading to improved water use efficiency (Phene et al., 1993). Intercropping or even multiple cropping of vegetable and melon crops with subsurface microirrigation increased yields, improved water use efficiency, and reduced water applications between cropping seasons (Bucks et al., 1981). Continuous cropping is a practical way to increase water use efficiency where water prices are increasing and urbanization has occurred.

1.3.1.1.1. Improved crop yields and quality

With microirrigation, the soil water content in the plant root zone remains essentially constant because water is applied slowly and frequently at a predetermined rate. These characteristics eliminate the wide fluctuations in the soil water content that are encountered under gravity and sprinkler irrigation methods that contribute to plant stress (Chapter 3). Explanation for the improvement in plant growth, yield, and crop quality are probably related to improved water distribution along the row which can reduce plant stress caused by variations in texture and water holding capacity in heterogeneous soils (Chapter 2).

1.3.1.1.2. Reduced nonbeneficial use

General agreement exist that irrigation water requirements can be less with microirrigation than with traditional irrigation methods. The savings, of course, depend on the crop, topography, soil, and environmental conditions, as well as management and the attainable on-farm efficiency. Primary reasons given for the water savings include irrigation of a smaller soil volume, decreased surface evaporation, reduced or elimination of irrigation runoff from sloping fields or hillsides (Fig. 1.5), and controlled deep percolation losses below the root zone.

1.3.1.1.3. Reduced deep percolation

Disposal of drainage water is one of the most pressing environmental problems facing irrigated agriculture. The source of this water is generally from inefficient irrigation practices and poor distribution uniformity. Microirrigation offers opportunities to reduce these losses to a minimum. Phene et al. (1993) identified subsurface drip irrigation as a best management practice (BMP) for controlling deep percolation.

1.3.1.2. Use of saline water

Considerable evidence indicates that higher salinity waters can be used with microirrigation than with other irrigation methods without greatly reducing crop yields (Shalhevet, 1994). Minimizing the salinity hazard to plants irrigated by microirrigation can be attributed to (1) keeping salts in the soil water more diluted because the high frequency irrigations maintain a stable soil water condition; (2) eliminating leaf damage caused by foliar salt application with sprinkler irrigation; and (3) moving salts beyond the active plant root zone. On the other hand, improper placement of the system in relation to the crop could increase the salinity hazard by moving the salt into the root zone (Ayars et al., 1995). The influence of salinity in microirrigation is discussed in Chapter 4.

Figure 1.5. Properly designed and operated microirrigation systems can be used for irrigation of wine grapes on both flat and sloping topography without excessive irrigation runoff. (Napa Valley, California, USA. Photo courtesy of Freddie Lamm, Kansas State University).

1.3.1.3. Improved fertilizer and other chemical application

Microirrigation can maximize flexibility in fertilizer and other chemical application scheduling. Frequent or nearly continuous application of plant nutrients with the irrigation water is feasible and appears to be beneficial for many crop production situations. Besides fertilizer, other materials, such as herbicides, insecticides, fungicides, nematicides, growth regulators, and carbon dioxide can be efficiently supplied to improve crop production (Chapter 8). The ability to apply small and frequent amounts of fertilizer and other chemicals has the potential to reduce total applications, leaching and runoff of these chemicals (Phene et al., 1993; Ayars et al., 1999).

1.3.1.4. Decreased energy requirements

Energy costs for pumping irrigation water may be reduced with microirrigation because the operating pressures are lower than other types of pressurized systems. However, most of the energy conservation should come from reducing the quantity of water pumped. Microirrigation systems can save energy over gravity or flood irrigation only when irrigation efficiencies are significantly increased.

1.3.1.5. Improved cultural practices

Microirrigation will not interrupt cultural operations such as spraying, weeding, thinning, and harvesting. More hedge plantings for tree crops, higher plant populations for row crops, and increased use of plastic, natural, and synthetic mulches are examples of improved cultural practices that are adaptable to microirrigation. Minimum tillage practices can be easily utilized along with microirrigation, because dry areas are available for controlled traffic. However, with some soil and crop scenarios dry surface soils can be a problem. Dry sand can cause traffic problems for harvest trucks with vegetable crops. Wind-carried dry surface soil can also scar young flowers on fruit and vegetable crops or decrease appearance and quality of field grown floricultural crops.

Weed infestation can be reduced under microirrigation because only a fraction of the soil surface is wetted and fewer weed seeds are delivered to the field in comparison with other irrigation methods. Selective herbicides have been applied through microirrigation systems with mixed results and further development of practices and water soluble products are needed.

1.3.1.6. Use of biological effluent and treated wastewaters

Biological and properly treated wastewater effluents represent valuable sources of water and in some cases nutrients. The presence of pathogenic organisms in the water raises important questions on how this water is to be applied and which crops are acceptable to receive these waters. Wastewater is a significant source of water in Israel and other water short areas in the Middle East (Shelef and Azov, 1996; Angelakis et al., 1999; Brenner et al., 2000). Wastewater reuse in agriculture is projected to be 36% of the total agricultural water supply in Israel by 2010 (Shelef and Azov, 1996). In the United States, biological effluent and treated wastewaters have been primarily used for irrigation of ornamentals and grasses in recreational areas, forage, fiber and forest crops, and for grain crops grown for animal feed. The use of biological effluent and treated wastewater in microirrigation (Fig. 1.6) is a rapidly expanding research area and is discussed in Chapter 9.

1.3.2. Disadvantages

Despite observed successes and possible advantages, several problems have been encountered with the economics and mechanics of applying water with microirrigation systems for some soils, water qualities, and environmental conditions. The disadvantages of microirrigation are highlighted in the following sections. While emitter clogging can sometimes still be a problem, the development of improved microirrigation system components and designs along with better filtration and chemical treatment has reduced some of the earlier difficulties associated with these systems (Chapter 11).

1.3.2.1. Extensive maintenance requirements

Complete or partial clogging of emitters still represents a serious problem with microirrigation. Clogging will adversely affect water and fertilizer application uniformity, increase maintenance costs, and cause crop damage and decreased yield unless the clogging is detected early and corrected. Other maintenance problems are pipeline and component damage such as leaks or flow restrictions that can be caused by rodent or other animals, personnel, poor installation procedures or machinery. Root intrusion can be a problem with some system designs, crops, and cultural practices.

Figure 1.6. Subsurface drip irrigation (SDI) applying treated municipal wastewater for citrus production near Tel Aviv, Israel, 1999. Photo courtesy of Freddie Lamm, Kansas State University.

1.3.2.2. Salt accumulation near plants

Where high salinity waters are used in arid regions, salts tend to accumulate at the soil surface and along the periphery of the wetted soil volume. Rain water may move harmful amounts of salts into the root zone causing injury to the plants (Chapter 4). Salt accumulation from a prior microirrigation operation can be a problem if seeds are located in resultant high salt concentration areas.

1.3.2.3. Restricted root development

Because microirrigation normally supplies water to a specific part of the total soil volume occupied by a plant, root development may be limited to the wetted soil volume near each emitter or along each lateral line. Excessive restriction of root development has the potential to decrease plant growth and yields. Also, good root development and distribution may be needed to anchor the plant against strong winds.

1.3.2.4. High system costs

Supporting equipment requirements (filters, controllers, valves) and extensive lateral networks make microirrigation systems initially expensive. Costs are generally less than solid-set sprinklers, but more than center pivot sprinkler systems. Actual costs may vary considerably depending on the crop, specific microirrigation system design attributes, filtration equipment, and automation that are selected. Operation costs for microirrigation can be comparable to other pressurized irrigation methods unless poor water quality conditions contribute to excessive maintenance costs.

1.3.2.5. Restricted crop rotation

This limitation usually applies to subsurface drip irrigation installations. The restriction results from the need to match row spacing with dripline installation. If the rows are positioned so that the dripline is not centered between two rows or centered under a bed, damage may occur from equipment during cultivation (Ayars et al., 1995). If the grower is willing to adopt a common row spacing for his crops or adapt specialized tillage procedures, this is not a serious restriction.

1.3.3. System Considerations

1.3.3.1. Design and installation considerations

The main design goal for a microirrigation system is to insure that an acceptable uniformity of water application is obtained throughout the field. The system designer must take into account a complex combination of emitter type, emitter uniformity, hydraulics, topography, desired water distribution uniformity, crop salt tolerance, water requirement, water quality, fertilizer injection, soil salinity, cultural practice, and other site-specific conditions. The microirrigation installer must not only be aware of minimum design recommendations, but communicate adequately with the users on the proper operation of the system. Specifics on design and operation are covered in Chapters 5 and 12 through 15.

1.3.3.2. Maintenance considerations

The primary goal of a maintenance schedule is to control emitter clogging to assure a suitable economic life for the microirrigation system. A maintenance schedule varies with water quality depending on three factors: (1) physical–the suspended inorganic (e.g., sand, silt, and clay and other debris such as plastic particles) and organic materials; (2) chemical–the precipitation of calcium or magnesium carbonate, calcium sulfate, iron compounds, heavy metal hydroxides, and some fertilizers; and (3) biological–the bacterial and algal filaments, slimes, and microbial-chemical deposits. System maintenance is very important and is covered in detail in Chapter 11.

1.3.3.3. Management considerations

The purpose of the total management scheme is to ensure optimum crop response coordinated with good environmental practices and responsible resource use. Management concepts that will be discussed in various chapters in this book include accurately measuring the water application, scheduling irrigation, and ensuring proper system operation. Automation and fertigation are management practices that can have a significantly positive impact on crop response (Chapter 7 and 8). Cultural practices and management will also have to be modified when microirrigation is included as part of the farming enterprise.

1.3.3.4. Economic considerations

Because yields are higher or more consistent on irrigated than rainfed lands, irrigation plays a major role in stabilizing food and fiber production. Problems of improving on-farm irrigation efficiencies will need to be addressed as the competition for limited water supplies increases. Microirrigation systems have the potential to obtain high efficiency (85 to 95 %) and may become even more economical in the future. An economic analysis of an irrigation system should stress the total system including operation and management rather than just the individual parts of the system. Such analysis must consider the cost of land, water, and drainage water disposal. Energy will also be a significant part of the cost analysis. Caswell et al. (1984) provide an analysis that takes into account land quality and the water cost. Land and water cost factors are two important factors for comparing different irrigation technologies. Other cultural costs (labor, tillage, weed control, fertilization, harvesting, etc.) and profits (higher yield, earlier ripening, price, product quality, etc.) must also be considered in a complete economic analysis to select of the most suitable irrigation method. A discussion of the economics of microirrigation is provided in Chapter 6.

1.3.3.4.1. System costs

Microirrigation systems are usually expensive and require more intensive management skills and farming practices than other irrigation methods. The initial costs of a microirrigation system in the United States in 2003 average about $1,500 to $3,500/ha, and maintenance costs range from about $50 to $200/ha-y. These costs will undoubtedly vary considerably for other countries. In some situations, the initial equipment and maintenance costs for microirrigation has decreased and may become even lower or remain stable in the future. In fact, system costs are currently lower today than in the previous decade, because line-source emitter systems with longer life spans are being used for a greater number of applications. With the increased need to conserve water, public agencies may need to subsidize new or improved irrigation systems through cost-sharing or tax incentive programs, similar to those presently available for soil conservation. Also, public and private groups could encourage additional research and development to enhance the economic attractiveness of microirrigation and other efficient irrigation methods.

1.4. SYSTEM COMPONENTS

Many significant advances have been made in the design of microirrigation components. The basic components of a microirrigation system include a pump, fertilizer injector, filters, distribution lines, emitters, and other control and monitoring devices. Whereas, a general discussion of these components will be provided in the following sections, greater detail will be provided in Chapters 5, 7, 8, and 11.

1.4.1. Emission Devices

Emitters are used to dissipate pressure and lower the rate of water application through the microirrigation system. Ideally, an emitter permits a small uniform flow or trickle of water at a constant discharge rate that does not vary significantly throughout the field or subunit. Many different emitters have been devised and manufactured with the concept that the emitters should be inexpensive, reliable (not clog), and compact as well as provide a uniform water discharge. Emitter designs include short-path, long-path, short-orifice, vortex, pressure-compensating, self-flushing, perforated single- and double-chamber tubings, as well as the aerosol emitters, foggers, misters, or the miniature sprays and sprinklers used in microsprinkler irrigation.

The point on or below the soil surface at which water is discharged from the emitter is called the emission point. Emitter designs are classified into two types, point-source and line-source. Point-source emitters discharge water from individual or multiple outlets that are spaced generally 0.76 to 1 m apart or according to wider plant spacing arrangements. Typically, point-source emitters are used for widely spaced plants such as trees, vines, ornamentals, and shrubs. However, some point-source emitters are also being used for closely spaced row crops. Bubbler and microsprinkler emitters are usually classified as point-source systems. Line-source emitters have perforations, holes, porous walls, formed indentations, or molded emitter inserts in the tubing that discharge water at close spacings (0.1 to 0.6 m) or even continuously along a lateral. Line-source emitter systems are frequently used on small fruits, vegetables, or other closely spaced row crops. Better materials and manufacturing have improved extrusion and molding of point-source emitters. Co-extrusion, laser technology, and plastic formulation techniques have also increased the reliability of line-source emitters.

Emitter construction and performance requirements are very important because all emitters are subjected to exposure to sunlight and chemicals applied through or on the emitters as the crop is grown, extremes in environmental changes, and physical abuse. Characterization of the uniformity of emission and distribution within the field is discussed in Chapter 10.

1.4.2. Distribution System

Distribution lines consist of a network of graduated pipe sizes starting with a single, large mainline followed by smaller submain and lateral lines (Fig.1.7). The buried mainline and submains are usually permanent installations and are usually made of polyvinyl chloride (PVC), asbestos-cement or polyethylene (PE) plastic pipe. Mainlines and submains often range from 40 to 250 mm inside diameter depending upon the required water flow and the economic tradeoff between power costs and installation costs. Both mainlines and submains should have valved outlets for periodic pipeline flushing. The submain may also contain pressure regulators, flow control valves, manual or automatic control valves, secondary filters, and other safety devices. Laterals are usually made of PE and range from 10 to 35 mm inside diameter. With increasing microirrigation use on annual row crops, larger diameter driplines are often being used.

In most cases, the submain connects the mainline to the lateral. However, for larger installations, there may also be a manifold or header line that is coupled between the submain and lateral line. The size, length, and maximum allowable pressure loss depend on topography, lateral flow rate, pressure loss in the laterals, and total pressure variation allowed for the emitters along the laterals. The hydraulic design of main, submain, and lateral lines are presented in Chapter 5.

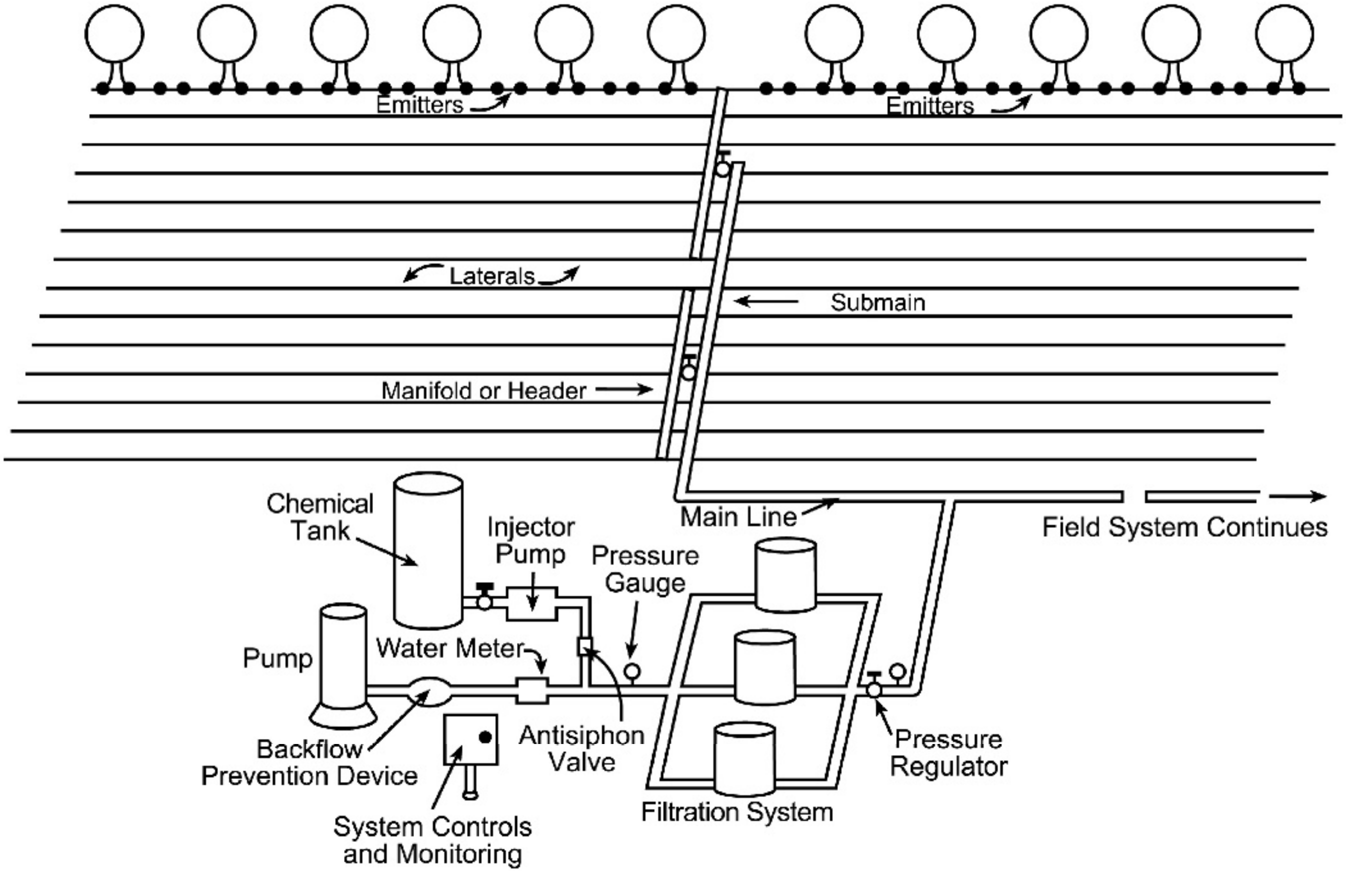

Figure 1.7. An example of a basic microirrigation system. Courtesy of Kansas State University.

As part of the design of a microirrigation system, the appropriate fittings or parts must be selected to connect together the main, submain, and lateral lines. Appropriate fittings are available for connecting both PVC and PE distribution lines. PVC fittings are solvent-cemented using specifically approved primers and cements, whereas PE equipment is non-cementable and connected with barbed or compression fittings. A barbed fitting is inserted inside the pipeline. The PE compression fittings are used routinely because they have less friction loss and exhibit fewer stress-cracking problems than barbed fittings.

1.4.3. Control and Automation

Microirrigation systems are well suited for automation (Fig. 1.8). The main control station for the microirrigation system is organized to measure, filter or screen, and treat the water, and to regulate pressure and time of water application. The control station includes the pump, backflow-prevention device, primary filter, pressure regulator (automatic or mechanical flow control valves), pressure gauge, water meter, and usually automation and chemical injection equipment (Fig.1.7). Prevention of emitter clogging is important for the successful operation of a microirrigation system. Details on emitter clogging and water treatment are presented in Chapter 11. Proper water filtration is essential and achieved by using either screen, disk, media (fine gravel and sand), or centrifugal filters either individually or in combination. The selection of the type, size, and capacity of the filtration unit depends on the initial water quality, system flowrate, and emitter design. Chemical injectors are used to apply fertilizer, acid, bacteriacide, or other chemicals through microirrigation systems. The different types of injectors, their operating principles, and safety precautions needed for injecting chemicals will be discussed in Chapter 11 on maintenance and Chapters 8 and 9 on application of agrochemicals and biological effluent.

Figure 1.8. Programming an automated microirrigation system. Photo courtesy of Freddie Lamm, Kansas State University.

The mechanical pressure regulator is used to maintain the design operating pressure at the emitter, which may range from 27 to 205 kPa for the different types of emitter systems. The water flowmeter is required to monitor flowrate and volume, to check the initial design flow conditions, to schedule irrigations, and to provide information on possible maintenance problems. Microirrigation systems are readily automated, as explained in Chapter 7, using single and multistation timers or controllers and related solenoid valves to eliminate the need to manually open and close flow control values. Filter backwashing and lateral line flushing for system maintenance can also be automated. Controllers are available that can operate on an electrical outlet, battery, or solar power sources. Automation can also be partial or total to include sequential operations from a few minutes in an hour, an entire day, or any number of cycles per day. Automation can be accomplished on a volumetric or timer basis, or by soil water and plant water stress sensors that actuate the controllers.

1.4.4. Filtration

Filtration is essential for successful operation of microirrigation systems. Appropriate filtration helps prevent clogging of the emitters from organic and inorganic particulate matter. The basic types of filter include centrifugal, screen, sand media, and disk. These are often used in combination, such as using a sand media for initial removal of large particulates and screen filters providing removal of the fine material. Selection of the filters depends on the source of water (e.g., surface water reservoirs, streams or groundwater wells). Media or disk filters are generally selected for the primary filtration when open water bodies or biological effluents are the source and quality of water (Fig. 1.9). These filters can be followed with screen filters for final cleanup. Screen filters alone are generally adequate for water from groundwater wells. This is discussed in more detail in Chapter11.

1.5. SYSTEM TYPES

Microirrigation systems are usually defined in terms of installation method, emitter discharge rate, wetted soil surface area, or mode of operation. The four basic types of microirrigation systems are surface drip, subsurface drip, bubbler, and microsprinkler.

1.5.1. Surface Drip Irrigation

Surface drip irrigation uses emitters and lateral lines laid on the soil surface or attached above-ground on a trellis or tree. This is the most widely used type of microirrigation system in the United States (Chapter 12). Surface drip irrigation has been primarily used on widely spaced perennial plants, but can also be used for annual row crops. Generally, discharge rates are less than 12 L/h for single-outlet, point-source emitters and less than 12 L/h-m for line-source emitters. Advantages of surface microirrigation include the ease of installation, inspection, changing and cleaning emitters, plus the possibility of checking soil surface wetting patterns and measuring individual emitter discharge rates. An example of a surface microirrigation emitter and lateral line is shown in Fig. 1.10.

Figure 1.9. Large complex of sand media filters used to filter sugarcane mill wastewater for microirrigation, Maui, Hawaii, USA. Photo courtesy of Freddie Lamm, Kansas State University.

Figure 1.10. Surface drip irrigation of lettuce near Fresno, California, USA. Photo courtesy of Tom Trout, USDA-ARS Water Management Research Laboratory.

1.5.2. Subsurface Drip Irrigation

In subsurface drip irrigation (SDI), water is applied slowly below the soil surface through buried emitters. The discharge rates are in the same range as those for a surface drip system. A typical soil surface wetting pattern from a subsurface drip system is illustrated in Fig. 1.11. This method of application is not to be confused with subirrigation, in which the root zone is irrigated through or by water table control. SDI systems have gained wider acceptance since earlier problems of emitter clogging have been reduced and improved methods of installation have been developed (Chapter 13). SDI is now being installed on small fruit and vegetable crops, and field crops (cotton, corn, tomato, alfalfa) (Nightingale et al., 1986; Phene et al., 1987; Ayars et al., 1992; Camp, 1998; Ayars et al., 1999; Camp et al., 2000). Experience has shown that emitter outlets should be pointed upwards and that maintenance requirements are similar to surface microirrigation systems. Advantages of SDI include freedom from dripline installation at the beginning and removal at the end of the growing season, little interference with cultivation or other cultural practices, and possibly a longer operational life. In addition, combination subsurface and surface microirrigation systems have been tried where the lateral lines are buried and the emitters are located on or above the soil surface through the use of riser tubing.

Figure 1.11. Line-source emitter system used for subsurface drip irrigation (SDI) of almonds showing the wetting pattern on the soil surface. It should be noted that often the soil surface is not wetted with SDI. (California, USA. Photo courtesy of Freddie Lamm, Kansas State University.)

1.5.3. Bubbler Irrigation

In bubbler irrigation, water is applied to the soil surface in a small stream or fountain from an opening with a point-source discharge rate greater than surface or subsurface microirrigation of 12 L/h, but usually less than 250 L/h. Because the emitter discharge rate normally exceeds the infiltration rate of the soil, a small basin is required to contain the distribution of water (Fig. 1.12). The use of bubbler application is extensive in landscape irrigation systems, but is use in agriculture is currently limited. Bubbler systems are well suited for perennial crops, particularly on orchards and vineyards with level typography. Advantages of the bubbler system include reduced filtration, maintenance or repair, and energy requirements compared with other types of microirrigation systems. However, larger size lateral lines are usually required with the bubbler systems to reduce the pressure loss associated with the higher discharge rates. Design procedures and management guidelines for bubbler irrigation is provided in Chapter 14.

Figure 1.12. Bubbler system with a small basin around each citrus tree to contain the high water application rate. Photo taken near Maricopa, Arizona, USA, provided by Edward Martin, University of Arizona.

1.5.4. Microsprinkler Irrigation

In microsprinkler irrigation, water is applied to the soil surface as a small spray, jet, fog, or mist. The air is instrumental in distributing the water, whereas in surface drip, subsurface drip, and bubbler irrigation, the soil facilitates and controls water distribution. Microsprinklers have discharge rates typically less than 175 L/h per microsprinkler and are used to irrigate trees or other widely spaced crops (Fig. 1.12). Microsprinkler systems can be vulnerable to high wind and evaporation losses, particularly when plants are young and have a limited crop canopy. However, both microsprinkler and bubbler systems normally have less filtration and other maintenance requirements than surface or subsurface drip irrigation systems. Microsprinklers also provide better freeze protection than drip irrigation systems. The cost for a microsprinkler systems ranges from $2,000 to $3,000/ha in the United States and thus represents a considerable investment for producers. The design and management of microsprinkler systems are covered in detail in Chapter 15.

Figure 1.13. Microsprinkler applying water to grapefruit in Florida. Photo courtesy of Brian Boman, University of Florida.

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

2. SOIL WATER CONCEPTS

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"In one drop of water are found all the secrets of all the oceans." Khalil Gibran

2.1. INTRODUCTION

2.1.1. Soil Water Regime for High Frequency Irrigation

Subsurface soil water regime is determined by the properties of the soil and the geometry and rates of water application and withdrawal from the profile. Factors that differentiate the soil water regime for microirrigation from standard surface and sprinkler irrigation systems are (1) the flow regime is 2 or 3-dimensional rather than vertical only; (2) the water is added at a high frequency; and (3) soil water content is maintained within a relatively narrow range. The multidimensional nature of flow from point or line sources leads to more complex mathematics if the system is to be modeled. The high frequency of application and narrow water content range tend to skew the concept of field capacity where soil properties control plant available soil water. Although the volume of water stored remains a key factor, water is added more often and presumably can be carefully controlled around prescribed target values. Plant rooting patterns under limited volume and non-stressed conditions lead to some new concepts relative to conventional irrigation. For example, when expressing water for evapotranspiration, should it be per unit of total land area, per unit of a strip that is farmed or per unit area of canopy? In addition, the desirability of distributing water to encourage root development over an extensive area is debatable and perhaps site specific.

2.2. SOIL WATER

2.2.1. Soil Water Content

The status of soil water can be described in two separate modes: the *soil water content,* which tells "how much" water is present, and *soil water potential,* which relates to the energy level (indicating how readily available for plant uptake or movement). Processes dealing with water balance are usually more directly related to water content; whereas processes dealing with water movement are usually more directly related to soil water potential. The types of instruments chosen for monitoring soil water depend on the mode that is of most relevance and this will depend on the purpose of measurement.

The basic definitions of soil water content include the water content by mass (θ_m) given by

$$\theta_m = \frac{\text{Mass of water}}{\text{Mass of solids}} \tag{2.1}$$

This is also called gravimetric water content and water content by weight. Water content is dimensionless, but often θ_m is followed by g/g or kg/kg to emphasize that the measurements are on a mass basis. Water content by volume (θ) is defined by

$$\theta = \frac{\text{Volume of water}}{\text{Total soil volume}} \tag{2.2}$$

and is the fraction of the soil's bulk volume occupied by water. Although dimensionless, values are often followed by cm^3/cm^3 or m^3/m^3 to emphasize a volume basis. The two water content expressions are related through the ratio of the soil bulk density (ρ_b) to water density (ρ_w):

$$\theta = \left(\frac{\rho_b}{\rho_w}\right)\theta_m \tag{2.3}$$

For most soils, the bulk density is greater than 1 Mg/m^3 and θ will be greater than θ_m. The preferred form of water content is determined on the basis of convenience.

Water content can also be expressed as an effective saturation (S_e)

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2.4}$$

where θ_s is the volumetric water content at saturation and θ_r is the residual water content. The residual water content is defined as the water content at which the corresponding hydraulic conductivity is appreciably zero, but very often it is used as an empirical constant when fitting hydraulic functions. Equation 2.4 can be used with $\theta_r = 0$. In any case, note that S_e ranges between 0 and 1.

2.2.2. Soil Water Potential

In addition to the content, soil water is also characterized by its energy state. Soil water is subjected to forces of variable origin and intensity, thereby acquiring different quantities and forms of energy. The two primary forms of energy of interest here are kinetic and potential. Kinetic energy is acquired by virtue of motion and is proportional to velocity squared. However, because the movement of water in soils is relatively slow (usually less than 0.1 m/h), its kinetic energy is negligible. The potential energy, which is defined by the position of soil water within a soil body and by internal conditions, is largely responsible for determining soil water status under isothermal conditions.

As with all other matter, soil water tends to move from a high potential energy to a lower one, in its pursuit toward equilibrium with its surroundings. The magnitude of the driving force behind such spontaneous motion is a difference in potential energy across a distance between two points of interest. At a macroscopic scale, potential energy is defined relative to a reference state. The standard state for soil water can be defined as pure and free water (no solutes and no external forces other than gravity) at a reference pressure, temperature, and elevation, and is arbitrarily given a value of zero.

The energy level is defined as energy per unit quantity relative to a reference state. The most fundamental energy components are with respect to elevation, pressure and solution composition. If it is assumed that the components are additive and by expressing the level as energy per unit weight, the total soil water potential ϕ_T is expressed as a length, and is

$$\phi_T = z + h + \pi + ... \tag{2.5}$$

The term z (L) is the elevation and is the potential due to gravity; h (L) is the pressure head and will be positive for submerged conditions and negative for water under tension; and π (L) the osmotic head is negative for other than pure water. The relationship for ϕ_T is written to emphasize that other factors may be important, but generally these are the three components considered. The reference (or zero point) for z is defined by the user; the reference for pressure head is usually atmospheric pressure, which is most often assumed equal to the air pressure in contact with the soil water; and the reference for π is pure water.

The matric potential (h_m) is the difference between the soil water pressure head *(h)* and the soil air pressure head ($h_{soil\ air}$):

$$h_m = h - h_{soil\ air} \tag{2.6}$$

For most natural systems, the soil air is assumed to be at atmospheric pressure for which h expressed as a gage pressure is the same as h_m. Thus, h is often used interchangeably with h_m for unsaturated conditions.

The general definition of soil water potential gives rise to alternative dimensions and units depending on what is considered to be the basic unit "quantity." For example, we can use energy per unit volume and the potential is $\phi_{T,v}$ which has dimensions of pressure and is related to ϕ_T by

$$\phi_{T,v} = \rho_w g \phi_T \tag{2.7}$$

with ρ_w the density of water and g the gravitational acceleration constant. Both ϕ_T and $\phi_{T,v}$ are commonly used, especially when describing the pressure components. For most flow considerations, ϕ_T is more convenient as the gradients are with respect to distance and the pressure head compares directly with elevation as a length. However, for soils that are moderately to very dry, the status is often expressed in pressure units (e.g., MPa, atm, or bar).

2.2.3. Soil Water Characteristic Curves

Although there are fundamental differences in expressing water status in terms of content or potential, nevertheless there are basic relationships between the pressure head h and water content. When h is greater or near atmospheric pressure, the system will be near saturation, and when h is less than atmospheric there will be a decrease in water content as h decreases. "Decrease" is used here in an algebraic sense (e.g., -10 is less than -0.1) with the soil air pressure at atmospheric. The relationship of matric potential to water content is called a soil water characteristic curve or a water retention curve. An example is shown in Fig. 2.1A. For $h = 0$, the corresponding value of θ must be near θ_s the saturated value. As h proceeds along the negative axis the value of θ decreases monotonically.

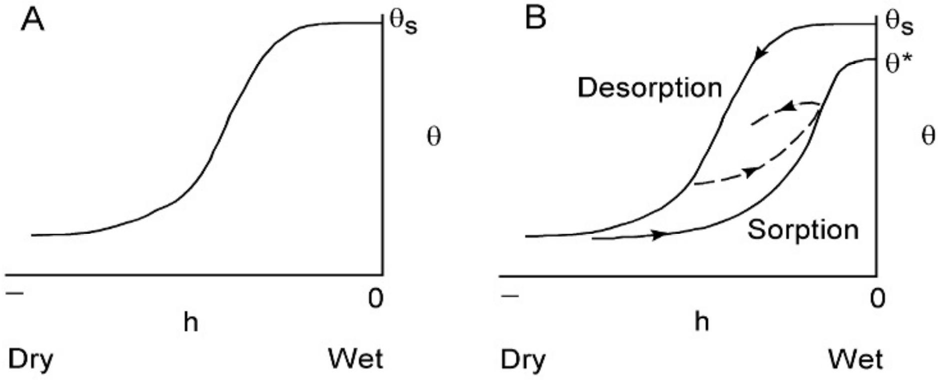


Figure 2.1. Soil water characteristic curves with Part B showing a hysteretic relationship ($h = h_m < 0$).

Water content and the potential energy of soil water are not uniquely related because the amount of water present at a given matric potential is dependent on the pore size distribution and the properties of air-water-solid interfaces. A soil water characteristic curve may be obtained by: (i) taking an initially saturated sample and applying suction (or pressure) to desaturate it (desorption); or by (ii) gradually wetting an initially dry soil (sorption). These two pathways produce curves that in most cases are not identical; the water content in the "drying" curve is higher for a given matric potential than that in the "wetting" branch (Fig. 2.1B). This is called capillary hysteresis.

Many algebraic relationships have been introduced in order to model soil water characteristic curves such as in Fig. 2.1A. Two of the more widely used forms were developed by Brooks and Corey (1964) and van Genuchten (1980) (Tab. 2.1). Both relationships are in terms of the effective saturation S_e given by Eq. 2.4 and empirical constants α_{VG} and m (or α_{BC} and m_{BC}). These forms are convenient to use for modeling results and have corresponding forms for the unsaturated hydraulic conductivity, which are also presented in Tab. 2.1.

Table 2.1. Hydraulic functional relationships.

	m	K/K_s	S_e
1. van Genuchten (1980)[1]	$0 < m < 1$	$S_e^p\left[1-\left(1-S_e^{1/m}\right)^m\right]^2$	$\left(1+\lvert\alpha_{VG}h\rvert^n\right)^{-m}$
2. Brooks & Corey (1964)[2]	$m_{BC} > 0$	$S_e^v \quad \left(\alpha_{BC}h < -1\right)$	$\lvert\alpha_{BC}h\rvert^{-1/m} \quad \left(\alpha_{BC}h < -1\right)$
		$1 \quad \left(-1 > \alpha_{BC}h > 0\right)$	$1 \quad \left(-1 > \alpha_{BC}h > 0\right)$

[1] Most often used with $p = 0.5$ and $n = 1/(1-m)$
[2] Use $v = 2m_{BC} + 3$ (Sometimes use $2m_{BC} + 1$ and $2m_{BC} + 2$)

Example 2.1.

In Fig. 2.2 plots of log |h| vs. S_e are made with $\alpha_{BC} = 1/62.2\ cm^{-1} = 0.0161$, $m_{BC} = 1/0.75 = 4/3$ using the Brooks-Corey relationship. Also plotted are results using $\alpha_{VG} = 0.01\ cm^{-1}$, $n = 2$ for the van Genuchten relationship. This comparison was made by Lenhard et al. (1989) to demonstrate how to match the fitting constants to obtain similar retention curves for the two alternative forms.

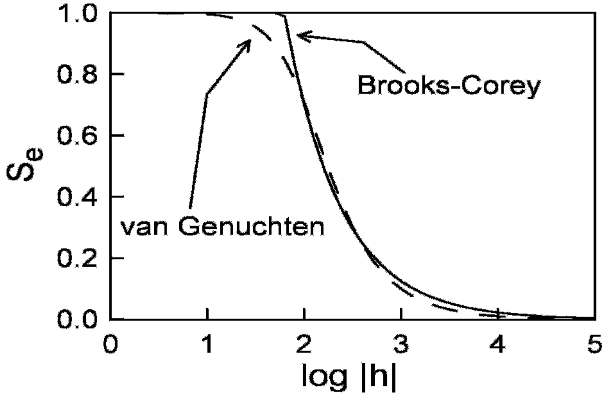


Figure 2.2. Comparison of effective saturation for Brooks-Corey and van Genuchten retention as a function of suction |h| (cm).

2.2.4. Soil Water Measurements

Measurements of soil water content and matric potential are critical for proper irrigation scheduling. Often, the amount of water to apply is calculated from the amount of soil water storage (water content), whereas the timing of irrigation is determined by the energy status of soil water as reflected by the matric potential. Detailed discussions of most available measurement methods of soil water content and potential are presented by Dane and Topp (2002). However, some commonly used methods appropriate for microirrigation will be discussed here. There are additional advantages, disadvantages, and qualifications other than those mentioned.

2.2.4.1. Gravimetric determination of soil water content

The gravimetric method determines θ_m over all ranges. Soil samples are dried in an oven at approximately 105 ^{o}C until no appreciable mass change occurs. The difference between the wet weight and the dry sample weight is the weight of the water contained in the original soil sample. This method involves practically no assumptions, and thus, serves as the standard against which all other methods are evaluated. Primary limitations include non-repeatability, relative long time from sampling to results, and generally a high labor requirement for each measurement point.

2.2.4.2. Neutron scattering

This is an indirect method by which volumetric water content θ is obtained over all ranges. A radioactive source of fast neutrons is lowered into an access tube where collisions with hydrogen nuclei cause a slowing of the fast neutrons. The detected flux of slow neutrons is proportional to the volumetric water content. Values can be obtained repeatedly at essentially all depths other than for the surface 0.15 m and can be a major limitation for microirrigation applications. Generally, a site-specific calibration curve is necessary. The soil volume measured is a sphere with a radius on the order of 15 cm that becomes larger for dryer conditions. The basic measurement device is moderately expensive and requires licensing due to the use of a radioactive source and health concerns.

2.2.4.3. Time domain reflectometry (TDR)

TDR measures volumetric water content θ over the entire range. The TDR method measures the apparent dielectric constant of the soil surrounding electrical waveguides dominated by the dielectric constant of water and is relatively insensitive to soil composition. The approximate measurement volume is a cylinder of diameter slightly larger than the wave-guide spacing and of a length approximated by the wave-guide length. The method is highly accurate, repetitive, and non-destructive. Calibration is minimal except for fine-textured or organic soils. Soil electrical conductivity (EC) values can be determined for moderate to low salinities, but neither EC or θ can be determined in highly-saline soils. The cost is moderately expensive.

2.2.4.4. Tensiometers

Tensiometers can be used for determining matric potential for $h_m > -8$ m. A tensiometer consists of a porous cup connected to a vacuum gauge through a water-filled tube. The porous cup (typically made of ceramic) is placed in contact with the soil and water moves through the cup into the soil thereby creating suction in the tensiometer sensed by the gauge. Water flows until the suction in the tensiometer equals the matric potential in the soil. Tensiometers are relatively simple and reliable, but the standard design requires frequent servicing. They can be read with a vacuum gage, portable pressure transducer or multiplexed with dedicated electronic pressure transducers. Costs are modest. Generally, they can be used for all soil types, provided adequate continuity exists between the tensiometer cup and the soil matrix.

2.2.4.5. Heat dissipation

Heat dissipation is used to evaluate matric potential for $h_m > -100$ m. A heat pulse is introduced within a porous block and the corresponding temperature response is related to the amount of water in the block and in turn is a function of h_m. Measurements can be made repetitively, are non-destructive, and are easy to automate. Considerable calibration is needed on individual units.

2.2.4.6. Electrical resistance

Electrical resistance (in porous blocks) can be used to evaluate matric potential for $h_m < -1$ m. Electrical resistance values of a porous matrix held between two electrodes are related to the water content of the matrix that is in hydraulic equilibrium with the surrounding soil. The sensors are relatively low in cost, simple and can be used repetitively on the same location. They require considerable calibration and are unreliable at higher water contents or in highly saline conditions.

2.2.4.7. Capacitance

Several new sensors are based on changes in electrical capacitance of the soil as a function of changes in water content. These and sensors based on frequency-shift (e.g., TDR), rely on soil dielectric properties that, as mentioned earlier, are dominated by the water phase. The primary difference from TDR is the relatively low frequency range of measurement (kHz-MHz). New capacitance sensors can be buried and monitored automatically. Cost is low to moderately expensive. The quality of installation is important to minimize air gaps between the device and the soil. This can be a problem in cracking clay soils for both capacitance and TDR devices.

2.3. SOIL WATER MOVEMENT

2.3.1. Darcy's Law

Darcy's Law gives the flux density $\vec{J}_w$ (L T^{-1}) as a function of the gradients of hydraulic head H,

$$\vec{J}_w = -K \operatorname{grad} H \tag{2.8}$$

where "grad" is a vector gradient operator (i.e., derivative of the hydraulic head with respect to space) and K (LT^{-1}) is the hydraulic conductivity. The hydraulic head H is the sum of the pressure head h and elevation. For the following, it is assumed that the z axis is downwards so the elevation is $-z$ for which the hydraulic head is given by

$$H = h - z \qquad (z \text{ positive downwards}) \tag{2.9}$$

The Darcian velocity $\vec{J}_w$ is a vector. The components expressed for Cartesian coordinates are

$$J_x = -K\frac{\partial h}{\partial x}$$
$$J_y = -K\frac{\partial h}{\partial y} \tag{2.10}$$
$$J_z = -K\left(\frac{\partial h}{\partial z} - 1\right)$$

Darcy's Law is empirically based and originally derived for saturated flow. K is a constant for saturated flow. Darcy's Law is extended to unsaturated flow by taking the conductivity to be a function of water status, either as a function of the matric potential or the water content.

In Fig. 2.3, hydraulic conductivity functions (i.e., K as a function of h) and the soil water characteristic curves are plotted for two soils, the Glendale clay loam and Berino loamy fine sand (Hills et al., 1989). Note that the ordinate is on a logarithmic scale and that K varies over several orders of magnitude which is typical for such functions. Also, note that the finer-textured clay loam has a lower saturated K. For lower values of the suction $|h|$, K remains less for the clay loam, but the two curves cross for higher suctions. This is a consequence of the pore size distributions of the two soils. Thus, for a finer-textured soil, there are fewer large pores to conduct water under saturated conditions compared with the coarser-textured loamy sand. However, more small pores are available in the clay loam, which remains filled with water at large suctions.

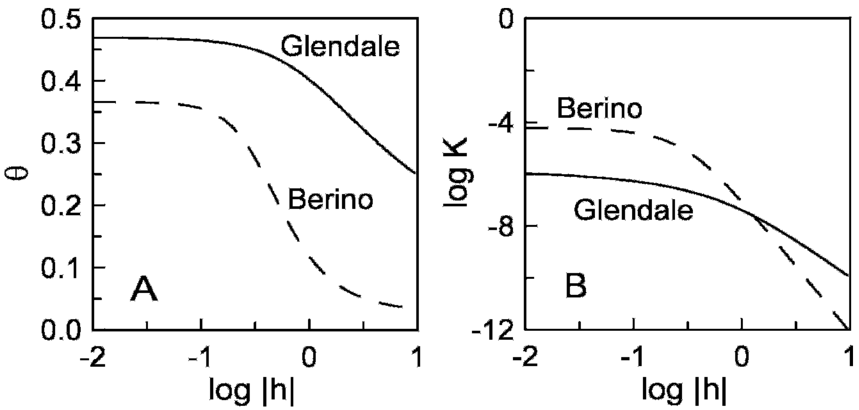


Figure 2.3. Soil characteristic (A) and hydraulic conductivity (B) for Glendale clay loam and Berino fine sand (units are m and s).

2.3.1.1. Alternative forms for Darcy's Law

Equivalent forms for Darcy's Law may be written using the relationship of intrinsic permeability k (L^2) where

$$k = \frac{\eta K}{\rho g} \tag{2.11}$$

with η ($ML^{-1}T^{-1}$) the viscosity. The value of k will be a property of the soil pore space geometry only and will not depend on the fluid provided the soil does not disperse or react with the fluid used. Generally, soil is reactive and values of k will depend somewhat on the fluid used, but the preceding equation still offers a convenient way to introduce the effects of temperature on viscosity of water on K, and as a means to use liquids other than water (e.g., gas flow measurements) to determine soil K. Additionally, pressure may be used in place of the pressure head with the result

$$\vec{J}_w = -\frac{k}{\eta} \text{ grad } (p - \rho g z) \tag{2.12}$$

In this case, z is still defined as positive in the downwards direction. Another form can be used with capillary pressure p_c, which is the air pressure minus the water pressure. In terms of capillary pressure, Darcy's Law becomes

$$\vec{J}_w = \frac{k}{\eta} \text{ grad } (p_c + \rho g z) \tag{2.13}$$

For simultaneous flow of air and water, normally both air and water are assumed to satisfy Eq. 2.13 independently with "k" the appropriate phase permeability.

2.3.2. Richards' Equation

Mass conservation of water requires

$$\frac{\partial \theta}{\partial t} = -\text{div}\, \vec{J}_w + A \tag{2.14}$$

with "div" the vector divergence and A (T^{-1}) a source or sink term such as water uptake by plant roots. This is a continuity equation expressing the rate of change of water stored at any infinitesimal volume element (the left-hand side) and must equal the sum of the net change in the rate of water entering (or leaving) the infinitesimal volume added to external sources/sinks A.

Expressing the flux $(\vec{J}_w)$ by means of Darcy's Law leads to

$$\frac{\partial \theta}{\partial t} = \text{div } (K \text{ grad } H) + A \tag{2.15}$$

or in Cartesian coordinates

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K \frac{\partial h}{\partial z}\right) - \frac{\partial K}{\partial z} + A \tag{2.16}$$

Eq. 2.16 is referred to as Richards' equation (Richards, 1931). Alternative forms of Richards' equation are also used. Equation 2.16 is a "mixed" formulation where two dependent variables h and θ are included. To eliminate h, a functional form of h in terms of θ is assumed to give the soil water diffusivity D (L^2 T^{-1}) defined by

$$D = K\frac{dh}{d\theta} = \frac{K}{C} \tag{2.17}$$

The specific water capacity C (m^{-1}) is given by

$$C = \frac{d\theta}{dh} \tag{2.18}$$

The result is the "θ-based" form of Richards' equation in Tab. 2.2 for one dimension. Similarly, the "h-based" form is given by using C to eliminate θ with the result also shown in Tab. 2.2. A third form is also given in the table that assumes the conductivity is exponential with h and under steady-state conditions. This allows direct solutions for ϕ (and subsequently h) from Richards' equation. Abundant techniques and existing solutions are available from existing textbooks and examples from a variety of applied science and engineering applications.

Table 2.2. Some alternative forms of Richards' equation. (Note: z-axis is directed down and source term A is assumed zero.)

Equation	Description
1. $\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D\frac{\partial\theta}{\partial z}\right) - \frac{\partial K}{\partial z}$	θ-based, 1-D
2. $C\left(\frac{\partial h}{\partial t}\right) = \frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right) - \frac{\partial K}{\partial z}$	h-based, 1-D
3. $\nabla^2\phi - \alpha\frac{\partial\phi}{\partial z} = 0$	Matric flux-based, steady state, $K = K_s \exp(\alpha h)$ (Quasi-linear)

2.3.3. Measurements of Soil Hydraulic Parameters

Measurements of soil hydraulic parameters can be grouped into direct, indirect and inverse methods (Radcliffe and Rasmussen, 2002). Not surprisingly, there are numerous ways of determining soil hydraulic parameters. An authoritative source is the Methods of Soil Analysis (Part 1) by the Soil Science Society of America (Dane and Topp, 2002), which gives a detailed discussion of these and other techniques.

2.3.3.1. Direct measurements

Laboratory methods generally involve a minimally-disturbed soil core. Saturated hydraulic conductivity can be run either under constant or variable hydraulic gradients. Analysis is straight forward and procedures are well specified. Unsaturated hydraulic conductivity is much more difficult to measure, is slower, and the analysis is more complex than the saturated case. The most common methods are with single or multi-step outflow, which are transient methods, based on how fast water comes out of the sample when a finite pressure gradient is established (once for single step or successively for the multi-step procedure).

Field methods to determine saturated hydraulic conductivity include the use of infiltration rings and borehole permeameters. Tension infiltrometers can be used for finding unsaturated hydraulic conductivity in the wet range (generally wetter than h = -30 cm). Simultaneous measurements of water loss from a soil profile and hydraulic gradient can also be used for small covered plots (the "instantaneous-profile" method).

2.3.3.2. Indirect measurements

Values based on the soil water characteristic curve can be used to fit unsaturated hydraulic conductivity using the van Genuchten (1980) or Brooks and Corey (1964) relationships of Tab. 2.1. In this case, the constants in the equations are "best-fit" for the h vs. S_e curve and then used in the K vs. S_e (or K vs. h) relationships. Generally, this can be done with any nonlinear regression procedure.

2.3.3.3. Inverse methods

Inverse methods can be applied to best-fit parameters using comprehensive solutions to Richards' equation. In this approach, some combination of measurements of flow input, water content, and pressure head are used to define an objective function, which is optimized by successive solutions to Richards' equation. Conceptually, the parameters come from the solution by best-fitting the objective function. Examples and software have become more and more sophisticated both for laboratory and field measurements (Simunek and Hopmans, 2002).

2.3.4. Shortcuts with Pedotransfer Functions

Pedotransfer functions can be used to provide estimates of parameters or constants which have not been measured. For soil water, this generally includes coefficients needed to express soil water characteristic curves or hydraulic conductivity. Necessary input may include particle size distributions, porosity or organic carbon.

A simple form of a pedotransfer function is to use a known or estimated textural class and use the class average as the value. For example, in Tab. 2.3, averages were based on 1209 measured retention curves and 620 saturated hydraulic conductivity values (Schaap et al., 1998). The constants needed for the van Genuchten (1980) hydraulic function, namely θ_r, θ_s, $\log(\alpha_{VG})$, $\log(n)$ and K_s are included. An important question is how good these values are for representing an unmeasured sample. A measure of reliability is indicated by the standard deviations (shown in parentheses in Tab. 2.3) that express the variation within the samples for each class. Also shown is the RMSE (root mean square error) which is a measure of the fit. A similar set for the parameters of Brooks and Corey (1964) is given by Rawls et al. (1982) and repeated by Radcliffe and Rasmussen (2002). The pedotransfer function can utilize additional information, if available, and estimates of soil hydraulic properties can be improved. For example, porosity, gravel, water retained at 10 kPa, and organic matter in addition to textural information can be considered.

Traditionally, pedotransfer functions were based on regression relationships. More recently, Schaap et al. (1998) and others have made use of neural networks for predicting soil hydraulic properties. Neural networks give a nonlinear fit to a training set without defining a model in advance. Accuracies are generally as good or better than conventional regression analyses applied to the same data although both conventional and neural networks can make use of additional input parameters. To make their neural network results convenient, Schaap and colleagues have developed the "Rosetta Program" that can be downloaded from the USDA-ARS George E. Brown, Jr. Salinity Laboratory website and used to estimate the van Genuchten (1980) water retention and hydraulic conductivity functions.

2.4. MODELING FOR EFFECTIVE MANAGEMENT AND DESIGN

Irrigation design and management require some form of predictive capabilities regarding relationships between water application rate, soil properties, and plant root uptake pattern, and their combined effect on the resulting soil water dynamics and distribution. These relationships are formulated in models that take many forms and include those that are physically-based, analog, and mathematical. The widespread availability of computers makes it possible to implement mathematical models ranging in complexity from simple formulas based on volume balance to complex solutions of Richards' equation depicting water movement. For most general conditions, Richards' equation can be solved only by numerical techniques, such as, finite differences and finite elements. Fortunately, improved and user-friendly software programs are rapidly appearing with refined user interfaces that facilitate quick set-up and solution to a wide variety of problems (e.g., HYDRUS-2D, Simunek et al., 1999). Our emphasis here will be on volume balance approximate solutions, and on specialized cases for which closed-form analytical solutions for the Richards' equation exist. In microirrigation of actively growing plants, one must consider the role of plant water uptake in modifying soil water distribution. Finally for many monitoring activities, spatial variations in soil properties affect the resultant soil water distribution, and thus must be taken into consideration.

2.4.1. Simplified Hemispherical Model

A simple relationship follows for infiltration from a point (single) emitter placed on the soil surface by assuming: (1) the water content in the wetted volume is constant, say θ_{wet},, and (2) the shape of the wetted volume is approximately hemispherical. Considering an initial soil water θ_{dry}, conservation of mass requires that

$$qt = (2/3)\pi r_f^3 \left(\theta_{wet} - \theta_{dry}\right) \tag{2.19}$$

with q the emitter discharge rate (L^3T^{-1}), t is elapsed time for water application, and r_f the radius of the wetted volume (wetting front position). The following example implements this simple model to estimate the wetting front position.

Example 2.2.

Water is applied from an emitter with a flowrate of 3L/h for 12 h on a sandy soil. The volumetric soil water content increases on average from θ = 0.05 to 0.15. For these conditions, a rearrangement of the hemispherical model (Eq. 2.19) gives

$$r_f = \sqrt[3]{(3/2)qt/(\pi(\theta_{wet} - \theta_{dry})}$$

$$r_f = \sqrt[3]{(3/2)(3000)(12)/[\pi(0.15 - 0.05)]} = 55.6 \quad cm$$

The solution for the wetting front position is r_f = 55.6 cm.

2.4.2. Quasi-Linear Solutions to Richards' Equation

Richards' equation simplifies for steady-state conditions ($\partial\theta/\partial t = 0$), furthermore, with a special form of the hydraulic conductivity function: $K(h) = K_s \exp(\alpha h)$, and it is amenable to analytical solutions via a linearization procedure. By taking the z-axis positive downward, the steady-state form without uptake is (Warrick, 2003):

$$\nabla^2\phi - \alpha\frac{\partial\phi}{\partial z} = 0 \tag{2.20}$$

where ϕ is the matric flux potential [L^2T^{-1}] defined as

$$\phi = \int_{-\infty}^{h} K(h)dh = \frac{K_s \exp(\alpha h)}{\alpha} \tag{2.21}$$

and "∇^2" is the Laplacian operator. Because Eq. 2.20 is linear in ϕ, linear combinations of such a solution are also valid solutions for steady state flow problems. This property allows solutions for many geometries relevant to microirrigation systems as will be illustrated in the following examples using standard analytical techniques. Values of K_s, the saturated hydraulic conductivity, and α, a soil specific parameter, are given in Tab. 2.4 for several soil types and textures. Generally, both K_s and α are larger for coarser than for finer textured materials.

Table 2.3. Average values and standard deviations (in parentheses) of fitted hydraulic parameters, root mean square error (RMSE), and the number of samples for nine textural classes (Schaap et al., 1998).

Class	θ_r	θ_s	log (α_{VG})	log(n)	RMSE	K_s
	m^3/m^3		log (cm^{-1})		m^3/m^3	log (cm d^{-1})
Sand	0.044 (0.019)	0.413 (0.057)	-1.57 (0.21)	0.462 (0.200)	0.019	2.71 (0.51)
Loamy sand	0.039 (0.037)	0.395 (0.072)	-1.49 (0.53)	0.194 (0.108)	0.018	1.92 (0.61)
Sandy loam	0.031 (0.049)	0.389 (0.094)	-1.57 (0.58)	0.150 (0.094)	0.021	1.53 (0.65)
Loam	0.054 (0.067)	0.356 (0.082)	-2.11 (0.82)	0.195 (0.140)	0.017	0.99 (0.63)
Silts†	0.065 (0.062)	0.441 (0.103)	-2.51 (0.49)	0.260 (0.131)	0.025	1.04 (0.54)
Sandy clay loam	0.076 (0.074)	0.379 (0.066)	-1.80 (0.66)	0.132 (0.100)	0.010	1.29 (0.70)
Clay loam	0.091 (0.067)	0.439 (0.077)	-1.95 (0.60)	0.188 (0.128)	0.016	0.67 (0.58)
Silty clay loam	0.111 (0.062)	0.460 (0.056)	-2.36 (0.38)	0.240 (0.110)	0.015	0.87 (0.55)
Clays††	0.081 (0.088)	0.441 (0.068)	-1.89 (0.55)	0.107 (0.059)	0.014	1.10 (0.43)

† Silt and silty loam

†† Clay, silty clay, and sandy clay

Table 2.4. Hydraulic conductivity parameters for different soils (Amoozegar-Fard et al. 1984).

Soil	α (cm^{-1})	K_s (cm/s)	r
For original references for these soil types, see Bresler (1978)			
Lamberg clay	3.27×10^{-1}	3.34×10^{-2}	0.98
Bet Netofa clay	6.62×10^{-2}	9.5×10^{-7}	0.99
Lakish clay	1.38×10^{-2}	8.10×10^{-5}	0.99
Yolo clay	3.67×10^{-2}	9.33×10^{-6}	0.99
Sheluhot silty clay	7.26×10^{-3}	1.44×10^{-6}	0.95
Touchet silt loam	1.56×10^{-2}	4.86×10^{-4}	0.93
Touchet silt loam	1.03×10^{-1}	6.64×10^{-4}	0.98
Silt loam	1.39×10^{-2}	5.74×10^{-5}	0.99
Yolo fine sandy loam	2.50×10^{-2}	4.07×10^{-5}	0.79
Plainfield sand fraction (210-250 μ)	2.62×10^{-2}	3.00×10^{-2}	0.21
Plainfield sand fraction (177-210 μ)	0.28	2.00×10^{-2}	0.69
Plainfield sand fraction (149-177 μ)	0.64	1.40×10^{-2}	0.92
Plainfield sand fraction (125-149 μ)	0.33	1.06×10^{-2}	0.74
Plainfield sand fraction (104-125 μ)	0.371	7.30×10^{-3}	0.73
Dackley sand	0.513	1.00×10^{-4}	0.89
Oso flasco fine sand	7.20×10^{-2}	2.00×10^{-2}	0.96
G.E. #2 sand	0.17	1.56×10^{-3}	0.94
For original references for these soil types, see Warrick et al. (1980)			
Clay loam	0.126	1.12×10^{-3}	-
Sandy loam	0.1111	1.00×10^{-3}	-
Plainfield sand	0.126	3.44×10^{-3}	0.97
Columbia sandy loam	0.100	1.39×10^{-3}	0.97
Guelph loam	3.40×10^{-2}	3.67×10^{-4}	0.99
Ida silt loam	2.60×10^{-2}	2.92×10^{-5}	0.93
Yolo light clay	1.90×10^{-2}	1.23×10^{-5}	0.94
Gila fine sandy loam	4.43×10^{-2}	2.43×10^{-4}	-
Latene clay loam	3.86×10^{-2}	5.21×10^{-5}	-
Panoche loam	4.16×10^{-2}	1.10×10^{-3}	-
Pima clay loam	1.40×10^{-2}	1.15×10^{-4}	-

r = coefficient of determination; and α and K_s = parameters fitted to $K = K_s \exp(\alpha h)$

2.4.2.1. Steady state solutions for point sources

Some possible emitter geometries are shown in Fig. 2.4. In the two-dimensional cases such as arising around a line source (along the y-axis) consider the horizontal axis to be x. For three-dimensional cases, such as around a point source, the radial axis is denoted by r. In Fig. 2.4A, a source of water provides a constant inflow q and the non-wetted boundaries are assumed to extend to infinity. For a buried point source, the appropriate solution to Eq. 2.20 is ϕ_{3B}:

$$\phi_{3B} = \left(\frac{\alpha q}{8\pi\rho}\right)\exp(Z - \rho) \tag{2.22}$$

with

$$\begin{aligned} Z &= 0.5\alpha z \\ R &= 0.5\alpha r \\ \rho^2 &= Z^2 + R^2 \end{aligned} \tag{2.23}$$

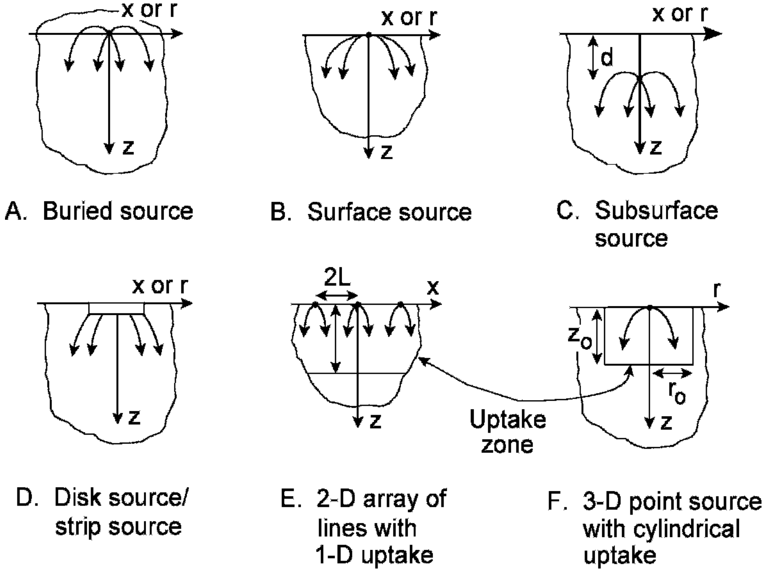


Figure 2.4. Flow geometries considered.

This is one of the simplest analytical expressions relevant to drip irrigation (or flow from a buried point source). The solution is useful for calculating pressure head distributions near an emitter, especially for large elapsed times and when evaluating conditions sufficiently far from surface boundaries. In order to calculate a pressure head from ϕ_{3B}, values of α, K_s and q must be known or assumed. The first step is to calculate the matric flux potential ($\phi = \phi_{3B}$) for the point of interest in the wetted volume using Eq. 2.22, and then h follows from Eq. 2.21

$$h = \alpha^{-1} \ln\left(\frac{\alpha\phi}{K_s}\right) \tag{2.24}$$

For all of the point and line source solutions, ϕ, and consequently h, becomes undefined as the singularity point is approached (Eq. 2.21 becomes undefined when ρ approaches 0). The region for which ϕ is large and $h > 0$ should be disregarded or an alternative solution sought.

A more realistic model for a surface point emitter is given in Fig. 2.4B showing a semi-infinite flow regime. If no flow occurs through the surface away from the source (i.e., $J_z = 0$ for $z = 0$) and $r > 0$, the solution to Eq. 2.20 is ϕ_{3B} given by

$$\phi_{3S} = 2\left[\phi_{3B} - \exp(2Z)\frac{E_1(Z-\rho)}{\rho}\right] \tag{2.25}$$

where $E_1\,(Z - \rho)$ is an exponential integral defined by

$$E_1(u) = \int_u^{\infty} t^{-1}\exp(-t)dt \tag{2.26}$$

Appropriate forms for evaluation of E_1 and tables are provided in Chapter 5 of Abramowitz and Stegun (1964). For arguments in the range $0 < u < 20$, the following series expansion may be applied for the evaluation:

$$E_1(u) = -\gamma - \ln(u) + \sum_{i=1}^{\infty}\frac{(-1)^i u^i}{i\; i!} \tag{2.27}$$

with Euler's constant $\gamma = 0.577216$.

Comparison of matric head values (units of m) measured and calculated for subsurface and surface sources is presented in Fig. 2.5. The surface emitter flowrate was $q = 1.19 \times 10^{-7}$ m^3/s, and the subsurface was $q = 4.44 \times 10^{-7}$ m^3/s, the hydraulic properties of the Millville silt loam soil were determined as $K_s = 6.38 \times 10^{-6}$ m/s and $\alpha = 5$ m^{-1} (Coelho and Or, 1997). Note that the matric head contour lines are nearly circular near either source. The contours become elongated vertically showing the effect of gravity as the distance progresses further away from the source.

2.4.2.2. Steady state solutions for surface ponding

For most soils and practical emitter flowrates, some ponding will occur at the soil surface. This is particularly significant for high flowrates and for soils of low permeability (e.g., fine textured soils). The radius of the saturated zone is shown to be approximately (Bresler, 1977)

$$r_o = \left(\frac{4}{\alpha^2 \pi^2} + \frac{q}{\pi K_s} \right)^{0.5} - \frac{2}{\alpha \pi} \tag{2.28}$$

This simple expression shows that r_o, (the radius of the pond), will increase with either increasing emitter flowrate (q) or decreasing K_s, (the saturated conductivity). The growth of the saturated radius may have important implications for selection of emitter flowrate and spacing to prevent overlap and potential runoff.

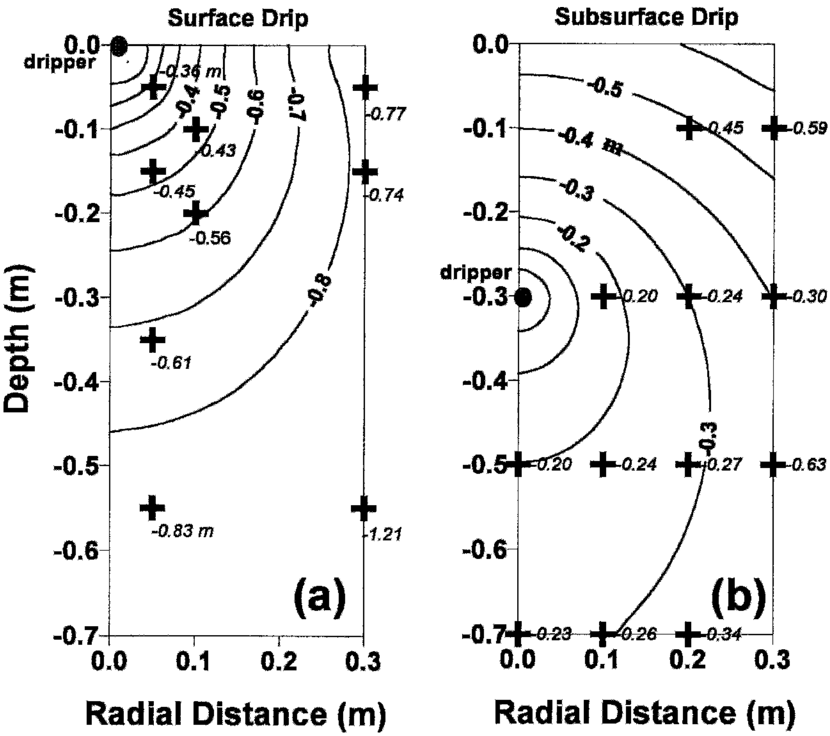


Figure 2.5. Steady-state distribution of soil water pressure head for buried (A) and surface (B) point sources. After Coelho and Or (1997).

2.4.2.3. Steady state solutions for line sources

For sufficiently small spacings between adjacent emitters, the flow system can be analyzed as for a line source. The solution of Eq. 2.20 becomes $\phi = \phi_{2B}$ for a buried line source in an infinite medium and is given by

$$\phi_{2B}(X,Z) = \left(\frac{q_L}{2\pi} \right) \exp(Z) K_o \left[(X^2 + Z^2)^{0.5} \right] \tag{2.29}$$

with K_o a modified Bessel function of the second kind (tables and approximations are provided in Abramowitz and Stegun, 1964), q_L the line strength (dimensions L^2 T^{-1} corresponding to a volume of flow per unit time per unit length of line) and the dimensionless X is equal to 0.5 αx and Z_o is 0.5 αz_o. The solution for surface and subsurface lines (Fig. 2.4) can be modeled by ϕ_{2B} or Eq.2.24 can be used for a surface line source by substituting ϕ_{2B} for ϕ_{3B} (Lomen and Warrick, 1978).

2.4.2.4. Transient (time-dependent) solutions

To capture dynamic changes in soil water associated with initial wetting and intermittent irrigation and redistribution, a transient linearized form of Richards' equation is used:

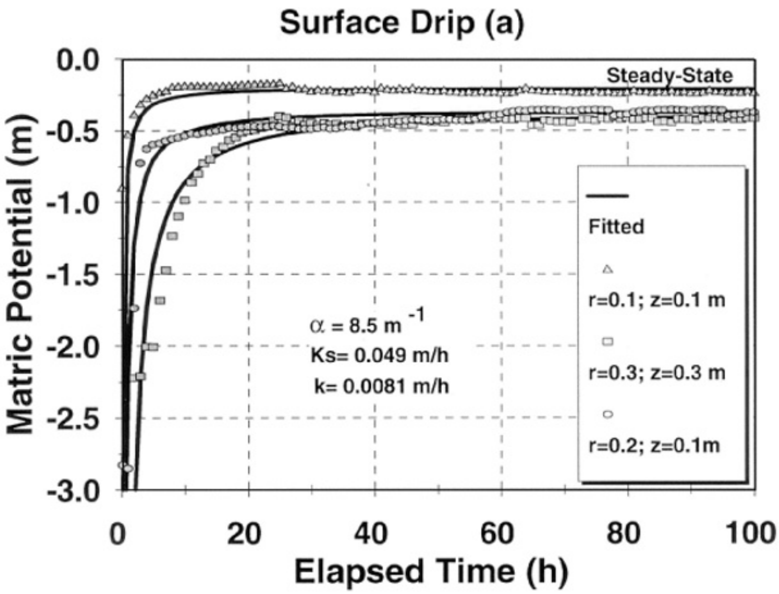
$$\frac{\partial \phi}{\partial t} = \frac{k}{\alpha} \nabla^2 \phi - k \frac{\partial \phi}{\partial z} \tag{2.30}$$

where $k = dK/d\theta$ is assumed to be constant (note that this critical assumption limits solution applicability to narrow increments of water content change within the wet soil volume). The solution to Eq. 2.30 is in Warrick (1974, 2003) and choices for determining k are discussed by Ben-Asher et al. (1978) and Coelho and Or (1997). Figure 2.6 shows measured and calculated matric potential values for the Millville silt loam using both surface and buried sources (at $z = 0.3$ m) with initial water content $\theta = 0.18$, and a flowrate of q=1.6 L/h (Coelho and Or, 1997). The results illustrate the transient nature of the flow process and subsequent attainment of steady state conditions. Furthermore, it shows that the steady state values are different for different locations in the soil relative to the emitter. For a cyclic input such as practiced under drip irrigation, the results depicted in Fig. 2.7 show the increase in matric potential (less negative) during 7 h water application (q=1.6 L/h) and subsequent decrease in matric potential during redistribution (note that there are no plants involved in these measurements).

2.4.3. Root Water Uptake

Management, monitoring and modeling of soil water distribution under cropped conditions requires information on water uptake patterns by plants. Uptake patterns influence water distribution, and thus, are essential for obtaining reliable predictions of water and matric potential distributions within the wetted soil volume. Additionally, information on root uptake patterns is important for design purposes to match application uniformity, emitter spacing and discharge with the extent of plant root systems, and to ensure uniform root accessibility to wetted soil volumes.

Finally, many microirrigation management schemes rely on soil water information in the wetted volume, whose dynamics are determined by soil and plant attributes affecting water flow and uptake patterns. This has been demonstrated by Coelho and Or (1997) where the analytical solution of Warrick (1974) for transient flow from point sources provided a reasonable description of soil-water dynamics in the absence of plants, but is inadequate under cropped conditions. Hence, the influence of uptake patterns must be considered in developing guidelines for soil water sensor placements used for monitoring soil water status and irrigation scheduling.



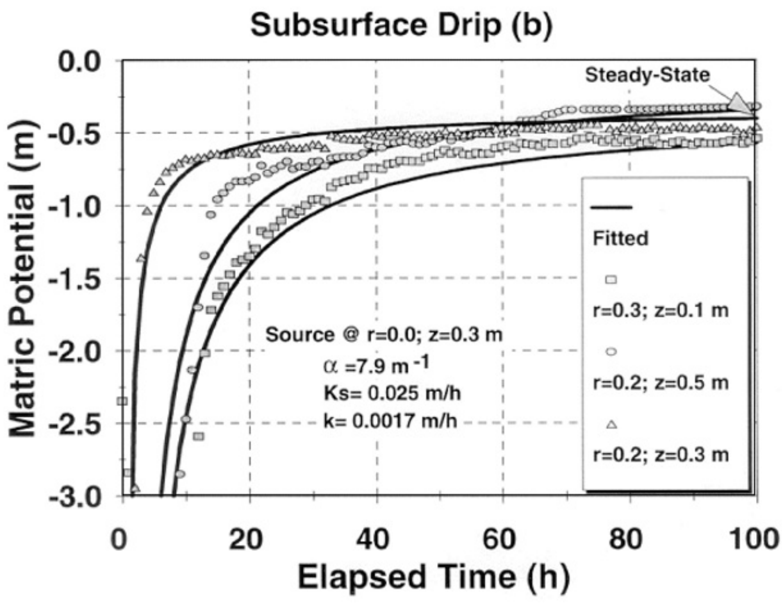


Figure 2.6. Measured and calculated values of matric potential as a function of time for a surface source (A) and a source buried at 0.3 m (B). Initial water content was θ = 0.18 and flowrate was 1.6 l h^{-1}. After Coelho and Or (1997).

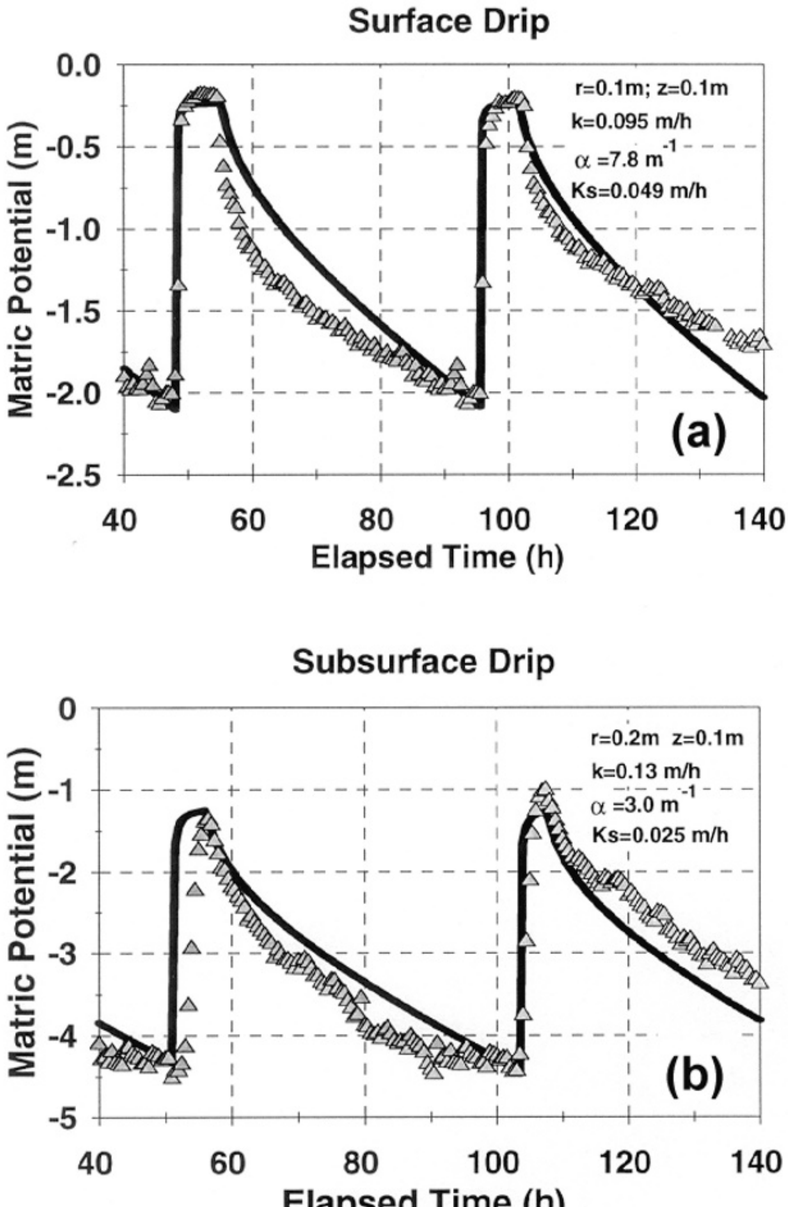


Figure 2.7. Observed and predicted matric potentials obtained for surface and buried (at 0.3 m depth) point sources at two locations within the wetted volume in Millville silt loam soil. Initial water content was $\theta = 0.18$ and flowrate was 1.6 l h^{-1} and duration of water application was 7 h in each cycle. After Coelho and Or (1997).

Empirical or parametric models for root uptake should reflect patterns that are commonly observed in the field (Feddes et al., 1974). Very few models for multidimensional uptake are available in the literature. The interrelation with water distribution patterns in most models is through the assumption of proportionality between uptake and water availability (Neuman et al., 1975; Warrick et al., 1980). Others have assumed a predetermined shape for the root density distribution (Landsberg and McMurrie, 1984). Generally speaking, parametric models for multi-dimensional root uptake and distribution for drip irrigated crops are lacking, as evidenced by the inconsistent and often qualitative presentation of root uptake and density information such as the data presented by Batchelor et al. (1990).

Two examples which illustrate nomographs relevant to point and line sources and plant water uptake are given below. The first is for simplified one dimensional steady state plant water uptake under an array of line sources; the second for constant cylindrical uptake with a steady point source water application (Amoozegar-Fard et al., 1984). Additionally, a two-dimensional parametric model is presented using the transient solution of Warrick (1974) that is suitable for microirrigation with partial soil wetting.

Example 2.3.

Consider a Pima clay loam soil with $\alpha = 0.014$ *cm*$^{-1}$ *and* $K_s = 9.9$ *cm/d where an array of driplines is located on the soil surface at a spacing* $L = 200$ *cm. The rooting depth is* $z_0 = 100$ *cm with the uptake rate from the profile of* $u = 0.75$ *cm/d.*

Determine the discharge necessary to provide a pressure head of $h_m = -350$ *cm for a reference point at depth* $z_M = 35$ *cm directly below the midpoint between the lines. The solution to this problem may be found using the nomograph in Fig. 2.8.*

Referring to the nomograph, the necessary steps are:

1. *Find* $\alpha z_0 = 1.4$, *(Point I on Fig. 2.8).*
2. *Proceed horizontally to curve* $\alpha z_M = 0.5$ *(Point II).*
3. *Proceed vertically upward to curve* $(K_s/u)\exp(\alpha h) = 0.098$ *(Point III).*
4. *Proceed horizontally to intersect scale C, (Point IV).*
5. *Find* $\alpha L = 2.8$ *(Point VIII).*
6. *Proceed vertically upward to curve* $\alpha z_M = 0.5$ *(Point VII).*
7. *Proceed horizontally to intersect scale A (Point VI).*
8. *Connect the two points on scales C and A (Points IV and VI).*
9. *Read the value of* $\alpha q/u = 3.2$ *(Point V), then calculate* $q = 171$ *cm*^{2}*/d.*

Note that a discharge of 171 cm^2*/ d is equivalent to a depth application of 0.86 cm/d over the entire area. Choosing the spacing between lines as 100 cm results in a calculated q of 75 cm*^{2}*/d.*

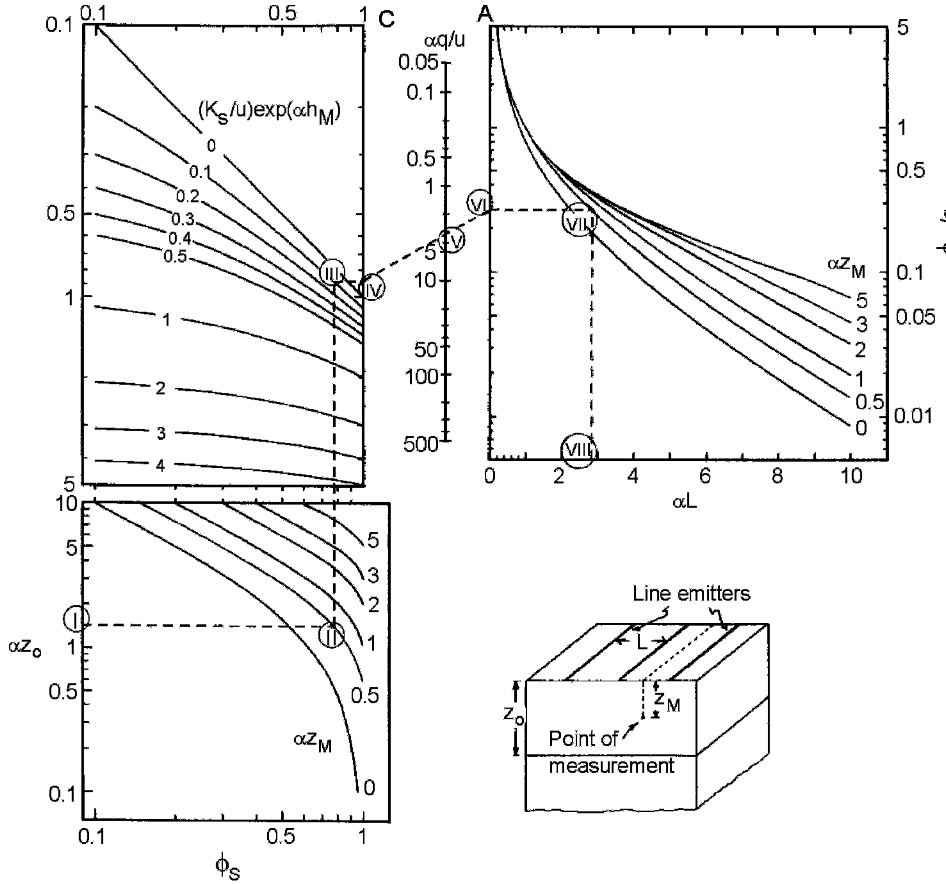


Figure 2.8. Nomograph for array of line sources located at the soil surface with plant uptake to depth to depth z_0 and reference point at depth z_M halfway between lines. After Amoozegar-Fard et al. (1984).

Example 2.4.

A second nomograph is for a cylindrical uptake region (Amoozegar-Fard, 1984). This is of use for modeling plant water uptake, particularly for trees and shrubs for which the root system is symmetric about the trunk. We assume a uniform uptake, 15 L/d within a cylinder 85 cm in diameter and 100 cm in depth. The soil is a Pima clay with $\alpha = 0.014$ cm^{-1} and $K_s = 9.9$ cm/d. The point source is located at the soil surface 60 cm away from the central axis of the cylinder with $q = 25$ L/d in Fig. 2.9. The fraction of water applied which is being removed (by plant *uptake) is u = 15/25 = 0.6. The reference point (point of measurement) is at z_0 = 100, r_o = 85 cm and the horizontal distance (r*) between the point source and reference point is 70 cm.*

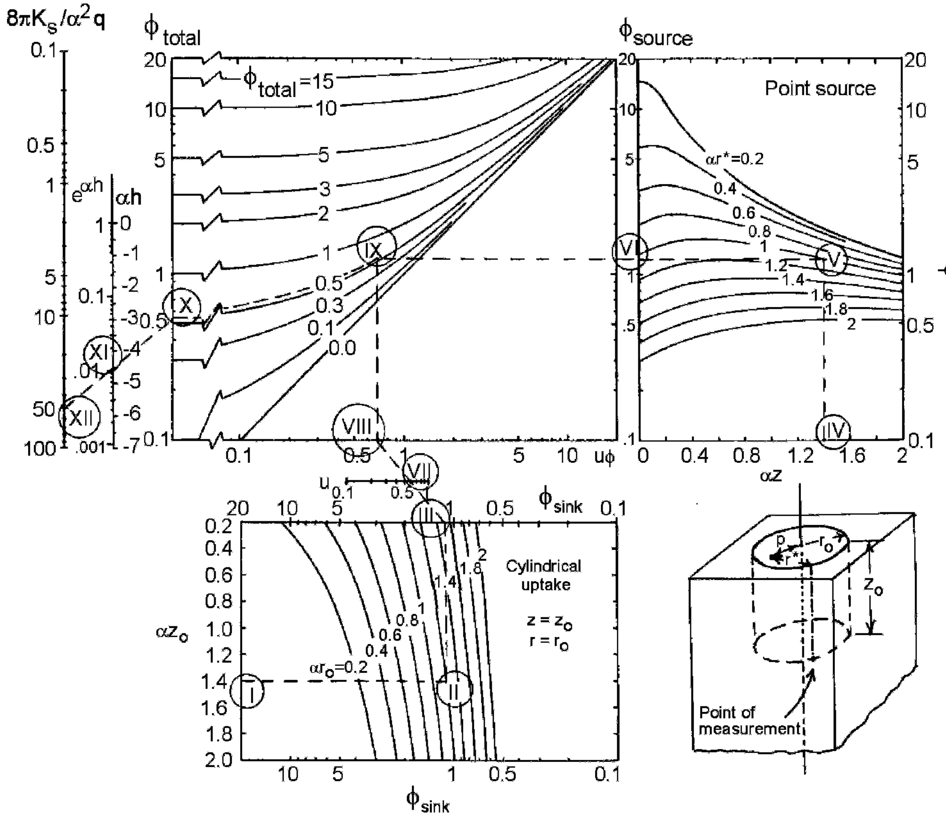


Figure 2.9. Nomograph for point emitter on the surface and uptake from a cylindrical soil volume. The total water uptake per unit time is u and the cylinder is of radius r_o and depth z_0. The $\Phi = 8\pi\phi(\alpha q)^{-1}$ is a dimensionless matric flux potential After Amoozegar-Fard et al. (1984).

Referring to the nomograph, the necessary steps are:

1. *Locate the value of αz_0 = 1.4 (Point I) on the lower part of the nomograph.*
2. *Proceed horizontally to intersect the curve αr_o = 1.19 at 1.2 (Point II).*
3. *Construct a vertical line to intersect the upper axis Φ_{sink} (Point III).*
4. *Find the value of αz_0 = 1.4 for the reference (see Point IV) on the upper right section of the nomograph for the point source.*

5. *Construct a vertical line to intersect curve $\alpha r^* = 1$, (Point V) and draw a horizontal line to intersect (Φ_{source} at Point VI).*
6. *Find the value of the fractional uptake $u = 0.6$ on the scale (Point VII), extend a straight line through points III and VII to intersect $u\phi$ at Point VIII.*
7. *Draw a vertical line from VIII and a horizontal line from VI to intersect at Point IX.*
8. *Follow the guide curves and find $\Phi_{total} = 0.55$ (Point X). [This is $\alpha q\phi/(8\pi)^{-1}$].*
9. *Calculate $8\pi K_o(\alpha^2 q)^{-1} = 51$ (Point XII).*
10. *Connect points X and XII and read the value of $\alpha h = -4.5$ at Point XI. (The h at the reference point is $-4.5/\alpha$ or -320 cm).*

2.4.3.1. Transient two and three-dimensional uptake functions

Coelho and Or (1996) proposed a parametric model for two-dimensional water uptake intensity $u(r,z)$ (expressed as volume of water extracted per soil volume per time) in the wetted volume of drip-irrigated crop. The pattern of root uptake was represented by an empirical (parametric) expression based on a bivariate Gaussian distribution for different plant-emitter configurations. The domain where uptake occurs was characterized by the position of the dripper relative to the plant row and the presence of no-uptake boundaries defined by: (i) the soil surface, and (ii) the borders of the wetted soil volume beyond which water contents are prohibitively low.

Comparisons between measured and fitted root uptake distributions for corn irrigated with surface and subsurface emitters under crop rows are shown in Fig. 2.10 for two different growth stages. The formal mathematical representation of the influence of water uptake on unsaturated flow regimes is based on introducing a sink term A into the Richards equation (see Eq. 2.16). Root water uptake models (e.g., Coelho and Or, 1996) provide detailed information on the spatial pattern and magnitude of the sink term. The parameterization of such uptake models is complicated by seasonal changes in the spatial patterns of plant root uptake, especially in drip irrigated field crops. Moreover, drip irrigation management aspects (amounts and frequency) and soil properties play critical roles in molding the shape of the root system (and uptake). The available information on changes in uptake patterns is limited, and often no distinction is made between root length density and root activity or uptake (Phene et al., 1991; Green and Clothier, 1995). The numerical model HYDRUS-2D (Simunek et al., 1999) is capable of incorporating plant root water uptake based on the root behavior outlined by Feddes et al. (1974). The problem in this application is to ascertain the spatial pattern of A.

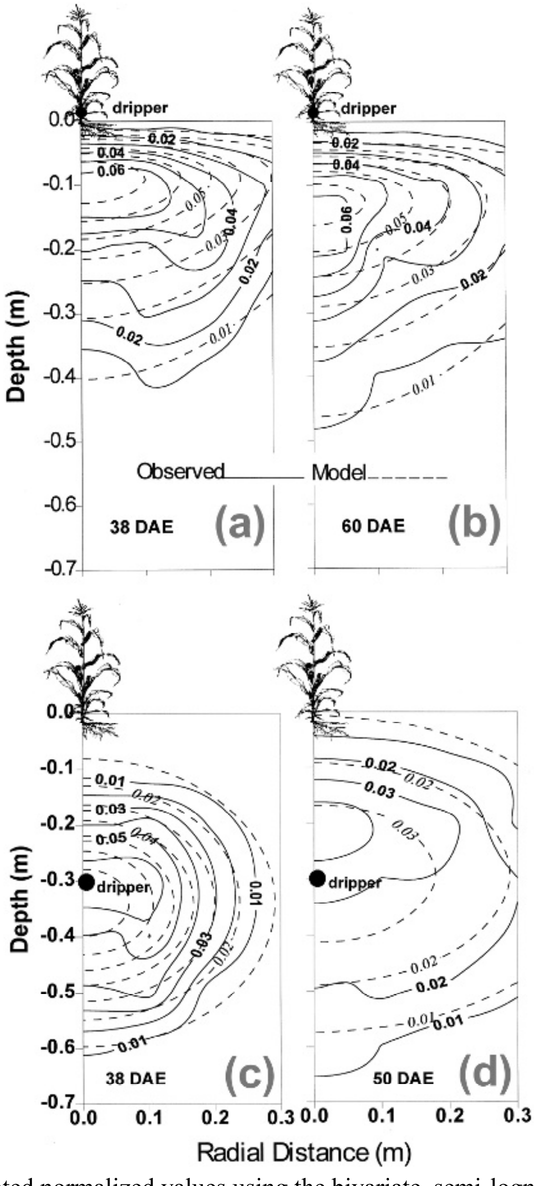


Figure 2.10. Calculated normalized values using the bivariate, semi-lognormal model and observed normalized values of uptake intensity around the surface point source in a container with 2-d irrigation interval. Results are for a surface source 38 days after emergence (DAE) (A), surface source at 60 DAE (B), subsurface source at 38 DAE (C) and subsurface source 50 DAE (D). After Coelho and Or (1996).

Or and Coelho (1996) have used their uptake model with the analytical solution of Warrick (1974) for transient flow from point sources to describe soil-water dynamics under drip irrigated corn at selected locations. The idea of modeling soil water dynamics at a few locations in the wetted root zone is appealing, in particular, for the selection of potential locations for soil water sensors (most of which are point measurements that "sense" changes in their immediate neighborhood). The localized water balance approach computes changes in water content at a point (or a small soil volume) as a superposition of two processes, water flow (in or out of that volume), and the fraction of water uptake from that volume. The primary advantage of this approximation is that the two processes (flow and uptake) are decoupled and solved separately. Results from the Or and Coelho study are illustrated in Fig. 2.11 for surface emitters for two irrigation intervals (one- and two-day). Note the large difference between the localized water balance approach (data and bottom line), and the top line representing the analytical solution of Warrick (1974) for transient flow with no plant root uptake. Finally, it should be reiterated that Warrick et al. (1979) have considered the influence of hypothetical root uptake (which varies with depth only) on steady state flow from point and line sources.

2.4.4. Influence of Soil Spatial Variability on Soil Water Distribution

Large variations in soil properties (even for uniform emitter discharge such as obtainable with pressure-compensating emitters) affect the ability to reliably monitor soil water status using sensors buried in the soil. Apart from the selection of a proper location relative to the dripper and the crop row for sensor placement, large variations in water content and matric potential may exceed the range of operation for certain sensors (e.g., tensiometers). Several studies were conducted to understand the extent and patterns of spatial and temporal variations in water content and matric potential within drip irrigated fields (Hendrickx and Wierenga, 1990; Or, 1995, 1996). Unlike soil water monitoring with most other irrigation methods, nonuniform water distribution from an emitter requires careful consideration of sampling distance relative to the emitter. Two studies aimed at relating spatial variations in soil hydraulic properties (K_s and α) to soil water content and matric potential were conducted by Or (1995; 1996). Steady state analytical solutions for water flow from point sources were used as the basis for analysis along with statistical representation of variations in soil hydraulic properties (in terms of their means, variances and spatial covariances).

An example from Or's (1995) analysis relates known mean values of $K_s = \langle K_s \rangle$ and $\alpha = \langle \alpha \rangle$ and their variances (as measures of soil properties and their variability), to the mean and variance of the resulting matric potential near the emitter. The expressions are derived for known emitter discharge (q), steady state flow conditions, and for relatively mild variations in soil properties. The variance of the matric potential (h) around a subsurface emitter is given as a weighted sum of the variances of the two soil properties (ignoring correlation between K_s and α) as:

$$\sigma_h^2(p) = A_\alpha^2(p)\sigma_\alpha^2 + A_Y^2\sigma_Y^2 \tag{2.31}$$

where $Y = \ln(K_s)$ and $p^2 = r^2 + z^2$. The weight functions are $A_Y = 1/\alpha$, and $A_\alpha(p)$ given by

$$A_\alpha(p) = \frac{2 + \langle \alpha \rangle [z - p - 2 \langle h(p) \rangle]}{2 \langle \alpha \rangle^2} \tag{2.32}$$

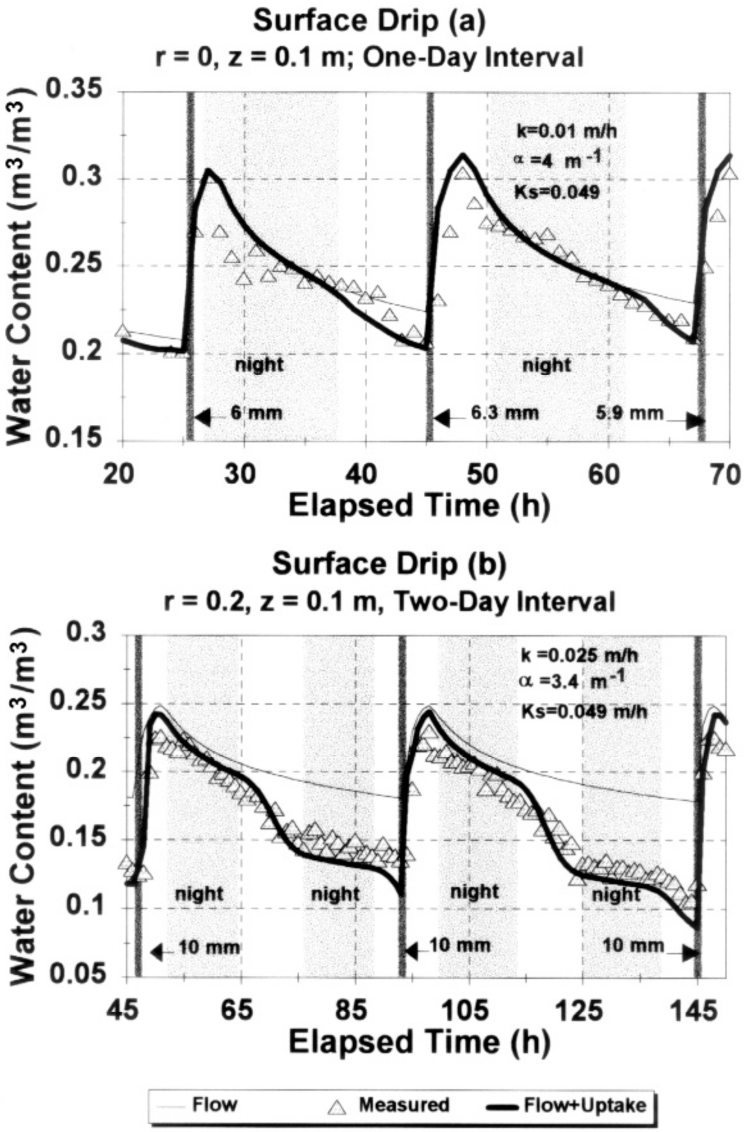


Figure 2.11. Measured (symbols) and calculated (lines) soil water contents during two irrigation cycles for (a) $r = 0.0$ m, $z = 0.1$ m for one-day irrigation interval; and (b) $r = 0.2$ m, $z = 0.1$ m for a two-day interval and a surface dripper on crop row with a flowrate of 1.6 l h^{-1}. Calculations considering plant water uptake correction to the Warrick (1974) transient flow model (thin line) are denoted by a thick line. After Coelho and Or (1997).

In this case, the mean h is denoted by $<h(p)>$ and the mean value of α by $<\alpha>$. For a subsurface emitter the mean is (see Eqs. 2.22 and 2.24)

$$< h(p) > = \frac{1}{<\alpha>} \ln\left[\frac{<\alpha> q \exp\left[0.5 <\alpha> (z-p)\right]}{4\pi <K_s> p}\right] \tag{2.33}$$

These expressions (Eqs. 2.31 to 2.33) enable calculation of the mean and variance of h around a subsurface emitter as a function of: position relative to the emitter, emitter discharge, and soil variability. Similar expressions were developed for surface emitters and for variations in soil water content. However, the numerous simplifying assumptions involved in these derivations, limit the use of such expressions to screening tools only. Limited field tests, such as depicted in Fig. 2.12 (Or, 1996), show that these expressions were capable of capturing the correct trends. However, the exact values may be quite different when emitter discharge variability and plant root uptake are added to the picture.

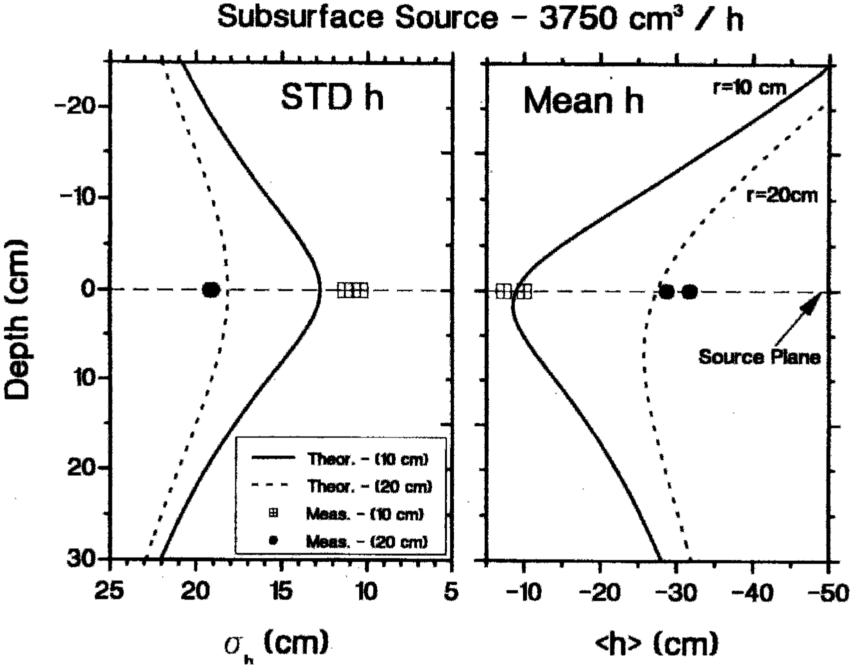


Figure 2.12. Comparisons between model predictions (lines) and measurements in Millville silt loam soil (symbols) of steady state mean value of soil matric potential (right) and the standard deviation of the matric potential (left) for subsurface emitters with constant flowrate of 3.75 L/ h buried at 26 cm below the soil surface. After Or (1996).

ACKNOWLEDGMENTS

This chapter is supported in part by Western Regional Project W-188. We acknowledge helpful comments by the editors and colleagues.

LIST OF TERMS AND SYMBOLS

A	source coefficient, s^{-1}
A_a	coefficient describing variance (also A_Y)
C	specific water capacity, m^{-1}
D	soil water diffusivity, m^2/s
$E_1(u)$	exponential integral of order 1
EC	electrical conductivity, dS/m
g	gravitational acceleration constant, cm/s^2
h	pressure head, cm
H	hydraulic head, m
h_m	matric potential, m
$h_{soil\ air}$	pressure head of soil air, m
$\vec{J}_w$	Darcian velocity for water (also J_x, J_y, J_z, J_l), m/s
k	intrinsic permeability, m^2
K	hydraulic conductivity (also K_s, K_x), m/s
K_o	modified Bessel function of order zero
L	spacing, cm
m	fitting constant for water retention/hydraulic conductivity functions F
m_{BC}	fitting constant for water retention/hydraulic conductivity functions
n	fitting constant for water retention/hydraulic conductivity functions
p	pressure, Pa [also spherical radius $(r^2 + z^2)^{0.5}$, m]
p_c	capillary pressure, Pa
q	flowrate, m^3/s
q_L	flowrate, m^2/s
r	radial axis, m
r_f	radius of wetting front, cm
r_o	radius of surface wetted area, cm
r^*	water uptake, m/s, (Ex. 2.3) and fractional water uptake (dimensionless) (Ex. 2.4)
R	dimensionless radial coordinate

RMSE root mean square error

S_e effective saturation

t time, s

TDR time domain reflectometry

u water uptake intensity, m/s [also fractional water uptake in Example 2.4]

X dimensionless horizontal coordinate

Y natural log of K_s

z elevation or depth, m

Z dimensionless depth

α constant for algebraic water retention/hydraulic conductivity, m^{-1} (Gardner)

α_{BC} constant for algebraic water retention/hydraulic conductivity, m^{-1} (Brooks Corey)

α_{VG} constant for algebraic water retention/hydraulic conductivity, m^{-1} (van Genuchten)

ϕ matric flux potential **(ϕ_{2B}, ϕ_{3B})**, m^2/s

ϕ_{3S} surface matrix flux potential, m^2/s

ϕ_T total potential, m

$\phi_{T,v}$ total potential expressed as energy per volume, Pa

γ Euler's constant = 0.577216

σ standard deviation (also σ_h, σ_{α}, σ_{γ})

η viscosity , kg/m-s

π osmotic head, m^{-1}

θ volumetric water content (also θ_a, θ_{dry}, θ_{wet}, θ^w, θ^d)

θ_m water content by mass

θ_r residual water content

θ_s saturated water content

ρ dimensionless radius

ρ_w water density, kg/m^3

ρ_b bulk density, kg/m^3

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

3. IRRIGATION SCHEDULING

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USDA-ARS, Bushland, Texas, USA
"Good is the enemy of great." Jim Collins

MOSHE MERON
MIGAL Galilee Technological Center, Kiryat Shmona, ISRAEL
"The art of irrigation is manipulation of soil water content to achieve desired plant responses."

3.1. INTRODUCTION

Irrigation scheduling generally determines the time of the next event and the amount of water to apply. For microirrigation this is the decision of when to start an irrigation cycle and how long to irrigate the zone or set. Scheduling microirrigation is inherently different from other irrigation methods because the application amount per irrigation is small and the applications are typically more frequent. Martin et al. (1990), Heermann et al. (1990), and Hill (1991) provide a thorough discussion of irrigation scheduling principles. This chapter covers principles and application techniques applicable to microirrigation systems.

Microirrigation scheduling integrates elements of the system hydraulic design and maintenance together with various aspects of the soil and the crop characteristics with the atmospheric evaporative demand. It involves providing managers with the irrigation needs of the crop that must be organized together with the cultural aspects of growing and harvesting the crop. Microirrigation scheduling is often integrated into the system controls through automation (see Chapter 7). Irrigation scheduling involves long-term decisions (strategic) and short-term decisions (tactical) that must consider the producers' risks and management goals in harmony with the agronomic or horticultural requirements for the crops being grown across the irrigation block, field, farm, or even across a broader scheme (i.e., irrigation district or hydrologic basin). Because microirrigation has a relatively high investment cost, it is more often used on higher valued crops and with water supplies designed to meet the peak crop water use rates.

Microirrigation scheduling is generally controlled by (1) measuring or estimating crop water needs, (2) measuring a soil water status, or (3) measuring a plant water status property. The latter two conditions are frequently used to determine irrigation needs and are easily integrated into an automated control system (Phene et al., 1990). The former, traditionally, has been used through an evapotranspiration-water balance model and is adaptable to both indicating the need as well as the amount of water that should be applied (Jensen et al., 1990; Allen et al., 1998). Other factors influencing the scheduling of microirrigation systems may include soil salinity, impact of water deficits on crop quality, or the impact of rain on salt leaching into the root zone.

3.1.1. System Capacity

System capacity, S_c, is a critical design and operational parameter. System capacity is typically expressed as the ratio of the system flowrate (Q in m^3 s^{-1}) to the land area (A in m^2), resulting in units of m s^{-1}. It is typically more convenient to express the ratio in units of mm d^{-1} as follows:

$$S_c\ (m\,s^{-1}) = \frac{Q\ (m^3\ s^{-1})}{A\ (m^2)}\ or\ S_c\ (mm\ d^{-1}) = \frac{86.4\ x\ 10^6\ \ Q\ (m^3\ s^{-1})}{A\ (m^2)} \qquad (3.1)$$

When expressed by the second equation of Eq. 3.1, S_c is in equivalent units to daily evapotranspiration rates, and commonly used units for the system application rate. S_c becomes a direct index useful in determining the irrigation scheduling flexibility to meet the crop needs, time available for system maintenance, time available for cultural needs, and time available to recover from equipment failures. S_c must exceed the peak evapotranspiration rate less any dependable short-term effective precipitation to provide the necessary ability to meet the crop water use rate with minimal soil water depletion and to meet other non-operational periods required for maintenance and routine repairs or equipment replacement. S_c should not exceed a system application rate that is greater than the ability of the soil to infiltrate adequately the applied water.

3.1.2. System Uniformity Effects on Scheduling

Irrigation systems cannot apply water uniformly across an irrigation set or field due to inherent variabilities in soil hydraulic properties (see Chapter 2), soil topography, and system hydraulics (see Chapter 5 and Chapter 10). For microirrigation, emitter flow variations from clogging may need to be considered as well (Nakayama and Bucks, 1981). In addition, each of these factors will vary temporally and spatially and may not always be statistically independent of each other.

Many estimation methods have been used to characterize the application variations for microirrigation systems (Tab. 3.1). Initially, microirrigation system flow variations were characterized using technology adopted from sprinkler irrigation. Two such parameters are the Christiansen uniformity coefficient, *Cu* (Christiansen, 1942), and the distribution uniformity, *Du,* of the low quarter of the field taken from surface irrigation that was used by the USDA-NRCS (formerly the USDA-Soil Conservation Service) since the late 1940s (Kruse, 1978; and Merriam and Keller, 1978). For microirrigation, the emitter flowrate was often used in the *Cu* and *Du* computations rather than the application amount or the amount infiltrated because it was easier to measure. Table 1 indicates the similarity of many of these measures.

Hart (1961) demonstrated that the Christiansen *Cu* for a normal distribution of application amounts was a function of the coefficient of variation (C_v, $\sigma / \bar{x}$; where σ is the standard deviation and $\bar{x}$ is the mean). The Hart *Cu* is often called the *HSPA* (Hawaiian Sugar Planter's Association) *Cu*. Because microirrigation systems often have more than one emission device per plant, Keller and Karmeli (1975) derived the design emission uniformity *(Eu)* based on the low quarter flow distribution uniformity (*Du*), the emitter manufacturing flow variability, the number of emitters per plant, and the ratio of minimum to mean emitter flow. Solomon and Keller (1978) illustrated the impact of increased Cv_m (manufacturing coefficient of variability) on decreased uniformity. Nakayama et al. (1979) derived a design coefficient of uniformity (Cu_d) based on the average emitter flowrate for microirrigation. Both Eu and Cu_d indicate an improvement when the number of emission devices (with the same manufacturing Cv_m) is increased per plant. Of course, the investment cost will increase with a greater number of emitters per plant. Microirrigation uniformity increases, nearly proportionally, with lower Cv_m values indicating the importance of precision in the manufacturing. Bucks et al. (1982) classified Cv_m values and presented recommended ranges for Eu and Cu_d for arid areas. Wu and Gitlin (1977) used the emitter flow variation, q_{var}, defined as 1 - (q_n / q_m), where q_n is the minimum emitter flowrate and q_m is the maximum emitter flowrate. Warrick (1983) evaluated Cu and Du for six assumed statistical distributions and found no effect of the statistical distribution for small values of $Cv < 0.25$, as would likely occur for many microirrigation systems. He demonstrated that approximate values of Cu and Du each depended mainly on the Cv of the distribution and that a unique relationship existed between Du and Cu (see Tab. 3.1).

Table 3.1 Examples characterizing irrigation application variations

Term	Reference	Equation
Cu	Christiansen (1942)	$Cu = [1 - (\Sigma\| x - \bar{x} \|) / \Sigma x]$
HSPA Cu	Hart (1961)	HSPA $Cu = [1 - (2/\pi)^{1/2} (C_v)]$
Eu	Keller & Karmeli (1975)	$Eu = [1 - 1.27 (Cv_m) n^{-1/2}] (q_n / \bar{q})$
CU_d	Nakayama et al. (1979)	$Cu_d = [1 - 0.798 (Cv_m) n^{-1/2}]$
Du	Kruse (1978); Merriam and Keller (1978)	$Du = x_{lq} / \bar{x}$
q_{var}	Wu and Gitlin (1977)	$q_{var} = [1 - (q_n / q_m)$
DU^*	Warrick (1983)	$Du^* = 1 - 1.3\ Cv$ or $Du^* = -0.6 + 1.6\ Cu^*$ [Note: Du^* is for $Cv < 0.25$]

x - individual emitter application rate
$\bar{x}$ - mean of "N" samples for emitter application rates
Cv - coefficient of variation (σ / x; where σ is the sample standard deviation in flow)
Cv_m - manufacturer's coefficient of variation
n - number of emitter per plant
q_n - minimum emitter application rate (typically at the minimum pressure)
$\bar{q}$ - mean emitter application rate
x_{lq} - mean emitter application rate for the lowest 25% (low quarter) of the emitters
q_m - maximum emitter application rate
NOTE: All terms expressed as decimal fractions and $(2/\pi)^{0.5} = 0.798$.

Bralts et al. (1981) illustrated that the hydraulic flow variability was sufficiently independent of the flow variation from manufacturing for single-chamber microirrigation tubing that the total coefficient of flow variability (C_{vt}) could be expressed as

$$Cv_t = \sqrt{\left(Cv_h^{\ 2} + Cv_m^{\ 2}\right)} \tag{3.2}$$

where Cv_h is the coefficient of variation in emitter flow due to hydraulic factors. However, when the Cv_h exceeded 15%, Clemmens (1987) and Wu et al. (1985) found that Eq. 3.2 under predicted the total flow variation, which was attributed to departure from the assumed normal distribution. Clemmens and Solomon (1997) developed a generalized procedure to estimate the distribution uniformity for any fractional area of the field together with methods for defining the confidence interval of the result.

An example of microirrigation application distributions for a mean amount of 10 mm with *Cu* values of 0.76, 0.84, and 0.92 for an assumed normal distribution with the resulting *Cv* values of 0.3, 0.2, and 0.1, respectively, is presented in Fig. 3.1. This illustration highlights the within irrigation set or field variations in applications that could affect measurements of soil or plant water status affecting irrigation scheduling and water management. The spread in amounts is particularly noticeable as the *Cu* declined from 0.92 to 0.84 or lower. Bucks et al. (1982) reported measured *Cv* values for eight emitters that ranged from 0.06 to 0.15 from initial laboratory measurements, and the values increased substantially in some cases, just four years later by up to 400% based on field measurements. Their results varied by emitter design and depended on water treatment techniques for the Colorado River water used in their study. Nakayama and Bucks (1981) observed significantly reduced uniformity when only 1 to 5% of the emitters were clogged even with 2 to 8 emitters per plant. These in-field performances would further skew the applications and greatly reduce irrigation uniformity and efficiency.

Although emitter flow uniformity is important in microirrigation, the goal remains to apply the necessary water to each plant. The soil (see Chapter 2) and the plant roots dictate the success in meeting this goal in combination with the irrigation system. The soil water properties, the crop rooting characteristics, and the irrigation system uniformity all affect irrigation scheduling decisions with microirrigation to a larger extent than with other irrigation methods. This is because not all the soil surface is wetted and the soil wetting and crop root water extraction patterns are three dimensional in most cases.

3.1.3. System Maintenance Effects on Scheduling

The heart of microirrigation success lies in system maintenance (see Chapter 11) and management. System maintenance begins with the design (see Chapter 5) and installation and continues with routine system performance and evaluation (Chapter 10). These are integral procedures of system management, and therefore, directly related to irrigation scheduling. As with irrigation scheduling, system maintenance has long-term (strategic) components that include off-season repairs and checks, and short-term (tactical) components such as recording water flowmeters, pressure gages, fertilizer injections, water treatment chemical injections, and routine filter and line flushing. Often these tactical maintenance operations can be automated by computerized controllers.

Water flowmeters and pressure gauges are critical components of the system and must be included in the system installation. These measurement devices provide critical feedback data needed for irrigation scheduling. Similarly, successful irrigation scheduling must include the time requirements to maintain and calibrate water treatment equipment, fertilizer or other agrochemical injection equipment, the time needed to clean or backflush filters, and the time to flush mainlines, submains, and lateral lines. Time will be needed for tactical emergency equipment repairs and replacements. Preventative maintenance will likely minimize this, but equipment failures are impossible to forecast even in the best situation. Most operational maintenance and management (filter backflushing, flowmeter and pressure gauge observations) can be performed while the system is operating. However, some operations (e.g., screen washing, line flushing) will require additional time when the system is not operating. The water supply quality (biological, chemical, and physical) will greatly impact filtration design and operational needs. Management plans must consider the time estimates for these operations in addition to the normal time requirements for irrigation as governed by system capacity.

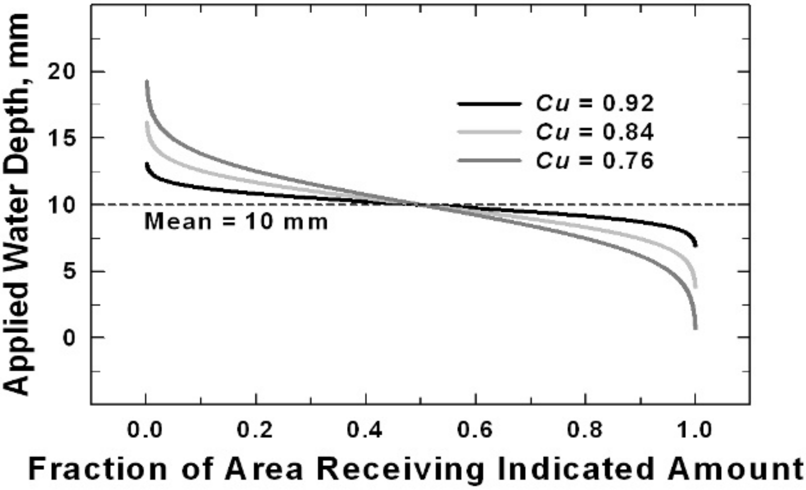

Figure 3.1. Diagram illustrating variability of applied water for a mean application of 10 mm for *Cu* values varying from 0.92 to 0.76.

3.1.4. Scheduling Constraints

Many operational, agronomic, or horticultural cultural practices require time that cannot be used for irrigating, and thus, increase the required irrigation design capacity. Fortunately with microirrigation, many tasks can be performed simultaneously with the irrigation (e.g., applying fertilizer or spraying the crop or orchard). The principal constraints to irrigation scheduling of microirrigation systems are the available water flowrate, and in some cases the available water volume or amount, and the water delivery schedule.

The simplest case is a sole-source supply such as a well or a dedicated reservoir. With a well, the groundwater formation basically determines the well yield (flowrate) and its draw down (dynamic pumping lift). With a reservoir, its location determines the pumping lift, and its volume and water supply determine the sustained yield (flowrate). In most cases, some regulations may apply to these water sources, and permits or laws may restrict the pumping rate or pumping volume.

More commonly, irrigation supplies may be shared water resources. Often in these cases, the water may only be available on a set or prior request basis. Depending on the exact circumstances, the grower may need to provide a surface reservoir to supply a demand-based microirrigation system. The energy supply may become a constraint. Unless the supply reservoir or canal is sufficiently higher than the irrigated field, some type of water pumping system is required with microirrigation systems. For many systems, centrifugal pumps are used that generally require priming. If priming is required, automation is more difficult. In addition, energy supplies may be controlled or regulated to curtail peak summer demand loads on electrical generating plants requiring pumps to be idled or turned off during certain hours.

3.2. IRRIGATION SCHEDULING TECHNIQUES

Microirrigation systems are routinely scheduled for irrigations using either (a) a demand system based on knowing or predicting the crop water needs, (b) a soil-water control feedback or feed-forward system that measures soil water contents in the root zone, or (c) a plant-water-status control system based on measuring the crop water status. Obviously, these different methods of irrigation scheduling can be used simultaneously, but often labor or equipment may limit that approach. The grower should view each system as providing information rather than an exact answer. This information can then be weighted along with their experience to determine the irrigation needs of the crop. The latter method has long been used based on crop appearance and the experience of the grower. The soil water system could be as simple as manually coring or spading into the root zone to observe the soil wetness by feel. The demand-based system can be based on relatively simple criteria such as historical records or evaporation pans to more complex and extensive computer models using elaborate weather station equipment. Regardless of the method used, several considerations must be evaluated:

- ease of integration into the farm or horticultural management
- labor, equipment, technology, and capital required to implement the system(s)
- accuracy and reliability of the system(s)
- ability to forecast irrigation needs
- ability to identify problem areas in an irrigation set or a field
- ability to adjust and handle seasonal temporal and spatial changes
- ability to monitor the irrigation system performance

More than one of these scheduling methods may be required to handle these considerations.

3.2.1 Water Balance (Evapotranspiration Base)

The water balance approach is based on ascertaining the water inputs and water outflows from the field. It is best described as a checkbook approach with irrigations and rainfall as the deposits, and evapotranspiration (*ET*, crop water use) as the main withdrawal. Percolation beneath the crop root zone could be considered as a service fee or a necessary expense to control salinity. Based on this analogy, the soil water becomes the bank (or checkbook) balance, where the grower tries to maintain a minimum balance to avoid endangering the crop yield or quality without exceeding a maximum amount that might not be insured against loss from runoff or drainage beneath the root zone. When the available soil water declines too low or reaches the minimum account balance, the crop will suffer a stress that will reduce *ET* and perhaps yield.

The one-dimensional water balance equation is

$$\theta z_{i+1} = \theta z_i + (P_i - Q_{roi}) + I_{ni} - ET_i - Dz_i \tag{3.3}$$

where θz_i is the soil water content on day *i* integrated over the root zone depth *z*, *P* is rainfall, Q_{ro} is runoff, I_n is net applied irrigation, *ET* is crop water use from the root zone, and *Dz* is deep percolation beneath the root zone at depth z. *Dz* is generally negative as indicated in Eq. 3.3, but it could be positive if water moved upward from a shallow water table. Each term in Eq. 3.3 is expressed in water depth units (mm), and *P*, Q_{ro}, and I_n are at the soil surface. *ET* is considered as the sum of evaporation (*E*) from plant or soil surfaces and transpiration (*T*) is from the plant leaves. The term, *P*- Q_{ro}, is the effective precipitation or the amount of the precipitation that would be expected to infiltrate into the root zone. Similarly, I_n is usually taken as the amount of "net" irrigation, which is the gross irrigation amount multiplied by the irrigation application efficiency. Each term will vary spatially and temporally (Gardner, 1960), so that in practice the mean values must be assumed due to the difficulty in determining the spatial distribution of the terms. The one-dimensional water balance expressed by Eq. 3.3, although widely used in microirrigation, requires careful integration and measurement of the terms to approximate the three-dimensional patterns expected in microirrigation. Runoff (Q_{ro}) is particularly difficult to estimate. Fortunately, losses to Q_{ro} from microirrigation applications are usually minimal; however, Q_{ro} losses from rainfall can be significant in some cases even with a partially dry soil surface that is characteristic of microirrigation applications. Williams (1991) describes runoff models used in EPIC (erosion productivity impact calculator) (Williams et al., 1983) that could estimate rainfall runoff. The precipitation, *P*, that strikes the plant canopy will be intercepted by the leaves and stems and then distributed in relation to the canopy architecture (e.g., trees at the canopy edge, corn at the stem). This makes estimating *P* in orchards and vineyards that reaches the ground (throughfall) difficult to estimate accurately over the plant spatial ground area. *E* and *T* losses will be discussed in more detail in the succeeding sections. Losses to *Dz* are also difficult to estimate, but they are likely to approach one-dimensional flow patterns near the root-zone bottom (Hillel, 1998). Deep percolation, *Dz*, below a 1.4-m soil depth was greater for driplines spaced 2.3 and 3.1 m than for a 1.5-m spacing for subsurface drip irrigated corn on a silt loam soil in Kansas (Darusman et al., 1997a). In a related study at the same location, Darusman et al. (1997b) determined that *Dz* was significant for subsurface drip-irrigated corn when in-season irrigations exceeded about 400 mm. For in-season irrigations that were less than 300 mm, they determined that about 20 mm of water moved into the root zone from upward capillary flow. Richards et al. (1956) showed that the decrease in soil water content occurred inversely proportional to time as

$$Dz = -\frac{d\theta}{dt} = -a\, t^{-b} \tag{3.4}$$

where θ is the soil water content in mm and *a* and *b* are empirical constants related to the boundary conditions and the soil hydraulic conductivity, $K(\theta)$. Assuming an exponential function between $K(\theta)$ and θ, Hillel (1998) demonstrated that *Dz* was equal to $K(\theta)$ for gravity drainage alone at θ_z at the bottom of the root zone.

Shallow groundwater tables can provide significant water to a crop depending on the water table depth, the groundwater salinity, and the crop rooting characteristics. Wallender et al. (1979) reported that cotton extracted up to 60% of its ET from a saline (6 dS m^{-1}) perched water table, and Ayars and Schoneman (1986) that cotton extracted up to 37% of its *ET* from a more saline water table (10 dS m^{-1}), but irrigation management greatly affected the groundwater uptake. Ayars and Hutmacher (1994) demonstrated a practical approach for managing irrigations over a shallow (1.2 to 2 m), moderately saline (5 dS m^{-1}) perched water table that permitted 25% of the *ET* from groundwater without any adverse effects on crop growth or yield. Cotton can use water from a water table as deep as 2.7 m even under a favorable irrigation regime (Namken et al.,1969). Kruse et al. (1993) found that alfalfa used saline or nonsaline water from shallow water tables in its first year, but that a salinity buildup reduced yields with saline water tables in subsequent years. Corn and wheat were less affected by the salinity, but the crops used less water from a 1.0-m water table. Upward water flowrates into the crop root zone from water tables 2 to 4 m deep were predicted to range from 2 to 6 mm d^{-1} by Doorenbos and Pruitt (1977). Soppe and Ayars (2003) measured groundwater use exceeding 3 mm d^{-1} from a shallow, saline (14 dS m^{-1}) water table by safflower with groundwater contributing up to 40% of the daily water use.

3.2.1.1. Climatic factors affecting crop water use

Weather parameters directly influence crop water use (Allen et al., 1998). The principal factors are solar irradiance (R_s), air temperature (T_a), relative humidity (*RH*) or air dew point temperature (T_d), barometric pressure (P_b), and wind speed (*U*). Solar irradiance is reduced to net radiation (*Rn*), which is the main solar factor affecting crop water use, as follows:

$$R_n = (1 - \alpha) R_s - R_{nl} \tag{3.5}$$

where α is the albedo or short-wave reflection (fraction) and R_{nl} is net long-wave radiation. The albedo of most crops will be about 0.20 to 0.23, whereas the soil albedo will be less, about 0.1 to 0.15 depending on the soil and its water content. The net long-wave radiation term depends on several surface and atmospheric parameters. Basically, long-wave radiation is proportional to the surface temperature to the fourth power times the surface emissivity and a proportionality constant known as the Stefan-Boltzman factor. A perfect emitting surface has an emissivity of 1.0. The emissivity of most soils and crops is near 0.98, while the emissivity of the sky is much lower and will depend on the atmospheric water content. Because the sky emissivity and the sky temperature are not routinely measured, *Rnl* is estimated using routine air temperature data, relative humidity data, and estimates of cloud cover (Allen et al., 1998). The weather parameters at or over the crop affect its water use. However, it is largely impractical to measure weather parameters over the crop, except for research, so weather parameters are typically measured at a weather station situated to represent the crop environment. Although many organizations have attempted to standardize the weather station siting and the instrumentation, in most cases this is difficult to achieve. Allen et al. (1998) discusses the impact of the station siting, instrument maintenance, and other factors on the quality of weather data for estimating crop water use.

Although many equations can estimate crop water use based on climatic data, the Penman (1948) combination equation has become widely used. It is expressed as

$$ET_o = \frac{[\Delta\ (R_n\text{-}G)] + [(\gamma\ \ W_f\ )\ (e^o{}_s\ \text{-}\ e_a\ )]}{[\lambda\ \ \rho_w(\Delta\text{+}\gamma)]} \tag{3.6}$$

where ET_o is the ET of grass that is well-watered and fully covering the soil in mm d^{-1}, Δ is the slope of the saturated vapor pressure curve at the mean air temperature in kPa °C^{-1}, G is the heat flux into the soil in MJ m^{-2} d^{-1}, γ is the psychrometric constant in kPa °C^{-1}, W_f is an empirical wind function in MJ m^{-2} d^{-1} kPa^{-1} [W_f = 6.43 + (3.453 U_2), where U_2 is the mean daily wind speed in m s^{-1} at 2.0 m height over grass], $e^o{}_s$ is the saturated vapor pressure at the mean daily air temperature in kPa, e_a is the mean ambient vapor pressure in kPa, λ is the latent heat of vaporization in MJ kg^{-1}, and ρ_w is water density (1.0 Mg m^{-3}). For irrigated grass with a full cover, daily G is approximately zero MJ m^{-2} d^{-1}. The psychrometric constant, γ, is proportional to barometric pressure, which is inversely related to elevation. The Penman equation was not widely used initially because it was rather complex for its time (before calculators/computers), and it was difficult to compute all the parameters and find locations with the necessary meteorological data. Despite these drawbacks, Van Bavel (1956) recognized its potential and its conservative nature as well as its usefulness for determining water use from large areas with non-limiting soil water and for estimating the irrigation need. Monteith (1965) characterized the empirical wind function using the atmospheric aerodynamic resistance (r_a in s m^{-1}) and added a bulk surface resistance term (r_s in s m^{-1}), which resulted in the following equation:

$$ET_o = \frac{[\Delta\,(R_n - G)] + [(86.4\,\rho\ C_p)\,(e_s - e_a)\,/\,r_a]}{[\lambda\ \rho_w(\Delta + \gamma^*)]} \tag{3.7}$$

where ρ is air density in kg m^{-3}, C_p is the specific heat of moist air [1.013 kJ kg^{-1} °C^{-1}], e_s is the mean saturated vapor pressure at the daily maximum and minimum air temperature in kPa, and an adjusted psychrometric constant, $\gamma^* = \gamma\ (1 + r_s\ /\ r_a)$ in kPa °C^{-1}. Table 3.2 gives the recommended equations for estimating the parameters along with the appropriate constants for grass from Allen et al. (1998) and Allen et al. (1994). Jensen et al. (1990) recommended two standardized reference surfaces, 0.12-m for tall grass and 0.5-m tall for alfalfa. They recommended r_s be set to 45 s m^{-1} for alfalfa and to 70 s m^{-1} for grass. The resulting functions for defining r_a (in s m^{-1}) using air temperature and humidity data from a 2.0-m height were 110 / U_2 and 208 / U_2, respectively, for alfalfa and grass. Allen et al. (1998) used only a grass reference equation and simplified the parameters in Eq. 3.7 to the following:

$$ET_o = \frac{[0.408\ (R_n\text{-}G)] + [\gamma\ \dfrac{900}{(T_{ma} + 273)}\ U_2\ (e_s - e_a)]}{\rho_w[\Delta + \gamma\ \ (1 + 0.34\ U_2)]} \tag{3.8}$$

where T_{ma} is mean daily air temperature at 2 m in °C. For a day (24 h), G in Eq. 3.8 can be assumed to be zero MJ m^{-2} d^{-1}. Equation 3.8 (also known as the FAO Penman-Monteith Eq.) is the recommended method for calculating world-wide standard grass reference ET (FAO-56, Food and Agriculture Organization of the United Nations), replacing FAO-24 (Doorenbos and Pruitt, 1977) that was also based on a grass reference, but that required empirical correction factors for humidity, wind speed, and day to night wind speed variations (Frevert et al., 1983).

Table 3.2. Equations for estimating parameters in the Penman and Penman-Monteith equations for grass reference *ET* (*ETo*) from Allen et al. (1998); (1994).

Term	Unit	Equation
T_{ma}	^oC	$(T_{min} + T_{max})/2$
λ	MJ kg^{-1}	$2.501 - (2.361 \times 10^{-3})\ T$ or assume $\lambda = 2.45$
P_b	kPa	$101.3\ [(293 - 0.0065\ z) / 293]^{5.26}$
γ	kPa $^oC^{-1}$	$0.00163\ P_b / \lambda$
$e^o(T_{ma})$	kPa	$0.6108 \exp [(17.27\ T_{ma}) / (T_{ma} + 237.3)]$
e_s	kPa	$[e^o (T_{min}) + e^o (T_{max})]/2$
e_a	kPa	$0.6108 \exp [(17.27\ T_{dew}) / (T_{dew} + 237.3)]$
Δ	kPa $^oC^{-1}$	$4098\ \{0.6108 \exp [(17.27\ T_{ma}) / (T_{ma} + 237.3)]\} / (T_{ma} + 237.3)^2$
G	MJ m^{-2} d^{-1}	0.0 [for a day or 24 hr]
d_r	radians	$1 + 0.033 \cos[(2\ \pi\ J) / 365]$
δ	radians	$0.409 \sin[(2\ \pi\ J) / 365) - 1.39]$
ω_s	radians	$\arccos[-\tan(\nu) \tan(\delta)]$
R_a	MJ m^{-2} d^{-1}	$[(1440\ G_c\ d_r) / \pi]\ [\omega_s \sin(\nu) \sin(\delta) + \cos(\nu) \cos(\delta) \sin(\omega_s)]$
R_{so}	MJ m^{-2} d^{-1}	$(0.75 + 2 \times 10^{-5}\ z)\ R_a$
T_{minK}	K	$T_{min} + 273.16$
T_{maxK}	K	$T_{max} + 273.16$
R_{nl}	MJ m^{-2} d^{-1}	$\sigma\ [(T_{minK} + T_{maxK}) / 2]\ (0.34 - 0.14\ e_a^{1/2})[1.35 - 0.35\ (R_s / R_{so})]$
R_{ns}	MJ m^{-2} d^{-1}	$(1 - 0.23)\ R_s$
R_n	MJ m^{-2} d^{-1}	$R_{ns} - R_{nl}$
T_K	K	$T_{ma} + 273.16$
Tv_K	K	$T_K\ [1 - 0.378\ (e_d / P_b)]^{-1}$
ρ	kg m^{-3}	$3.486\ (P_b / Tv_K)$
C_p	kJ kg^{-1} $^oC^{-1}$	1.013
r_s	s m^{-1}	$r_l / (0.5\ LAI)$ or 70 for 0.12-m tall grass
LAI	–	$24\ h_c$
d	m	$(2/3)\ h_c$
Zo_M	m	$0.123\ h_c$
Zo_H	m	$0.0123\ h_c$
r_a	s m^{-1}	$\{\ln[(Z_m - d)/Zo_M] \ln [(Z_h - d)/Zo_H]\} / (k^2\ U_z)$ or $208 / U_2$ for Z_m and $Z_h = 2.0$ m for 0.12-m tall grass
γ^*	kPa $^oC^{-1}$	$\gamma\ [1 + (r_s / r_a)]$ $\gamma\ (1 + 0.34\ U_2)$

Table 3.2. Equations for estimating parameters in the Penman and Penman-Monteith equations for grass reference *ET* (*ETo*) from Allen et al. (1998); (1994). *Cont.*

T_{min}	-	minimum daily air temperature, ^oC
T_{max}	-	maximum daily air temperature, ^oC
T_{dew}	-	mean daily dew point temperature, ^oC
z	-	elevation above sea level, m
d_r	-	inverse relative distance Earth to the Sun, radians
J	-	integer day of year
δ	-	solar declination angle, radians
ω_s	-	sunset hour angle, radians
ν	-	latitude, radians
R_a	-	daily extraterrestrial radiation, MJ m^{-2} d^{-1}
G_c	-	solar constant [0.0820 MJ m^{-2} min^{-1}]
R_{so}	-	clear sky daily solar irradiance, MJ m^{-2} d^{-1}
R_s	-	daily solar irradiance, MJ m^{-2} d^{-1}
T_{minK}	-	minimum daily absolute air temperature, K
T_{maxK}	-	maximum daily absolute air temperature, K
R_{nl}	-	net outgoing long-wave radiation, MJ m^{-2} d^{-1}
σ	-	Stefan-Boltzman constant [4.903 x10^{-9} MJ m^{-2} K^{-4} d^{-1}]
R_{ns}	-	net short-wave radiation, MJ m^{-2} d^{-1}
R_n	-	net radiation, MJ m^{-2} d^{-1}
T_K	-	mean daily absolute temperature, K
Tv_K	-	virtual absolute temperature, K
r_l	-	leaf resistance, s m^{-1} [100 s m^{-1}]
LAI	-	leaf area index
h_c	-	grass height, m [0.12 m]
Z_m	-	measurement height of wind speed, m [usually2 m]
Z_h	-	measurement height of air humidity, m [usually 2 m]
k	-	von Karman constant [0.41]
U_z	-	mean daily wind speed at height Z_m, m s^{-1}
U_2	-	mean daily wind speed at 2 m, m s^{-1}

3.2.1.2. Crop factors affecting *ET*

Several crop factors were mentioned in the previous section. These include the short-wave reflection (α, albedo) and long-wave emissivity (ε) that affect net radiation and the partitioning of solar irradiance into the various energy balance terms. Two crop architectural characteristics, crop height (h_c) and leaf area index (LAI), affect crop water use in various manners. Both parameters are important in determining the soil cover by the crop that affects solar radiation penetration to the ground which in turn affects the sensible energy entering or leaving the ground as soil heat flux. Crop height is an important factor in determining the aerodynamic resistance of the canopy (r_a) to latent and sensible heat flux. Leaf area index largely determines the amount of plant foliage exposed to the direct solar irradiance and the amount of shaded plant foliage exposed to transmitted and reflected diffuse solar radiation. Usually, taller crops will have a lower r_a value and a higher water use rate for similar surface resistance (r_s) values. Typically, a

LAI value between 3 and 4 (three to four times the leaf area of one side of the leaves per unit ground area) will be sufficient to maximize transpiration and fully shade the ground.

The plant species largely determines the leaf stomatal resistance to water vapor transfer and carbon dioxide uptake. Generally, the type of photosynthetic pathway in the plant species (either C_3, C_4, or *CAM*) affects the leaf surface resistance to water vapor transport through the leaf stomata that determines the leaf resistance (r_l). The leaf resistance, fraction of shaded and sunlit leaves, and the *LAI* largely determine the canopy surface resistance (r_s). Crop development and growth processes change both of these key crop parameters (h_c, and *LAI*) that determine the water use potential of the crop (Fig. 3.2). Perennial plant species have different annual growth cycles. In most cases for trees or vines, the annual change in height may be small and limbs may even be removed through pruning. These species will have a distinct leaf and fruit bearing cycle. Non-destructive light interception or simple ground-cover measurements are often used instead of measured *LAIs* for trees and vines because the *LAI* measurements are difficult to make.

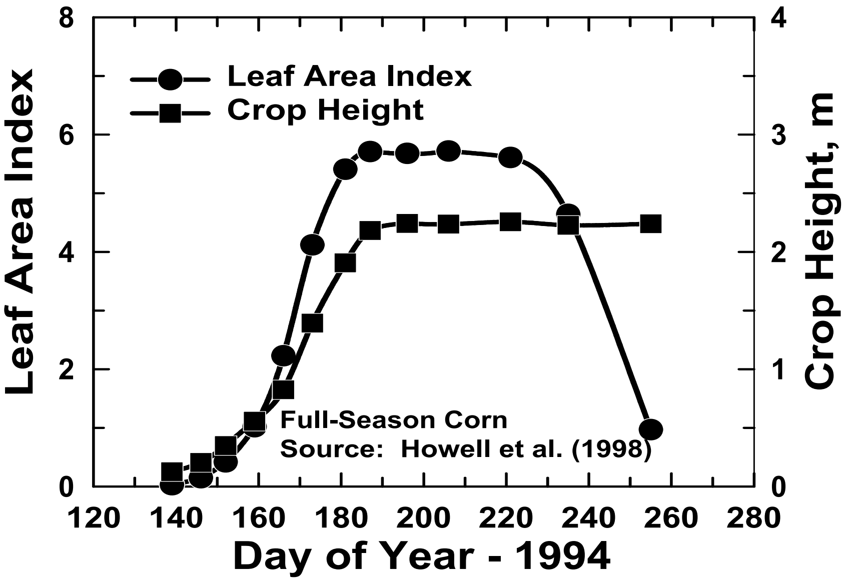

Figure 3.2. Leaf area index and crop height of irrigated corn at Bushland, Texas illustrating typical crop development rates (Howell et al., 1998).

Allen et al. (1998) provides two methods for estimating the crop effects on water use based on the computed grass reference ET_o (Eq. 3.8). These are designated as the single (K_c) and dual (K_{cb}) crop coefficient approaches based on

$$ET = K_c\ (ET_o) \tag{3.9}$$

$$ET = (K_{cb} + K_e)\ ET_o \tag{3.10}$$

where *ET* represents the crop water use for both soil and plant water evaporation (*E*) and plant transpiration (*T*); K_{cb} is the basal crop coefficient when the soil surface is visually dry (Wright, 1982), but the crop transpiration is not restricted by soil water deficits; and K_e is the coefficient representing the soil water evaporation from a wet soil surface. By examining Eqs. 3.9 and 3.10, ones sees that the single crop coefficient is simply equated to $K_{cb} + K_e$, and for a visually dry soil surface case, K_c equals K_{cb}. In principle, ET_o normalizes the evaporative demand of the atmosphere. However, because ET_o represents a short, smooth crop that is well watered, the grass water use may be different from that of a real crop or orchard / vineyard. The crop coefficients, K_c or $K_{cb} + K_e$, are designed to make the transformation in water use from the idealized standard grass represented by the characteristics embodied in Eq. 3.8 to the real crop. Any of the preceding crop characteristics, albedo, emissivity, height, surface resistance, and the degree of soil wetness and soil salinity of the root zone (to be discussed in the next section) can affect K_c. The single K_c approach assumes a more generalized approach in determining the crop water use that cannot account for some of the soil factors embodied in the dual K_{cb} approach, especially different soil water evaporation rates that may be important with microirrigation. Equations 3.9 and 3.10 predict crop water use under standard conditions. It is thought to be an upper envelope (Allen et al., 1998) representing conditions without limits on crop growth or water use from a soil water deficit, with normal crop density, with healthy plants without disease or insect damage, without weeds, and without soil salinity effects on crop growth or water use.

The K_c and K_{cb} values are temporally dependent on the crop growth characteristics (h_c and *LAI*) that affect the *real* crop's r_a and r_s values. The idealized K_c and K_{cb} crop curves for wine grape are illustrated for standard crop development rates in Fig. 3.3.

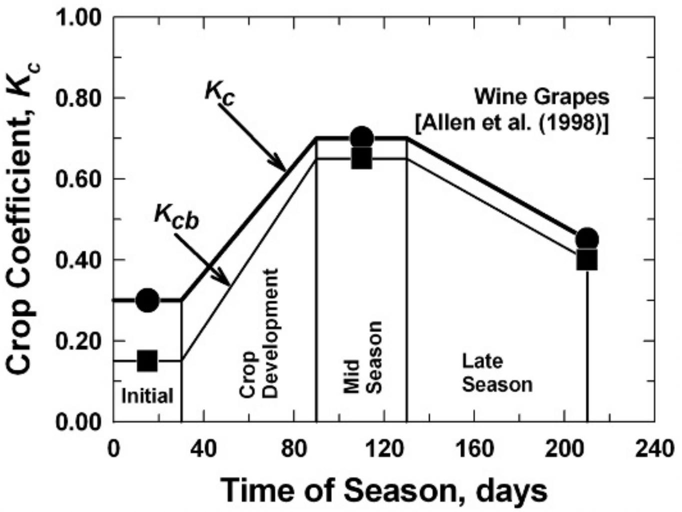

Figure 3.3. Example of seasonal crop coefficient curve for wine grape representing the major crop growth periods – initial development, crop development (developing ground cover), mid season (reproduction, fruiting, etc.), and late season (maturation and harvest). The heavy line with the circle points is the K_c curve, and the lighter line with the square points is the K_{cb} curve. Adapted from Allen et al. (1998).

Allen et al. (1998) summarized and presented a vast list of K_c and K_{cb} values based on defining the annual crop development cycle into its initial phase (planting, emergence, early growth), crop developmental phase (rapid vegetative growth, early reproductive development), mid-season phase (full-canopy development, reproductive phases, fruiting, bloom, pollination, early maturation), and ending phase (senescence, fruit maturity, grain filling, dry down). Tables 3.3 through 3.5 adapted from Allen et al. (1998) give K_c and K_{cb} values for several crops that are often microirrigated. They provide appropriate crop growth stage length periods (L) for the initial (sub "ini"), crop development (sub "dev"), mid season (sub "mid"), and the end of season (sub "end") growth phases that can be used to construct seasonal crop growth curves as the example in Fig. 3.3. Extended treatment with greater in-depth descriptions and specific details about these values, and data for crops not listed here is given by Allen et al. (1998). They also discuss and review procedures for developing crop coefficients for locations and crops not listed in Allen et al. (1998) or Doorenbos and Pruitt (1977).

Fereres and Goldhamer (1990) presented mid-season crop coefficients for a grass reference *ET* for deciduous fruit and nut trees. They also discussed prior literature reporting crop coefficients considerably larger than the more common maximum K_c value of around 1.20 for densely-populated peach and pecan trees. Fereres et al., (1981a) reported that micro-advection in young developing orchards from the large amount of surrounding non-evaporating bare soil had small differences in *ET* compared with the more mature orchards once the younger orchards developed about 50 to 60% ground cover. The *ET* of young microirrigated almond orchards was dependent on irrigation frequency and the soil wetting patterns (see next section in this chapter), but it was highly related to the area of the ground shaded by the trees at noon (Fereres et al., 1982) (Fig. 3.4). Close agreement was found between estimates of evapotranspiration for young almond trees calculated using mature orchard crop coefficients (Eq. 3.9 and 3.10) as modified by the shaded-area percentage (Fig 3.4) and those obtained through using extensive soil water balance measurements (Sharples et al., 1985).

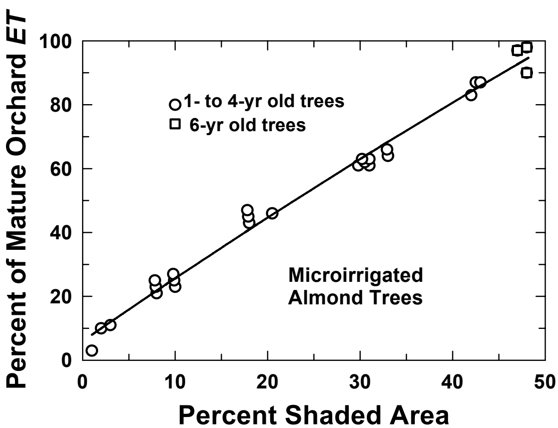

Figure 3.4. Relationship between shaded area and *ET* for young almond trees relative to *ET* from a mature almond orchard. Data were obtained from 1- to 4-yr old trees (circles) and 6-y old trees (squares) using soil water balance methods. Adapted from Fereres et al., 1982.

Table 3.3. Vegetable and tuber K_c and basal K_{cb} values and length of typical growth stages (days) with planting dates and their regions. Adapted from Allen et al. (1998).

Crop	$K_{c\ ini}$ $K_{cb\ ini}$ L_{ini}	L_{dev}	$K_{c\ mid}$ $K_{cb\ mid}$ L_{mid}	$K_{c\ end}$ $K_{cb\ end}$ L_{end}	Plant date	Region
Bell pepper	0.70		1.05	0.90		
	0.15		1.00	0.80		
	25/30	35	40	20	April/June	Mediterranean
	30	40	110	30	October	Arid
Broccoli	0.70		1.05	0.95		
	0.15		0.95	0.85		
	35	45	40	15	September	California, USA
Cabbage	0.70		1.05	0.95		
	0.15		0.95	0.85		
	40	60	50	15	September	California, USA
Cantaloupe	0.50		0.85	0.60		
	0.15		0.75	0.50		
	30	45	35	10	January	California, USA
	10	60	25	25	August	California, USA
Carrot	0.70		1.05	0.95		
	0.15		0.95	0.85		
	30	50	90	30	October.	California, USA
	30	40	60	20	Feb./Mar.	Mediterranean
Cauliflower	0.70		1.05	0.95		
	0.15		0.95	0.85		
	35	50	40	15	September	California, USA
Celery	0.70		1.05	1.00		
	0.15		0.95	0.90		
	25	40	95	20	October	Arid
	25	40	45	15	April	Mediterranean
Lettuce	0.70		1.00	0.95		
	0.15		0.90	0.90		
	20	30	15	10	April	Mediterranean
	30	45	25	10	Nov./Jan.	Mediterranean
	25	35	30	10	Oct./Nov.	Arid
Onion (dry)	0.70		1.05	0.75		
	0.15		0.95	0.65		
	20	35	110	45	Oct./Jan.	Arid
	15	25	70	40	April	Mediterranean
Onion (green)	0.70		1.00	1.00		
	0.15		0.90	0.90		
	25	30	10	5	April/May	Mediterranean
	30	55	55	40	March	California, USA

Table 3.3. Vegetable and tuber K_c and basal K_{cb} values and length of typical growth stages (days) with planting dates and their regions. Adapted from Allen et al. (1998). *Continued.*

Crop	$K_{c\ ini}$ $K_{cb\ ini}$ L_{ini}	L_{dev}	$K_{c\ mid}$ $K_{cb\ mid}$ L_{mid}	$K_{c\ end}$ $K_{cb\ end}$ L_{end}	Plant date	Region
Potato	0.50		1.15	0.75		
	0.15		1.10	0.65		
	25	30	45	30	May	Continental
	45	30	70	25	April/May	Idaho, USA
Pumpkin	0.50		1.00	0.80		
	0.15		0.95	0.70		
	20	30	30	20	Mar., Aug.	Mediterranean
Squash	0.50		0.95	0.75		
	0.15		0.90	0.70		
	25	35	25	15	Apr., Dec.	Mediterr., Arid
	20	30	25	15	May/June	Mediterr., Europe
Sweet melon	0.50		1.05	0.75		
	0.15		1.00	0.70		
	25	35	40	20	May	Mediterranean
	30	30	50	30	March	California, USA
Sweet potato	0.50		1.15	0.65		
	0.15		1.10	0.55		
	20	30	60	40	April	Mediterranean
Tomato	0.70		1.15	0.7-0.9		
	0.15		1.10	0.6-0.8		
	35	40	50	30	April/May	California, USA
	30	40	45	30	April/May	Mediterranean
Watermelon	0.40		1.00	0.75		
	0.15		0.95	0.70		
	20	30	30	30	April	Italy
	10	20	20	30	May/Aug.	Near East (desert)
Artichoke	0.50		1.00	0.80		
	0.15		0.95	0.90		
(Perennial crop)	40	40	250	30	April (1st y)	California, USA
	20	25	250	30	May (2nd y)	(cut in May)
Asparagus	0.50		0.95	0.30		
	0.15		0.90	0.20		
(Perennial crop)	50	30	100	50	February	Warm Winter
	90	30	200	45	February	Mediterranean

Table 3.4. Tropical crops, fruits, grape, and orchard K_c and basal K_{cb} values and length of typical growth stages (days) with planting dates and their regions. Adapted from Allen et al. (1998).

Perennial crops	$K_{c\ ini}$ $K_{cb\ ini}$ L_{ini}	L_{dev}	$K_{c\ mid}$ $K_{cb\ mid}$ L_{mid}	$K_{c\ end}$ $K_{cb\ end}$ L_{end}	Plant date	Region
Almond	0.40		0.90	0.65		
	0.20		0.85	0.60		
	30	50	130	30	March	California, USA
Apple/Cherry	0.45		0.95	0.70		
	0.35		0.90	0.65		
	30	50	130	30	March	California, USA
Avocado (no ground cover)	0.60		0.85	0.75		
	0.50		0.80	0.70		
	60	90	120	95	January	Mediterranean
Banana (1st y)	0.50		1.10	1.00		
	0.15		1.05	0.90		
	120	90	120	60	March	Mediterranean
Banana (2nd y)	1.00		1.20	1.10		
	0.60		1.10	1.05		
	120	60	180	5	February	Mediterranean
Berry	0.30		1.05	0.50		
	0.20		1.00	0.40		
	20	50	75	60	March	California, USA
Citrus (70% canopy, no ground cover)	0.70		0.65	0.70		
	0.65		0.60	0.65		
	60	90	120	95	January	Mediterranean
Grape (table / raisin)	0.30		0.85	0.45		
	0.15		0.80	0.40		
	20	50	75	60	March	California, USA
	20	40	120	60	April	Low Latitudes
Grape (wine)	0.30		0.70	0.45		
	0.15		0.65	0.40		
	30	60	40	80	April	Mid. Latitudes
Olive (40 to 60% ground cover)	0.65		0.70	0.70		
	0.55		0.65	0.65		
	30	90	60	90	March	Mediterranean
Peach/Apricot	0.45		0.90	0.65		
(no ground cover)	0.35		0.85	0.60		
(no frost)	30	50	130	30	March	California, USA
Pistachio (no ground cover)	0.40		1.10	0.45		
	0.20		1.05	0.40		
	20	60	30	40	February	Mediterranean

Table 3.4. Tropical crops, fruits, grape, and orchard K_c and basal K_{cb} values and length of typical growth stages (days) with planting dates and their regions. Adapted from Allen et al. (1998). *Continued.*

Perennial crops	$K_{c\ ini}$ / $K_{cb\ ini}$ / L_{ini}	L_{dev}	$K_{c\ mid}$ / $K_{cb\ mid}$ / L_{mid}	$K_{c\ end}$ / $K_{cb\ end}$ / L_{end}	Plant date	Region
Strawberry†	0.30		0.75	0.70		
	0.20		0.70	0.65		California, USA
	60	160	60	30	October	(Mulch culture)
Sugar cane (virgin)	0.40		1.25	0.75		
	0.15		1.20	0.70		
	35	60	190	120		Low Latitudes
	50	70	220	140		Tropics
	75	105	330	210		Hawaii, USA
Sugar cane (ratoon)	0.40		1.25	0.75		
	0.15		1.20	0.70		
	25	70	135	50		Low Latitudes
	30	50	180	60		Tropics
	35	105	210	70		Hawaii, USA
Walnut (no ground cover)	0.50		1.10	0.65		
	0.40		1.05	0.60		
	20	10	130	30	April	Utah, USA

† Strawberry data from Hanson and Bendixen (2004).

Table 3.5. Legume, fiber, and cereal crop K_c and basal K_{cb} values and length of typical growth (days) stages with planting dates and their regions. Adapted from Allen et al. (1998).

Annual crops	$K_{c\ ini}$ / $K_{cb\ ini}$ / L_{ini}	L_{dev}	$K_{c\ mid}$ / $K_{cb\ mid}$ / L_{mid}	$K_{c\ end}$ / $K_{cb\ end}$ / L_{end}	Plant date	Region
Bean (green)	0.50		1.05	0.90		
	0.15		1.00	0.80		California,
	20	30	30	10	Feb./March	Mediterranean
Cotton	0.35		1.15-1.2	0.70-0.50		
	0.15		1.1-1.15	0.50-0.40		
	45	90	45	45	March	California, USA
	30	50	55	45	April	Texas, USA
Corn (grain)	0.30		1.20	0.35		
	0.15		1.15	0.15		
	30	40	50	30	April	Spain, California
	30	40	50	50	April	Idaho, USA

Table 3.5. Legume, fiber, and cereal crop K_c and basal K_{cb} values and length of typical growth (days) stages with planting dates and their regions. Adapted from Allen et al. (1998). *Continued.*

Annual crops	$K_{c\ ini}$ $K_{cb\ ini}$ L_{ini}	L_{dev}	$K_{c\ mid}$ $K_{cb\ mid}$ L_{mid}	$K_{c\ end}$ $K_{cb\ end}$ L_{end}	Plant date	Region
Corn (sweet)	0.30		1.15	1.05		
	0.15		1.10	1.00		
	20	25	25	10	May/June	Mediterranean
	30	30	30	10	April	Idaho, USA
	20	40	70	10	January	California, USA
Peanut (groundnut)	0.40		1.15	0.60		
	0.15		1.10	0.50		
	35	45	35	25	May/June	Mediterranean

Other sources for crop coefficient values using alfalfa reference ET (ET_r) instead of the grass reference ET (ET_o) are found in Burman et al. (1980), Burman et al. (1983), Jensen et al. (1990), Wright (1982), and Stewart and Nielsen (1990).

Because the standard ET_o represents an irrigated grass under normal subhumid conditions with moderate wind speed [$RH \geq 45\%$ and $U_2 \leq 2$ m s^{-1}] (Allen et al. 1998), the K_c and K_{cb} for crops grown under more extreme environments (higher winds, lower humidity, differing day to night wind regimes, etc.) may require modifications to reflect properly the expected ET in those environments. Allen et al. (1998) provided an adjustment equation for the mid-season and end – of-season K_c and K_{cb} values as:

$$K_c = K_{c\,(Tab)} + [0.04\ (U_2 - 2) - 0.004\ (RH_{min} - 45)] \left(\frac{h_c}{3}\right)^{0.3} \tag{3.11}$$

where $K_{c\,(Tab)}$ is the tabular value of K_c or K_{cb} from Tab. 3.3 to Tab. 3.5, RH_{min} is the mean value for the daily minimum relative humidity in percent during either the mid- or end-of-season growth stage, and h_c is the mean crop height in m during the respective growth stage. When wind speeds are measured at a height different than 2 m, the wind speed should be adjusted to 2 m using procedures in Allen et al. (1998). Equation 3.11 is not recommended when h_c is greater than or equal to10 m or when $K_{c\ end}$ or $K_{cb\ end}$ is less than 0.45.

Although Allen et al. (1998) and Doorenbos and Pruitt (1977) expressed their tabulated crop coefficients in the cardinal growth periods described previously, other temporal scales have been used. Jensen and Haise (1963) used a dual-time scale that expressed the time from planting until full or effective full cover *(EFC)* in percent, and then they used a day scale after *EFC*. Hill (1991) presents examples of polynomials fit to the dual-time step crop coefficients. Doorenbos and Pruitt (1977) listed monthly values for permanent orchard and vineyard crops. Stegman (1988) used polynomial functions for corn crop coefficients fit to relative growing degree days that performed well in North Dakota. Sammis et al. (1985) developed crop coefficients for several crops in New Mexico based on growing degree days. The thermal time indexed through the growing degree day concept usually improves the transferability of K_c values from differing locations and for differing growing season conditions compared with time-based K_c values. Ritchie and Johnson (1990) proposed procedures for estimating K_c values based on modeling *LAI* through thermal time procedures and using functions for estimating soil evaporation and transpiration similar to functional models of Ritchie (1972) and Hanks (1985).

Crop rooting is an important factor in determining extractable soil water needed to schedule irrigations. Klepper (1990) provides a detailed review of root growth dynamics, root physiology, and root water uptake. The maximum range of typical crop root depths is given in Tab. 3.6 showing the genetic potential for root development in uniform, fertile soils that do not have chemical or physical impediments or shallow water tables. Although crop roots may extend to the depths listed in Tab. 3.6, irrigations are typically managed for a zone considerable less than the maximum crop rooting depth. The management depth may only be about 0.6 to 0.8 m deep reflecting the soil layers of most active water uptake and the penetration of typical irrigations.

Perennial or permanent orchard crops have relatively constant root depths, although new roots may develop each year. Annual crops and some perennial crops that are grown as an annual crop (e.g., cotton, sorghum), develop a new root system during the initial and crop development growth phases and reach their maximum depth by the mid season growth phase. Roots also decay and become partially or wholly inactive in water uptake over time. Klepper (1990) classified three basic root patterns of development – diffuse or fibrous (many monocotyledonous plants), taprooted, or a modified taproot (characteristic of many dicotyledonous plants). Martin et al. (1990) and Jensen et al. (1990) discuss root depth growth rates. The taproots of dicots and the main seminal axes of cereals generally grow downward due to positive orthogeotropism (Klepper, 1990). Lateral roots generally will grow perpendicular to the parent root. Martin et al. (1990) provides an equation and several empirical methods to estimate vertical root zone development:

$$Z_r = Z_{min} + (Z_{max} - Z_{min})\, R_f \tag{3.12}$$

where Z_r is root zone depth in m, Z_{min} is the minimum root zone depth in m (typically the planting depth), Z_{max} is the maximum rooting depth expected in m, and R_f is the root depth development factor (fraction). For a linear root development, Martin et al. (1990) suggested that R_f could be estimated as either the fraction of days from germination to the number of days to reach maximum effective root depth or by the fraction of growing degree days from germination to the growing degree days required to reach maximum effective root depth. As with plant leaf appearance rate, plant root development has been described by the phyllochron (the unit of time between equivalent leaf growth stages) (Klepper, 1990), so the linear characterization of R_f by growing degree days has an attractive physiological basis. Martin et al. (1990) and Allen et al. (1998) suggested that R_f could be estimated as the ratio of the difference in the current basal crop coefficient from the *initial* basal crop coefficient (i.e., K_{cbi} - $K_{cb\,ini}$) to the difference between the *mid season* and *initial* K_{cb}, (i.e., $K_{cb\,mid}$ - $K_{cb\,ini}$). However, with the segmented K_{cb} curve (Allen et al., 1998), this method does not initiate root zone development until the crop development growth phase starts (Fig. 3.5).

Table 3.6. Range of maximum effective rooting depth (Z_r) for selected fully grown crops and management allowed depletion (*MAD*) levels in percent with minimal reduction in *ET* rates. Adapted from Doorenbos and Pruitt (1977), Martin et al. (1990), and Allen et al. (1998).

Crop	Rooting depth (Z_r), m	Management allowed depletion, %	Crop	Rooting depth (Z_r), m	Management allowed depletion, %
Almond	1.0-2.0	40	Cotton	1.0-1.7	65
Apple/Cherry	1.0-2.0	50	Grape	1.0-2.0	35-45
Artichoke	0.6-0.9	45	Lettuce	0.3-0.5	30
Asparagus	1.2-1.8	45	Olives	1.2-1.7	65
Avocado	0.5-1.0	70	Onion	0.3-0.6	30
Banana	0.5-0.9	35	Peach/Apricot	1.0-2.0	50
Bean (green)	0.5-0.7	45	Peanut	0.5-1.0	50
Bell pepper	0.5-1.0	30	Pistachio	1.0-1.5	40
Berry	0.6-1.2	50	Potato	0.4-0.6	35
Broccoli	0.4-0.6	45	Pumpkin	1.0-1.5	35
Cabbage	0.5-0.8	45	Squash	0.6-1.0	50
Cantaloupe	0.9-1.5	45	Strawberry	0.2-0.3	20
Carrot	0.5-1.0	35	Sugar cane	1.2-2.0	65
Cauliflower	0.4-0.7	45	Sweet melon	0.8-1.5	40
Celery	0.3-0.5	20	Sweet potato	1.0-1.5	65
Corn (grain)	1.0-1.7	55	Tomato	0.7-1.5	40
Corn (sweet)	0.8-1.2	50	Walnut	1.7-2.4	50
Citrus (70% cover)	1.2-1.5	50	Watermelon	0.8-1.5	40

Borg and Grimes (1986) presented another empirical approach to estimate the root zone extension as

$$Z_r = Z_{max} \left\{ 0.5 + 0.5 \, Sin\left[3.03 \left(\frac{D_{ag}}{D_{max}} \right) - 1.47 \right] \right\} \tag{3.13}$$

where D_{ag} is the days after germination, D_{max} is the number of days from germination until maximum effective rooting, and the argument of the Sin function is in radians. Equation 3.13 starts the root zone at zero depth. It can be modified to match the concepts in Eq. 3.12 as

$$Z_r = Z_{min} + (Z_{max} - Z_{min}) \left\{ 0.5 + 0.5 \, Sin\left[3.03 \left(\frac{D_{ag}}{D_{max}} \right) - 1.47 \right] \right\} \tag{3.13a}$$

These root zone development functions for cotton are demonstrated in Fig. 3.5 where the roots are assumed to have a Z_{min} of 0.15 m. For irrigation scheduling needs, the linear function will usually be sufficient. Klepper (1990) suggests that root axes extend at rates near 10 mm d^{-1}, especially for cereals. The linear root extension rate in Fig. 3.5 is about 14 mm d^{-1}, which is not much different from Klepper's estimate and well within the range of the uncertainty about root depth extension. However, the requirement for prior experience is evident in the need to develop reasonable values for both Z_{min} and Z_{max} for the individual circumstances. Coelho et al. (2003) describe a root length density and root depth model used in a cotton soil-water balance model with daily root depth extension in mm d^{-1} of 3.0•*GDD*, where *GDD* is daily growing degree days in °C-d that was constrained based on soil water availability and soil strength (penetration resistance).

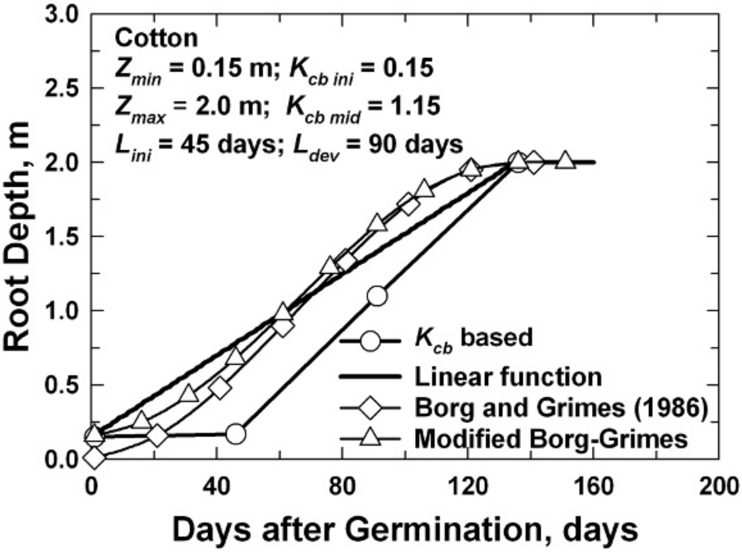

Figure 3.5. Examples of root zone development functions for cotton.

3.2.1.3. Soil factors affecting *ET*

The soil influences crop water use in three important processes: (1) the effect of root zone salinity on root water uptake; (2) the effect of soil water content on transpiration through reduced root water uptake; and (3) the effect of soil wetting from irrigation and rainfall on evaporation from the soil. The effects of salinity on the crop *ET* are basically additive to the effect of soil water deficits (see Chapter 4; Letey et al., 1985; Hoffman et al., 1990; Rhoades and Loveday, 1990; Shalhevet, 1994). The salinity of the root zone adds an additional chemical potential, the osmotic potential, which further reduces the root water potential (an increased plant stress) for water to flow into the plant roots. Specific salts such as boron, chloride, or sodium can cause phytotoxicity or nutrient imbalances (Hoffman et al., 1990; Rhoades and Loveday, 1990) besides affecting salinity of the root zone. In addition, sodium can cause sodic conditions with aggregate instability, clay migration, and poor soil particle bonding (Rhoades and Loveday, 1990; Oster, 1994). The sodium content of the soil and the irrigation water is the best indicator for soil sodicity problems and is characterized by the sodium adsorption ratio, *SAR* (see Chapter 4). Microirrigation generally does not apply salt-rich water to the leaves so leaf salt burn that occurs with sprinkler applications is avoided.

With microirrigation, higher soil water content is usually maintained just beneath the emitters or around the line-source microirrigation laterals (Chapter 2), so that salts are usually leached to the outside or away from the wetted zone. Thus, the crop can extract soil water similar in salinity to the irrigation water instead of the more saline water where the salt accumulates (Chapter 4). However, even with a uniform microirrigation system (Fig. 3.1) there can be reduced applications in small areas of a zone or field that might not be as effective in maintaining this leached zone for the crop roots. With subsurface drip irrigation (SDI) systems, salinity accumulation can occur from the upward capillary flow as water evaporates from the soil near the soil surface. For these systems and, possibly other types of microirrigation systems, rainfall could leach these salts that are accumulated near the soil surface into the crop root zone. The amount of the rainfall may be important as well for controlling salinity accumulation. It can be important to irrigate during or following rainfall to maintain or reestablish the salinity distribution and dilution occurring from microirrigation. However, Hoffman et al. (1985) observed minimal salinity effects on lettuce yields of a 30-mm rainfall event. The added rainfall further diluted the soil salinity distributions that were built-up prior to the rain event.

Plants transpire water through leaf stomates that open in response to light to permit CO_2 diffusion where it can be assimilated by the photosynthetic process (along with any associated photorespiration). Transpiration is largely a byproduct (or a physiological cost) of maintaining this crop uptake of CO_2 for growth and nutrient translocation within the plant. This transpired water must be re-supplied by the roots through soil water absorption (Klepper, 1990). Generally, root water replenishment will lag behind transpiration losses resulting in a slight decrease in plant tissue water content during the daylight period with a rehydration during evening or night as stomata close due to photoresponse. This creates a water potential gradient to move water from the soil immediately in contact with a root into the plant proper. This water uptake flux is often described using the Ohm's law analogy with two types of resistances arranged in series, one to the root resistance to water uptake and the other to the soil resistance to water flow in the immediate vicinity of the crop root or roots. The later resistance is inversely related to the soil hydraulic conductivity, which in turn depends upon the soil texture and its water content (see Chapter 2). Neither of these resistances is constant (Klepper, 1990).

For irrigation scheduling, the effect of reduced soil water on transpiration and *ET* have been largely based on the amount of plant available water (*PAW*) that can be extracted from the soil where *PAW* is basically a field characterization of the concept of field capacity that depends on the soil texture (see Chapter 2). Hillel (1998) and Gardner (1960) emphasize that *PAW* may be a useful description, but one that is difficult to define precisely and certainly not a constant for a given soil. Nevertheless, *PAW* has become widely used to describe the effects of water deficits on transpiration (Ritchie, 1972; Ritchie, 1973; Nimah and Hanks, 1973a 1973b; Hanks, 1974; Ritchie and Johnson, 1990). The most common procedure to describe the effect of a soil water deficit on *ET* has been to express it as a water stress function that depends on *PAW* through use of a crop water deficit coefficient, K_s (Jensen et al., 1971; Martin et al., 1990; Allen et al., 1998). Howell et al. (1979) reviewed and discussed several of these water deficit functions. This crop water deficit coefficient is multiplied by either K_c or K_{cb} in the single- and dual-crop coefficient approaches of Allen et al. (1998) as follows:

$$ET = (K_s\ K_c)\ ET_o \tag{3.14}$$

$$ET = [(K_s\ K_{cb}) + K_e]\ ET_o \tag{3.15}$$

Figure 3.6 illustrates several characterizations for K_s. Allen et al. (1998) adopted the linear function based on defining a critical *PAW* (PAW_c) as the point at which the soil water deficit begins to reduce *ET*, or in actuality *T* (transpiration). When irrigating for maximum yield, the soil water deficits will typically be minimal, unless the particular crop develops a higher quality product when stressed for water. In such instances many of the approaches, demonstrated in Fig. 3.6 can perform acceptably (Martin et al., 1990).

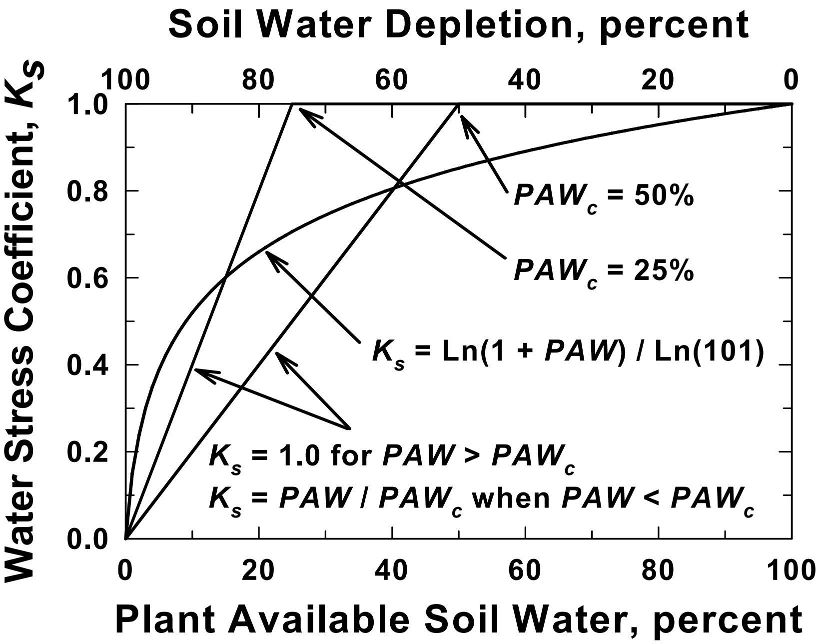

Figure 3.6. Examples of functions to estimate the soil water deficit influence on crop water use expressed as the K_s water stress coefficient.

Soil wetting results in evaporation from the soil (*E*). Evaporation also occurs from droplets or surface ponded water. Because droplets from microirrigation typically are exposed to air for only a short time, their evaporation can usually be ignored. In contrast, droplet evaporation from sprinklers or spray heads can often be 1 to 5% of the total applied water, especially when the droplets strike warmer bare soil or plant surfaces. Soil water evaporation is explicitly embodied into the single crop coefficient (K_c). Thus, any definition or set of K_c values must empirically represent the soil water evaporation resulting from the typical irrigation management (irrigation frequency, irrigation amount, and the irrigation method) and the regional rainfall characteristics (frequency, amount, etc.). In the dual crop coefficient approach, soil water evaporation is embodied similarly into K_{cb}, because even with a visibly dry soil surface (Wright, 1982), soil water evaporation can be a significant part of the total daily *ET* (both day and nighttime evaporation losses).

When the soil surface is wetted or only partially wetted as with most microirrigation systems, and particularly with a crop that partially covers the ground, soil water evaporation adds an extra amount of water use that must be considered. Estimating this soil water evaporation addition will depend on the amount of the soil surface area wetted, the maximum *ET* that could be expected under the climatic conditions, and the time since wetting. Soil water evaporation has been classically characterized into two stages, (1) a stage that has a constant rate approximated by the maximum evaporative power of the atmosphere, and (2) a falling rate stage where the soil hydraulic transport characteristics dominate (Philip, 1957; Ritchie, 1972; Ritchie and Johnson, 1990). Ritchie (1972) estimated maximum bare soil water evaporation as the potential *ET* rate computed by the Penman (1963) equation. R_n and G would be expected to be highly different for the bare soil than the full-cover reference grass evapotranspiration (ET_o) due to differences in albedos, emissivities, aerodynamic resistances, and surface resistances. Nimah and Hanks (1973a) describe an early numerical model of soil transport and root water uptake based on the earlier work of Hanks et al. (1969).

Allen et al. (1998) present a detailed procedure to estimate K_e that requires computing a separate water balance for the surface evaporative layer (0.1 to 0.15 m). Fortunately, Allen et al. (1998) provide a spreadsheet template in Appendix 8 of their manual that will perform these computations. The spreadsheet can be downloaded from the internet. Furthermore, the method of Allen et al. (1998) can be merged with the simpler method of Wright (1981 and 1982) to streamline and simplify the procedure with little loss in accuracy. The soil water evaporation coefficient can be estimated as

$$K_e = f_w \left(K_{c\,max} - K_{cb}\right) \left(1 - \sqrt{\frac{t}{t_d}}\right) \leq \left(f_w \; K_{c\,max}\right) \tag{3.16}$$

where f_w is fraction of the soil that is wetted, $K_{c\,max}$ is the maximum crop coefficient following rain or irrigation, t is time in days since the rain or irrigation, and t_d is the number of days it normally takes the soil to become visibly dry. The f_w factor for rain will be 1.0, and for microirrigation systems it will be between 0.1 and 0.5. The f_w will be small (0.1 to perhaps 0.15) for a SDI system or an orchard or vineyard crop with widely spaced plants, but it could be much larger (0.25 to 0.5) for every-row microirrigation of row crops. Allen et al. (1998) recommended that f_w be reduced by [1-(2/3)•f_c], where f_c is the fraction of the soil surface covered by vegetation [note: (1-f_c) is the fraction of soil exposed to sunlight]. Allen et al. (1998) defined $K_{c\,max}$ as

$$K_{c\,max} = Max\left[\left\{1.2 + \left[0.04\,(U_2 - 2) - 0.004\,(RH_{min} - 45)\left(\frac{h_c}{3}\right)^{0.3}\right]\right\},\ \left\{K_{cb} + 0.05\right\}\right] \tag{3.17}$$

where $K_{c\,max}$ is the maximum of either of the two terms inside the parentheses. The time required for a soil surface to visibly dry will depend on many factors including the soil texture, micro-relief (roughness), the amount of crop canopy shading, and even the ET_o rate. Wright (1981 and 1982) used 5 days for t_d of a silt loam soil at Kimberly, Idaho. Hill et al. (1983) provide typical t_d values of 10, 7, 5, 4, 3, and 2 days for clay, clay loam, silt loam, sandy loam, loamy sand, and a sand soil, respectively, and limited the cumulative evaporation by the amount of water received from rain or irrigation. Martin et al. (1990) list t_d values for different soils from Hill et al. (1983).

Allen et al. (2005) provide an extension for a detailed two-segment water balance (one wetted by irrigation and another wetted by rainfall) that computes separate *E* components that have application to microirrigation, especially where the irrigation only partly wets the soil surface area. Pruitt et al. (1984) and Bonachela et al. (2001) measured the soil *E* from a microirrigated row crop and from an orchard crop, respectively. Evett et al. (1995, 2000a) simulated the *E* and D_z losses from a row crop irrigated with SDI and differing depths. In all these examples, *E* losses from microirrigation were important and would affect irrigation water needs. However, Tarantino et al. (1982) reported ET from tomato irrigated by surface microirrigation and furrow irrigation was essentially identical (566 mm and 559 mm, respectively) based on weighing lysimeter measurements for a high water holding capacity clay loam soil. However, the microirrigated crop had 15% greater water use efficiency due to a higher yield. This emphasizes that reductions in evaporative losses can be counteracted by an increase in transpiration, which can in many cases result in higher yields.

3.2.1.4. A direct ET approach

Public irrigation management information systems can be localized to actual field conditions when crop coefficients are determined from local field measurements instead of tabulated or modeled ones (Meron et al., 1996). A simplified and direct approach to K_c estimation for the active crop growth stages consuming most of the water ("dev" and "mid", Fig. 3-3) was proposed by Meron et. al. (1990) using actual crop light interception *(LI)* in the field as an approximation of the relative radiation input. The radiation term of the Penman equation (based on modifications from Howell et al., 1984b) is factored with *LI* as:

$$ET_o = \frac{[\Delta\ R_n\ LI] + [(\gamma\ \ W_f\,)\ (e^o{}_s - e_a\,)]}{[\lambda\ \ \rho_w(\Delta+\gamma)]} \tag{3.18}$$

where ET_o is for an hour, *LI* is the fraction of intercepted radiation (synonymous with f_c for that hour), and W_f is defined as $a + b \bullet U_2$ with *a* and *b* defined for daytime hours as $a = 0.0434$ and $b = 0.0504$, and for nighttime hours $a = 0.125$ and $b = 03816$.

In practice, the daily ET_o is summed for daytime only. This is functionally equivalent to applying the Penman-Monteith equation on an hourly basis with the standardized reference surfaces, r_a set to constant value and r_l defined as a function of irradiance (Petersen et al., 1991). The growers receive calculated ET_o data for *LI* of 0.4 to 0.8, and for full cover. Local *LI* is fitted by measuring "shade -flecks" directly in the field at noon time, dividing the shaded parts of a meter stick across the row within the row spacing. This approach works well for short field crops such as peanut up to $LI < 0.8$ and for taller crops such as cotton up to $LI < 0.7$, and above which *LI* is considered as 1.0. This approach has been verified for cotton (6 seasons), peanut (6 seasons), sweet corn (2 seasons) using a neutron probe soil water balance and for processing tomatoes (2 seasons) using soil water sensors actuated automatic irrigation. No additional coefficients are needed under conditions of minimal surface evaporation occurring with microirrigation in arid conditions. For periods of exposed wetted soil and crop surfaces following rain, full cover is assumed including nighttime ET_o. Additional correction factors may be provided by extension specialists or crop advisors for modifications involving regulated deficit irrigation, intentional over watering or water reduction in the senescence phase.

A similar approach may be applied to orchards with partial cover (Fereres et al., 1982; Johnson et al., 2000). However, the diversity of species relative to basic canopy resistance, sensitivity to water stress, and intentional regulation of water deficit or water excess to achieve the desired economical results makes the water use estimates suitable for planning and design only. Water use per se in high-valued horticultural crops is often a negligible issue, and the more important economic aspect is the yield and fruit quality, especially size, color, and post-harvest properties.

3.2.1.5. Evaporation pans and atmometers

Evaporation pans are often used to determine the atmospheric evaporative demand in much the same way the Penman equation (Eq. 3.6) or the Penman-Monteith equation (Eq. 3.7) are used to estimate the water use by a reference crop. Several types of evaporation pans, their design, and use are discussed by Gangopadhyaya et al. (1966). The climatic factors that affect evaporation from a pan or from an atmometer do not differ from those embodied in the reference *ET* equations, but the boundary conditions and physics (radiation, turbulent exchange, etc.) of an evaporation pan are different from a crop evaporating surface (Brutsaert and Yu, 1968). For an evaporation pan, heat storage and release from the water is different from that of a crop. Evaporation pans and atmometers are widely used around the world because of their simplicity and ease of use compared with automated weather stations and detailed computer models. One of the older evaporation equations dating from the late 19th century was evaluated by Brutsaert and Yu (1968) in the form

$$\frac{E_{pan}}{(e_o - e_a)} = a + b\,U_z \tag{3.19}$$

where E_{pan} is the pan evaporation in mm h^{-1}, (e_o - e_a) is the vapor pressure deficit in kPa, U_z is wind speed in m s^{-1} at elevation *z*, and *a* and *b* are empirical constants. Equation 3.19 performs best for winds measured at 3 m, and is equivalent in form to the aerodynamic equation on the right-hand side of the Penman equation (Eq. 3.6). Although similar climatic factors affect E_{pan} and ET_o, it should be apparent they may influence E_{pan} differently than ET_o.

Many different types of evaporation pans have been developed for differing purposes (Tab. 3.7). The Colorado (Carpenter, 1889), Young (Young, 1942), and the *BPI* (Bureau of Plant Industry) pans are installed into the ground with their water level designed to be at the elevation of the soil surface. The U.S. Weather Bureau Class A evaporation pan is situated above the ground and air flows around the pan (Fig. 3.7). The *NOAA* (1989) *NWS* (National Weather Service) exposure guidelines require a fairly level, grass covered area free from obstructions. It should be in an enclosed fenced plot that is 3 m by 5 m (minimum). These guidelines differ slightly from those of the World Meteorological Organization adopted by *FAO* (Allen et al.,1998). The *NWS* recommends that the stilling well be located 0.25 m from the north side of the pan and that the pan be cleaned as necessary to prevent any material from altering the evaporation rate, particularly from oil films. Painting the pan is not recommended.

Table 3.7. Descriptions of commonly used evaporation pans.

Reference	Name	Description
Carpenter (1889)	Colorado Sunken Pan	The Colorado sunken pan has been widely used, especially in the western USA, for one of the longest continuous periods (Bloodgood et al., 1954). This pan is square 0.915 m (36 in.) on a side, 0.457 m deep (18 in.), and installed in the ground with its rim 100 mm (4 in.) above the ground. The water level is maintained at ground level, and the pan is made of 18-gage galvanized iron.
Horton (1921)	USDA-Bureau of Plant Industry	One of the first evaporation pans widely used in the U.S. was the Bureau of Plant Industry (BPI) developed and used mainly at dryland research stations in the western USA. The BPI pan is circular, 0.610 m (24 in.) in diameter, 0.610 m (24 in.) deep, installed 0.508 m (20 in.) below the ground, and made with 22-gage galvanized iron. The water level is maintained at the ground level. BPI pans are not in use today, but the historical records of BPI pan evaporation data are still used.
Young (1942)	Young Screened Pan	The Young screened pan was first used in 1936 and known as the Division of Irrigation screen pan. It was adopted as a standard by the International Boundary and Water Commission and by the Texas Agricultural Experiment Station (Bloodgood et al., 1954) because it had favorable factors when compared with 3.66 m (12 ft) pans and 25.9-m (85 ft) diameter reservoirs. This pan is made of 22-gage galvanized iron, 0.610 m (24 in.) in diameter, 0.914 m (3 ft) deep, installed in the ground 0.838 m (33 in.), covered with a 6 mm (0.25 in.) mesh hardware cloth screen, and the water level is maintained at ground level.
Kadel and Abbe (1916)	U.S. Weather Bureau Class A Pan	The U.S. Weather Bureau Class A evaporation pan is one of the most widely used both within the U.S. and the world as the *official* network instrument in the U.S. The National Weather Service (NWS) Class A Evaporation Pan is circular, 1.207 m (47.5 in.) inside diameter, 0.25 m (10 in.) deep, and the water level is to be maintained 50 to 75 mm (2 to 3 in.) from the pan rim. It is usually constructed with 22-gage galvanized iron or 0.8-mm thick Monel metal, placed on a wooden support that is 13 mm (0.5 in.) above the leveled and tamped ground (NOAA, 1989).

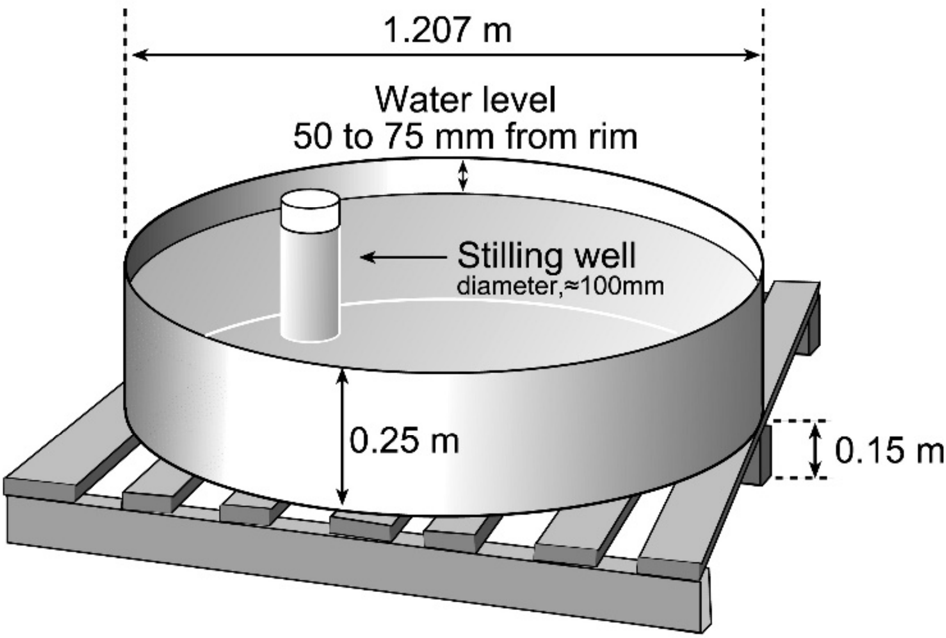

Figure 3.7. National Weather Service Class A Evaporation Pan schematic diagram illustrating the standard dimensions and the pan support. Adapted from Allen et al. (1998) and NOAA (1989).

Evaporation pans have long been used in irrigation management (Stanhill, 1961; Fuchs and Stanhill, 1963; Pruitt, 1966), especially when estimates of crop water use for 5 to 10 days are warranted. Two principle difficulties arise in using or in interpreting data measured with evaporation pans, (1) variations in types of evaporation pans, and (2) pan siting and local environment effects. Maintenance of the pans is still difficult, but many improved devices are now marketed to measure and refill the pans automatically (Phene et al., 1990). Doorenbos and Pruitt (1977) and Allen et al. (1998) discuss evaporation pan siting extensively.

The evaporation from the pan is related to grass reference ET_o with a pan coefficient, K_p, as

$$ET_o = K_p \, E_{pan} \tag{3.20}$$

where E_{pan} is the pan evaporation in mm d^{-1}. The Young sunken pan (Tab. 3.7) is screened to prevent animals from consuming the water. The *NWS* Class A Pan can be protected with lightweight screens (e.g., chicken wire, 50 mm mesh) (Campbell and Phene, 1976). The screen covering increased the K_p value in California from about 0.81 to 0.91 (Howell et al., 1983) due to shading and reduced wind speeds based on the Penman combination equation of Doorenbos and Pruitt (1977) for ET_o. The K_p will vary during the year as demonstrated by Wright (1981) compared with computed alfalfa reference ET_r and by Howell et al. (1983) compared with computed grass reference ET_o. This is caused by environmental changes around the pan and to the loss or storage of energy by the water in the pan itself. The pan coefficient is greatly influenced by the surrounding conditions. Allen et al. (1998) and Doorenbos and Pruitt (1977) classify these into two primary cases. One is where the pan is located on a short, green grass cover and surrounded by fallow soil (dry, non-cropped soil). The other is the opposite with the pan located on a dry, fallow soil and surrounded by a green crop. Doorenbos and Pruitt (1977) characterized the pan coefficients for these two cases with two climatic parameters, mean 2-m wind speed (U_2) in m s^{-1}, average relative humidity (RH_{mean}) in percent , and the fetch or distance in m of the identified surface type. Allen et al. (1998) provided regression equations using these three parameters for the NWS Class A Pan and the Colorado Sunken Pan (Tab. 3.8). They recommended that E_{pan} be calibrated against computed grass reference ET_o using Eq. 3.8.

Table 3.8. Pan coefficient (K_p) regression equations based on tabular data taken from Doorenbos and Pruitt (1977) by Allen et al. (1998).

Class A pan with green fetch	$K_p = 0.108 - 0.0286\ U_2 + 0.0422 \ln(FET)$ $+ 0.1434 \ln(RH_{mean}) - 0.000631 [\ln(FET)]^2 \ln(RH_{mean})$
Class A pan with dry fetch	$K_p = 0.61 + 0.00341\ RH_{mean} - 0.000162\ U_2\ RH_{mean}$ $- 0.00000959\ U_2\ FET + 0.00327\ U_2 \ln(FET)$ $- 0.00289\ U_2 \ln(86.4\ U_2) - 0.0106 [\ln(86.4\ U_2) \ln(FET)]$ $+ 0.00063 [\ln(FET)]^2 \ln(86.4\ U_2)$
Colorado sunken pan with green fetch	$K_p = 0.87 + 0.119 \ln(FET) - 0.0157[\ln(86.4\ U_2)]^2$ $– 0.0019 [\ln(\mathrm{FET})]^2 \ln(86.4\ U_2)+0.0138 \ln(86.4\ U_2)$
Colorado sunken pan with dry fetch	$K_p = 1.145 - 0.080\ U_2 + 0.000903 (U_2)^2 \ln(RH_{mean})$ $- 0.0964 \ln(FET) +0.0031\ U_2 \ln(FET)$ $+ 0.0015 [\ln(FET)]^2 \ln(RH_{mean})$
Range for variables	$1 \text{ m} \leq FET \leq 1{,}000 \text{ m}$ (these limits are rigid) $30\% \leq RH_{mean} \leq 84\%$ $1 \text{ m s}^{-1} \leq U_2 \leq 8 \text{ m s}^{-1}$
Parameters	K_p = pan coefficient U_2 = mean daily 2-m wind speed in m s^{-1} RH_{mean} = average daily relative humidity in % FET = fetch, or distance of the identified surface type (grass or crop or bare, fallow dry soil)

Phene et al. (1990) reviewed the use of several types of atmometers to estimate reference ET_o. Because of their low cost and ease of use, atmometers or evaporimeters have acceptance where weather station data or pan evaporation data are not available. Brutsaert (1982) indicated three types of atmometers are still in limited use today – the Piche evaporimeter developed in France, the Wild evaporimeter developed in Russia, and the Bellani-Livingston evaporimeter developed in Italy as a flat porous disk (Bellani) and in the U.S. by Livingston as a spherical porous surface. The Piche atmometer is constructed with a transparent glass tube sealed at the top that is about 0.2 to 0.3 m long and 10 to 30 mm in diameter with a disk of moist blotting paper that is 800 to 1300 mm^2 exposed on the bottom. A small hole on the side of the tube serves as an air vent. The tube is filled with water, and as water evaporates from the paper, which is held in place with a steel wire spring, the water level will sink in the tube. The instrument is installed about 1.2 m above the ground in an instrument shelter. The evaporation from the Piche atmometer was related to the drying power of the atmosphere (right-hand side of Eq. 3.6) by Stanhill (1962a) given as

$$\frac{\gamma}{\Delta+\gamma} E_A = a\, E_{pe} + b \qquad (3.21)$$

where $E_A = W_f\,(e^o{}_s - e_a)\,/\,\lambda$ from Eq. 3.6, E_{pe} is the Piche evaporation mm d^{-1}, and a and b are constants. Brochet and Gerbier (1972) empirically substituted the Piche evaporation into the Penman equation (Eq. 3.6) as

$$ET_o = a\,\frac{R_s}{\lambda} + b\, E_{pe} \qquad (3.22)$$

where R_s is solar irradiance in MJ m^{-2} d^{-1}, and they developed procedures to estimate the constants (a and b) for any latitude or time of year in France.

The Wild evaporimeter has a shallow cylindrical dish about 25 mm deep and 178.4 mm in diameter, filled with water and placed on a counter-balanced scale. The instrument is deployed similarly to the Piche atmometer at about 1.2 m above the ground in a shelter.

The Bellani-Livingston evaporimeter is a porous surface with a flat disk used for the Bellani type and a spherical surface used for the Livingston type (Livingston, 1935). This instrument, unlike the Piche and Wild evaporimeters, can be directly exposed to the environment. Altenhofen (1985) modified the Bellani atmometer by placing a green canvas cover over the ceramic top to simulate the resistance and albedo of a green leaf. Evaporation from this instrument has been shown to correlate well with reference ET equations using meteorological data (Broner and Law, 1991; Altenhofen, 1985). An electronic readout version of the instrument is now available for automatic recording or irrigation control (Parchomchuk et al., 1996) as well as canvas covers that simulate the surface resistances for either grass or alfalfa.

3.2.1.6. Scheduling principles using evapotranspiration

The estimation of crop water use is important in determining the amount of water to apply to the crop as well as the proper design flowrate needed to operate the irrigation system. Several key factors that affect the application amount relate to the soil properties as well as many crop specific parameters. One great advantage of microirrigation systems is that these systems can apply water frequently and in small amounts that are impractical with traditional surface or sprinkler irrigation systems. However, with frequent applications, the loss of applied water to soil water evaporation must be minimized or the irrigation frequency decreased and the application amount proportionally increased to maximize water used in transpiration by the crop. The application rate must be sufficient to match the crop needs while maintaining soil water above PAW_c, but not too large as to cause deep percolation by exceeding the field capacity and causing leaching in excess of that necessary for salinity control.

Martin et al. (1990) provide a good overview of irrigation scheduling methods using the estimate of crop *ET* in a soil water balance approach. They emphasized the need to monitor state variables (either soil water status or plant water status) as a check on *ET*-based scheduling. The monitoring of these state variables was reviewed by Phene et al. (1990) and will be discussed in relation to microirrigation control in the following sections of this chapter. The principles of applying these *ET* amounts in a soil water balance method for irrigation scheduling have not changed for many years (van Bavel, 1956; Stanhill, 1962b; Pruitt, 1966). This method can be applied using daily or weekly checkbook accounting approaches (Werner, 1978; Lundstrom et al., 1981; Yonts and Klocke, 1985; Lundstrom and Stegman, 1988) to more detailed computer models (Jensen, 1969; Jensen et al., 1970; Jensen et al., 1971; Wright and Jensen, 1978; Harrington and Heermann, 1981). The models of crop water use can be used to devise calendars for irrigations where good estimates of *ET* and expected rainfall are predictable (Fereres et al., 1981b; Hill and Allen, 1996).

All of these scheduling procedures depend on characterizing the plant available soil water. The concepts that describe the plant available water (*PAW*) and the management allowed depletion (*MAD*, Merriam, 1966) are illustrated by the schematic diagram in Fig. 3.8. The field capacity concept (Veihmeyer and Henderson, 1950) relates to the soil water content when the internal redistribution is presumed to be negligible after a few days following a thorough wetting event. In fact as Eq. 3.4 illustrates, it is the soil hydraulic conductivity [$K(\theta)$] that defines this soil water content. This water content is often based on the water content at -0.01 to -0.033 MPa soil pressure potential determined in the laboratory (Klute, 1986). However, Hillel (1998) points out that the definition of field capacity – "*the amount of water held in soil after excess water has drained away and the rate of downward movement has materially decreased, which usually takes place within 2-3 days after a rain or irrigation in pervious soils of uniform structure and texture*" (Veihmeyer and Hendrickson, 1950) – raises as many questions as it answers.

The water content at field capacity is usually determined from field measurements of soil water content integrated over several depths within the soil profile following a large irrigation or rain event and a predetermined drainage period. Campbell and Campbell (1982) illustrated that the field capacity could be estimated as

$$\theta_{FC} = \theta_{SAT} \left(\frac{\zeta}{K_{SAT}} \right)^{1/m} \tag{3.23}$$

where θ_{FC} is the water content at field capacity in m^3 m^{-3}, θ_{SAT} is the saturated water content in m^3 m^{-3}, ζ is the drainage rate considered negligible in mm d^{-1}, K_{SAT} is the saturated hydraulic conductivity in mm d^{-1}, and m is an empirical factor related to the soil water release curve (θ versus ψ, where ψ is the soil water pressure potential in MPa) for a soil. They suggested that estimates from Eq. 3.23 should be validated with reliable field measurements, but that the simple model values for θ_{FC} might be used as an initial approximation using appropriate soil parameter values. Figure 3.8 illustrates a static θ_{FC} value; however, it is a dynamic parameter depending on defining the evaporation flux rate from the soil surface, the drainage rate (*Dz*, see Eq. 3.4) at some depth z, and any root water uptake by the plants during or immediately following the wetting event. Equation 3.4 shows that there is no precise time when drainage ceases. The schematic illustration in Fig. 3.8 shows both a readily drainable water and a slowly drainable water fraction to demonstrate the difficulty in precisely determining θ_{FC} in the field. The drained upper limit (*DUL*) is illustrated to be less than θ_{FC} in Fig. 3.9 as an example, when it is also equally likely that *DUL* could be greater than or equal to θ_{FC}. Hillel (1998) suggested that ζ might be estimated as 10% or less of ET_o. Similarly, a static PAW_c value is illustrated in Fig. 3.9 where *ET* will decline below ET_o as defined by the K_s function (see Eqs. 3.14 and 3.15). The value of PAW_c will depend on the soil texture and will likely be different for each crop due to differing rooting depths, root density profiles, and root resistances to water uptake. Historically, a -1.5 MPa pressure potential has often been defined as the lower limit at which plants can extract water and described as the permanent wilting point (Veihmeyer and Hendrickson, 1950). However, the soil water content (θ) and the soil water potential (ψ) are never uniform throughout the root zone in the field, and therefore, it is difficult to determine a narrow range of either value that will reduce root water uptake. Also, other plant functions (photosynthesis, reproduction, carbon translocation, etc.) may be affected before *ET* is affected by stomatal closure and an increase in leaf resistance (and bulk canopy resistance, r_s). In addition, wilting and permanent wilting are difficult conditions to define precisely (Hillel, 1998). The lower limit of plant extractable soil water *(LLE)* might differ from the soil water content at wilting point (θ_{WP}); however, the relative positions of *LLE* and θ_{WP} in Fig. 3.8 are strictly for illustration, and it is equally likely that *LLE* could be greater than or equal to θ_{WP}. Bruce and Luxmore (1986) discuss field measurements of soil water retention properties.

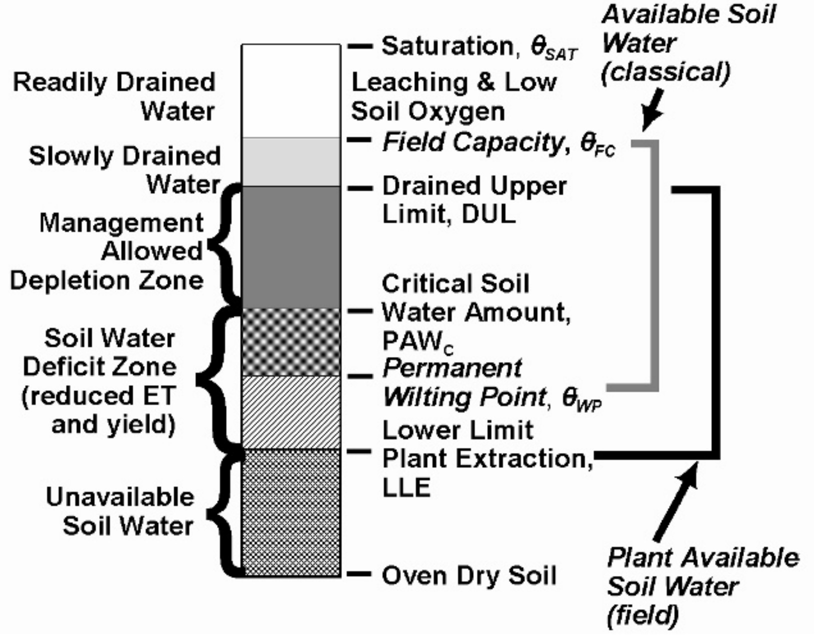

Figure 3.8. Schematic illustration of the soil water reservoir concepts.

Despite these shortcomings, the field capacity and wilting point are routinely used in traditional irrigation management to define the available soil water (*ASW*) as illustrated in Fig. 3.8. The plant available water (*PAW*) may differ from the classical definition of available soil water depending on how the dynamic features of field capacity and wilting point are interpreted. Although *PAW* is shown to be approximately equal to *ASW* (Fig. 3.8), this illustrates an idealized concept, and it could be equally likely that *ASW* could be greater than or equal to *PAW*. These soil water holding capacity terms are often defined as

$$ASW = 1000\ \left(\theta_{FC} - \theta_{WP}\right)\ Z_r \tag{3.24}$$

$$PAW = 1000\ \left(DUL - LLE\right)\ Z_r \tag{3.25}$$

where θ_{FC} is the soil water content at field capacity in m^3 m^{-3}, θ_{WP} is the soil water content at wilting point in m^3 m^{-3} , *DUL* is the drained upper limit in m^3 m^{-3}, *LLE* is the lower limit of plant extractable soil water in m^3 m^{-3}, Z_r is the root zone depth in m, and *ASW* and *PAW* are in mm. Table 3.6 lists soil water depletion as the management allowed depletion (*MAD*) as a percentage of either *ASW* or *PAW* before the soil water might reach the critical value, PAW_c.

In more traditional irrigation management, the questions are (1) when to apply water, and (2) how much water to apply. These answers are obtained by nearly depleting the soil water close to the PAW_c and then refilling the root zone to θ_{FC}. Martin et al. (1990) demonstrated that these decisions are bounded by the irrigation application amounts and the dates when an irrigation can be started to avoid excessive leaching or drainage (the earliest date) and when an irrigation can be started and avoid soil water deficits that could reduce yields (the latest date). The management objective then simply becomes one of maximizing the intervals between irrigations and applying sufficient water to refill the profile while providing only enough excess water to achieve necessary leaching.

With microirrigation, these traditional irrigation management decisions are largely negated by its ability to apply water frequently without incurring either excessive economic costs or needless waste of water (Rawitz, 1969; Rawlins and Raats, 1975). Therefore, with microirrigation, it has been shown by many (Bucks et al., 1982; Hillel, 1985; Phene, 1995; Camp, 1998) that it is desirable to maintain the soil water content in the crop root zone at a high level (low water depletion) while maintaining high soil water potential (less negative). This approach will provide a nearly optimum root environment for soil water, crop nutrients, salinity, and aeration simultaneously (Hillel, 1998). Microirrigation management is controlled, not by the crop water extraction as it is with more traditional irrigation methods, but by the flux of the water entering the soil (Rawlins, 1973). Thus, the soil as a water reservoir is less important with microirrigation, and the management becomes more closely focused on matching the crop transpiration needs while maintaining the soil water potential at the lowest part of the crop root zone at a level where the soil hydraulic conductivity controls the drainage flux and the salinity leaching.

The soil as a reservoir does become important with microirrigation when the crop root zone is partially wetted as it often occurs with orchard crops. Dasberg (1995) reviewed many studies of partial root zone wetting by microirrigation and under-tree spray and sprinkler systems of citrus orchards in Israel. They did not find any reduction in water use with partial wetting, but the irrigation frequency had to be adjusted with the smaller wetted areas to apply sufficient water necessary to achieve high yields. Bielorai et al. (1985) reported no short-term effects in the transition of mature citrus trees from complete wetting to partial root zone wetting, and that trees with a partially wetted root zone responded favorably to higher water and nutrient applications. Partial-area irrigation on a low-water holding soil in split root experiments in sunlit, environmentally controlled chambers in Florida led to increasingly severe water shortages that decreased the carbon exchange rate (*CER*), water use efficiency (*CER*/*ET*), and growth more severely than it decreased *ET* (Allen et al., 2000).

Cotton is known to respond favorably to a slight soil water deficit by enhanced earliness and yield (Grimes and Yamada, 1982). Carmi and Shalhevet (1983) postulated that partial root zone wetting for cotton could (1) alter the carbohydrate transfers into reproductive components (e.g., lint and seed for cotton) resulting in an increased harvest index or (2) better control of a mild water deficit in the crop. Fereres et al. (1985) did not find an advantage for microirrigation of cotton on low salinity, heavier soil in Spain, but cotton with 75% of estimated *ET* under microirrigation achieved high yields and earlier harvest potential even with one dripline per two rows. The earlier harvest was economically important to reduce the risks of grade loss from late season rains.

For microirrigation, the minimum irrigation frequency (sometimes called the irrigation cycle time) to complete the irrigation of a field is

$$I_M = \sum_{j=1}^{n} \left(\frac{I_j \; A_j}{8{,}640 \; Q_j \; Eia_j} + \frac{Tr_j \; A_j}{24} \right) \tag{3.26}$$

where I_M is the minimum time in days to apply an irrigation with "*n*" sets to a field , *I* is the gross applied irrigation in mm (equal to a L m^{-2}) to set "*j*", *Q* is the flowrate in $m^3\ s^{-1}$ for set "*j*", *Eia* is the irrigation application efficiency as a fraction (net divided by gross that infiltrates), *A* is the area in ha of set "*j*", and *Tr* is the maintenance time in h ha^{-1} required to service set "*j*". The application efficiency will depend on many factors of the design (see Chapter 5), system uniformity (see Chapters 5 and 10), and application losses to evaporation (especially for microsprinkler systems) and leaching (a portion or all of the leaching may be required, see Chapter 4). The minimum time to apply the irrigation amount, *I* in mm, must be greater than or equal to $3(I_j / S_c)$, where S_c is the irrigation capacity in mm d^{-1} (see Eq. 3.1). The maximum irrigation frequency is then given as

$$I_F = \sum_{j=1}^{n} \left(\frac{I_j}{S_c} - \frac{Tr_j \; A_j}{24} \right) \tag{3.27}$$

where I_F is the irrigation frequency in days to irrigate the field's "*n*" sets. Because most microirrigation systems are managed to apply the crop's *ET* rate, the "gross" irrigation amount, *I*, for the field will be

$$I = \sum_{j=1}^{n} \left(\frac{\sum_{i=1}^{I_f} ET_i}{Eia} \right)_j \tag{3.28}$$

with ET in mm d^{-1} for set "j" on day "i". Then, I_M and the resulting I amount can be set for the desired frequency between I_F and I_M to match ET or [ET-(P- Q_{ro})] (see Eq. 3.3) while keeping $\theta_{FCj} \geq \theta_{ij} \geq PAW_{cj}$ or $DUL_j \geq \theta_{ij} \geq PAW_{cj}$ for day "i" of irrigation set "j". Maintenance time (T_r) may not be required for each set on each irrigation. Often, it will be rotated for one or more sets in the field or sometimes no system maintenance may be required for an irrigation event. The application efficiency fraction, Eia, may also vary for the different zones or application events. Field performance validation checks (see Chapter 10) are important in determining the system operational parameters and in making performance improvements (Merriam and Keller, 1978).

When the irrigation capacity, S_c, and the net precipitation cannot match the crop ET rate, the soil water content, θ, will decline during the season and may even decline below PAW_c. The soil water reservoir can buffer short periods of these deficits. When S_c is intentionally designed to not meet the crop's ET rates [or net ET rate, ET-(P- Q_{ro})], then a deficit irrigation strategy must be developed for the soil, crop, S_c, and its environment (ET and P) (English et al., 1990). Under these conditions, it becomes important to avoid runoff (Q_{ro}) from precipitation, to avoid large soil water deficits at critical crop growth stages, and to spread the deficit evenly during periods that are less sensitive to soil water deficits. Deficit irrigation cannot be easily accommodated with saline soils or highly saline irrigation waters due to the decrease in yields from both the low soil water potential and low osmotic potential in the crop root zone.

3.2.2. Soil Water Control

Irrigations that maintain the soil water content in the optimum ranges previously described should provide the desired water for plant functions, the required leaching or dilution of soluble salts in the root zone so that the soil or irrigation salinity or sodicity will not affect soil or plant processes (e.g., aeration and root respiration), minimize losses of water to evaporation, percolation beneath the root zone, and runoff from either irrigation or precipitation.

Soil water can be directly estimated by measuring either the soil water content, θ, or the soil water potential, ψ. Soil water content expressed on a volumetric basis in m^3 m^{-3} is generally more useful in irrigation scheduling. However, θ_g expressed on a gravimetric basis in kg kg^{-1} is directly related to the volumetric water content, θ_v, by the soil bulk density, ρ_b in kg m^{-3}, as

$$\theta_v = \frac{\rho_b}{\rho_w} \theta_m \tag{3.29}$$

where ρ_w is the water density in kg m^{-3} (~ 1,000 kg m^{-3}).

Soil water potential (Hillel, 1998) can be expressed in terms of (1) the energy per unit mass basis (e.g., J kg^{-1}) which is generally considered to be the most fundamental basis; (2) the energy per unit volume basis, when water is considered incompressible, yields a unit with the dimension of pressure (e.g., MPa or kPa), or (3) the energy per unit weight, which is equivalent to the height of a water column equal to the pressure (e.g., m). These water potential bases are all interrelated as

$$\psi = \frac{P_s}{\rho_w} \tag{3.30}$$

where ψ is the water potential in J kg^{-1} (energy per unit mass), P_s is the water potential in Pa (1 Pa = 1 N m^{-2}), and ρ_w is the water density in kg m^{-3}, and

$$H = \frac{P_s}{\rho_w\ g} = \frac{\psi}{g} \tag{3.31}$$

where H is the water potential in energy per unit mass in m and g is the acceleration of gravity (i.e., gravitational constant, ~9.8 m s^{-2} on the earth's surface). The soil water potential comprises several components – matric, osmotic, pressure, and gravitational (Campbell, 1988) – where each may affect soil water movement and root water uptake, but not equally (e.g., osmotic potential has a limited effect on soil water movement except through the root membranes). The pressure potential is g multiplied by the distance from the measurement point to a free water surface above it, and the gravitational potential is g multiplied by the distance to a reference position. Both potentials are usually expressed as energy per unit mass (H). The matric potential is derived from the attraction of water molecules to each other and the affinity of the soil capillary pores to hold the water columns. The soil texture (see Chapter 2) affects the pore size distribution. In a soil without a water table (i.e., a free water surface), often the terms matric and pressure potential are used synonymously. The matric potential and the soil water content are related through the soil water retention curve that describes the function between θ_w or θ_g versus soil matric pressure potential, ψ_m. The conversion factors for various soil water potential units are listed in Tab. 3.9.

Table 3.9. Conversion factors among soil water potential units.

	Energy per unit mass J kg^{-1}		Energy per unit volume J m^{-3}		Energy per unit weight J N^{-1}	
Potential	-1.00 J kg^{-1}	-0.01 bars	-1.00 kPa	-0.001 MPa	-0.102 m†	-102.0 mm
Suction or tension	1.00 J kg^{-1}	0.01 bars 1.00 cb	1.00 kPa	0.001 MPa 1 000 Pa	0.102 m	102.0 mm

† Head of water based on acceleration of gravity, g = 9.80 m s^{-2}.
One standard atmosphere = 10.33 m (H_2O) = 1.01.3 kPa = 1.013 bar = 1,013 mb.

The osmotic potential is derived for only the water solution in the soil in relation to the energy of pure, free water. The presence of solutes lowers the vapor pressure of the soil water as

$$\psi_o = \frac{R T_K}{M_w} \ln\left(\frac{e}{e_o}\right) \tag{3.32}$$

where ψ_o is the osmotic potential expressed in energy per unit volume as Pa, R is the universal gas constant (~ 8.31 J mol^{-1} K^{-1}), M_w is the molecular mass of water (~ 18×10^{-6} m^3 mol^{-1}), T_K is the absolute temperature in K, e is the solution vapor pressure in kPa, and e_o is the vapor pressure within the soil in kPa of a body of pure, free water (Note: $e\ e_o^{-1}$ equals the relative humidity as a fraction). Water potential is generally a negative pressure. The negative terms are often called suction or tension so that the values can be expressed without a negative sign, particularly in irrigation scheduling applications.

3.2.2.1. Soil water measurement and controls

Both soil water content and soil water potential measurements are regularly used in microirrigation to (1) check the maintenance of adequate irrigation rates to match crop water use, (2) check over-irrigation by monitoring the bottom of the root zone, (3) bypass automatically scheduled irrigations when rain or prior irrigations were adequate, (4) initiate irrigations when pre-set thresholds are exceeded, and (5) automate irrigation control systems (see Chapter 7). Soil water measurements have been reviewed by Schmugge et al. (1980), Campbell (1988), and Phene et al. (1990). A historical perspective on soil water measurement was provided by Gardner (1988). Recently, Charlesworth (2000) compiled a useful manual on soil water measurement technologies and illustrations for their use in irrigation scheduling.

Soil water content has long been measured based on physically sampling the soil. The water content of the sample can be estimated by feeling the sample and by estimating its texture (NRCS, 1997a, b; Tab. 3-10). These samples do not have to preserve the natural soil bulk density and are obtained by auguring, coring, or spading the soil from within the crop root zone. The feel method can be fairly reliable, ± 5%, (NRCS, 1997b) after careful training and, especially, with extensive personal experience by the sampler in a particular soil or similar soil textures. It does not supply highly quantified results, but is widely practiced by trained, experienced irrigation specialists. The gravimetric method uses similar sampling techniques, but the samples are sealed in the field in plastic bags, cans, or containers to prevent evaporation from the sample until it can be weighed and dried in an oven. When the gravimetric samples cannot be securely sealed in the field, it becomes critical that the samples be weighed quickly. The samples are weighed to determine their wet mass less the tare mass of the container after which the samples are dried in an oven usually at 105°C, weighed until no further mass change is observed (typically for 24 h for convection oven; Gardner, 1986). The gravimetric water content, θ_g, is computed as the ratio of the mass of the water (wet mass minus the dry mass of the sample) to the dry mass of the soil sample. Gardner (1986) further describes precautions and procedures for measuring θ_g. The oven temperature of 100 to 110°C (with a typical value of about 105°C) has become a standard, but this temperature could oxidize and decompose materials from organic soils or cannot completely remove the absorbed water on some clay soils (Gardner, 1986; Hillel, 1998). In addition, repeated sampling and soil disturbance may be undesirable in some cases. Microwave ovens can be used to reduce the drying time, but they require calibration because of differences in oven properties, sample size, etc. (Gardner, 1986).

Table 3.10. Estimating soil water content by the feel and appearance method. Adapted from NRCS (1997a and b).

Available soil water %	*Coarse texture* fine sands to loamy fine sands	*Moderately coarse texture* sandy loam to fine sandy loam	*Medium texture* sandy clay loam, loam, & silt loam	*Fine texture* clay loam to silty clay loam
	Available Water (mm/m)			
	50-100	108-142	125-175	108-200
0-20	Dry loose, will hold together if not disturbed, loose sand grains on fingers with applied pressure	Dry, forms a very weak ball†, aggregated soil grains break away easily from ball.	Dry, soil aggregations break easily, no water standing on fingers, clods crumble	Dry, soil aggregates easily separate, clods are hard to crumble with applied pressure
25-50	Slightly moist, forms a weak ball with well defined finger marks, light coating of loose and aggregated sand grains remain on fingers	Slightly moist, forms a weak ball with defined finger marks, darkened color, no water staining on fingers, grains break away	Slightly moist, forms a weak ball with rough surfaces, no water staining on fingers, few aggregated soil grains break away	Slightly moist, forms a weak ball, very few aggregations break away, no water stains, clods flatten with applied pressure
50-75	Moist, forms a weak ball with loose and aggregated sand grains remaining on fingers, darkened color, heavy water staining on fingers, will not ribbon ‡	Moist, forms a ball with defined finger marks, very light soil water staining on fingers, darkened color, will not stick	Moist, forms a ball, very light soil water staining on fingers, darkened color, pliable, forms a weak ribbon	Moist, forms a smooth ball with defined finger marks, light soil water staining on fingers, ribbons
75-100	Wet, forms a weak ball, loose and aggregated sand grains remain on fingers, darkened color, heavy water staining on fingers, will not ribbon	Wet, forms a ball with wet outline on hand, light to medium water staining on fingers, makes a weak ribbon	Wet, forms a ball with well defined finger marks, light to heavy water coating on fingers, ribbons	Wet, forms a ball, uneven medium to heavy soil water coating on fingers, ribbons easily
Field capacity (100%)	Wet, forms a weak ball, light to heavy water coating on fingers, wet outline of soft ball remains on hand	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy water coating on fingers	Wet, forms a soft ball, free water appears briefly on soil surface after squeezing or shaking, medium to heavy water coating on fingers	Wet, forms a soft ball, free water appears on soil surface after squeezing or shaking, thick soil water coating on fingers, slick and sticky

† Ball is formed by squeezing a hand full of soil very firmly with one hand.
‡ Ribbon is formed when soil is squeezed out of hand between thumb and forefinger.

Gravimetric soil water values must be either volumetrically sampled using precise soil coring techniques that do not change the sample bulk density, ρ_b, or previously measured ρ_b values used in Eq. 3.28 to determine the volumetric soil water content, θ_v. Although ρ_b values will not likely change significantly at the deeper soil profile depths, the ρ_b near the soil surface will likely vary considerably due to tillage, aggregate dissolution and consolidation, or implement (or foot) traffic during the growing season. The root zone soil water content is determined as

$$\theta_Z = \int_0^{Z_r} \left(\theta_{gz}\ \rho_{bz}\right)\, dz \tag{3.33}$$

where θ_Z is the profile root zone soil water content in mm and dz is the sampling interval in mm. For the volumetric soil water content,

$$\theta_Z = \int_0^{Z_r} \left(\theta_{vz}\right)\, dz \tag{3.34}$$

The profile root zone soil water content clearly will depend on the accuracy in determining θ_v, θ_g, or ρ_b within the root zone (Z_r), the presence of any abrupt changes in either ρ_b or θ_v, θ_g, and the size of the increment (dz) used to measure the profile soil properties. Also, it is difficult to sample precisely either ρ_b or θ_v near the soil surface (z=0) or near a saturated zone.

Soil at the wetted depth can be quickly sampled qualitatively by probing the wetted area with a cylindrical steel shaft (10 mm) with a bulbous tip (12 mm) on the end with a "tee" handle (Merriam, 1996). These probes are commonly used to locate subsurface drain lines (a tile probe) or to locate buried pipelines. Although some initial training is required, Merriam (1996) indicated that the wetted depth could be accurately estimated. These probes could be used to determine the locations of inadequate wetting volume or places where irrigations are wetting the soil deeper than desired.

The variation in water applications has already been discussed. Plant differences (e.g., growth, development, rooting, and plant density), boundary layer micrometeorological factors, soil water levels and distribution, and the inherent soil physical and chemical factors also can affect the spatial variability in crop water use. Warrick (1998) presented general guidelines for the number of samples for selected soil properties as follows: low variation (Cv < 0.15) – bulk density, porosity, and saturated soil water content; medium variation (0.15 < Cv < 0.5) – soil particle size fractions (sand, silt, and clay) and water retained for various matric potentials; high variation (Cv > 0.5) – saturated hydraulic conductivity, infiltration under ponded conditions, solute concentration, pore water velocity, electrical conductivity, scaling coefficients, and unsaturated hydraulic conductivity. The low, medium, and high variability descriptions were arbitrary, and he estimated the number of samples, n, for each variability class for the mean to be within two confidence intervals with probability > 0.95 as 9, 9 < n < 96, n > 96, respectively. These sample numbers are for soil parameters assumed to be independent. Soil properties can have some spatial correlation (i.e., a sample is not then independent from an adjacent sample), and in certain situations, a high spatial correlation. Geostatistical (correlations over a distance) and kriging (correlations between nearest neighbors), fractal modeling, pedo-transfer functions, artificial neural networks, fuzzy sets, and fuzzy logic techniques can be used to quantify soil variability

(Warrick, 1998). This variability directly affects sampling of soil water or soil water potential for irrigation scheduling and/or controlling irrigations with soil water sensors. It may be even more important with microirrigation applications to recognize the inherent soil property variations that will affect the required number of measurements as well as the placement of soil sensors in relation to the water emission points and the crop root zone development dynamics.

Soil water sensors are characterized as (1) porous bodies (Campbell and Gee, 1986; Cassell and Klute, 1986; Charlesworth, 2000) or (2) direct measurements of the soil dielectric constant (capacitance), hydrogen content, or heat dissipation (Gardner, 1986, Hillel, 1998; Charlesworth, 2000). The porous bodies are expected to equilibrate to the water status of the soil with water moving into the porous body if the surrounding soil is wetter or losing water to a drier surrounding soil. The sensor hysteresis may not always be in phase with soil hysteresis (Campbell and Gee, 1986) so that appreciable errors are possible using a sensor calibration based on a drying cycle and attempting to measure soil water during a wetting cycle. Soil water sensors based on porous bodies of gypsum (Bouyoucos and Mick, 1940), nylon, ceramic, fiberglass (Colman and Hendrix, 1949), or a granular mixture of porous media (Larson, 1985) have been used in soil water sensors and applied for irrigation scheduling. Porous bodies tend to equilibrate to the soil water matric potential more directly than to the soil water content (Campbell and Gee, 1986; Hillel, 1998). The water potential or water content of the porous body can be determined by the electrical resistance or capacitance between electrodes embedded in the block, by the thermal heat dissipation from the block when electrical current is applied to a heater (Phene et al., 1989) or to a needle embedded in the porous block, or by the vacuum from the soil matric potential in contact with a water column through a porous body (e.g., a tensiometer). The typical measurement ranges for several types of soil water potential sensors are compared in Fig. 3.9. Tensiometers are not affected by the electrical conductivity of the soil water solution that should equilibrate through the ceramic cup porous tip, but they have a limited range of measurement (~ 75 kPa) (Cassell and Klute, 1986). When tensiometers are placed at deeper depths, they will have less sensitivity due the hydrostatic head of the water column in the tensiometer. Tensiometers are manufactured with manual vacuum gauges, electronic pressure transducers, or with integral switch relays to control microirrigation valves. Tensiometers are easily adapted for microirrigation control (Smajstrala and Locascio, 1996). Psychrometers (wet-bulb types) or dew-point hygrometers with ceramic tips equilibrate to the vapor pressure of the soil water solution and measure the combined osmotic and matric potentials (Rawlins and Campbell, 1986).

The soil dielectric constant measures the soil matrix (soil-water-air) capacity to conduct electromagnetic waves or pulses (Charlesworth, 2000), and it is influenced by the soil water and soil solution electrical conductivity. The dielectric constant of water is large (~80) and greater than that of moist soil (~3 to 5), which is much greater than air (~1; a poor electromagnetic conductor). Soil dielectric properties can be measured with time domain reflectometry *(TDR)*, which measures the time for a signal to transfer down and return from wires (wave guides) [historically used to determine separated or broken electrical cables], or by frequency domain reflectometry *(FDR),* which measures the capacitance of a soil media between plates. With *TDR,* the signal return time varies with the soil dielectric constant and is related to the soil water content. *TDR* is essentially independent of soil texture, temperature, and salt content (Topp et al., 1980; Topp and Davis 1985). *TDR* also has been demonstrated to measure bulk soil electrical conductivity (Dalton et al., 1984). *FDR* measures the capacitance by applying a voltage to plates within a soil media that results in a frequency change related to the soil dielectric constant.

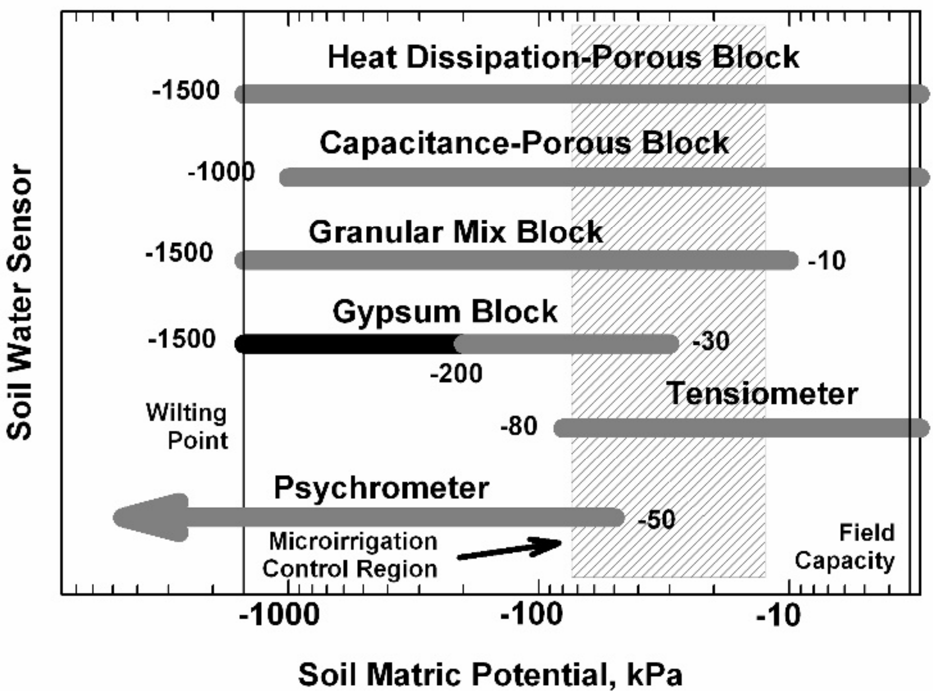

Figure 3.9. Measurement ranges for several types of soil water matric potential sensors. The field capacity (3.3 kPa) and wilting point (1500 kPa) lines are for illustration along with an idealized microirrigation control soil-water potential between -12 and -70 kPa. Gypsum blocks perform best in the range of -30 to -70 kPa.

Hydrogen has a high nuclear cross-section that thermalizes (slows) fast moving neutrons originating from Ra-Be or Am^{241}/Be (~>5 MeV). Hydrogen makes up a large part of the soil water content, but is also part of the organic matter and clay particles. Fast neutrons may also be slowed by other elements such as fluorine, chlorine, potassium, iron, boron, or manganese when they are present in high quantities. Neutron moderation *(NM)* has been widely used for nearly a half century to measure soil water content (Gardner and Kirkham, 1952; van Bavel et al., 1956) and commercial equipment is available for agricultural use in irrigation scheduling (Campbell and Campbell, 1982).

Soil thermal conduction is related to its water content, mineral composition, and organic matter content (de Vries, 1963). Heat dissipation *(HD)* within a porous body installed in the soil can be used to measure soil water potential (Phene et al., 1971).

Soil water measurements using porous bodies including *HD* devices require good contact with the soil media. Problems occur in soils that crack. *TDR* and *FDR* do not measure large volumes of soil, and thus, they are influenced primarily by soil water contents and soil contact near the probe and must be considered as basically point measurement devices. *NM* measures soil water in a considerably larger soil volume and has problem measuring water contents near the soil surface. *TDR* and *FDR* systems can be automated to record long-term events, although at great expense. *NM, TDR,* and *FDR* essentially measure the same soil volume repeatedly, which is advantageous if the instruments are installed correctly. Significant disadvantages of *NM* are radiological safety and the need to follow federal/state licensing and routine testing, and storage regulations. As a result of these disadvantages, *NM* has been primarily confined to research or consulting uses.

3.2.2.2. Placement and implementation

Soil water sensors must be placed in the active root zone volume and in proximity to the emitter. Typically, for surface microirrigation systems, the point-devices are installed about 0.3- to 0.5-m deep and about 0.3 m away from the emitter. Their placement in *SDI* systems vary, but are typically located midway between the emitters. In some cases, deeper placement is desirable for automated control or to monitor deep percolation. *NM* and *FDR* probes require access tubes that are installed vertically or in an angled position for specialized purposes.

3.2.3. Plant Water Deficit Indicators

Plant physiology research has developed a great variety of water stress indicators (for a good treatise see Kramer and Boyer, 1995) and/or plant water measurement methods (Phene et al., 1990). However, only a relatively small number of plant water measurement techniques have been integrated into irrigation scheduling practice. Plants are the best indicator of irrigation need because they integrate their soil state [from the soil nutrient level, soil water status in the root zone, or salinity (osmotic potential) of the root zone] and the atmospheric evaporative demand. The status can be visually observed by leaf rolling, color changes, wilting, or fruit abscission, to less visible responses including thermal changes (temperature) or leaf/plant physiological changes (increased r_l or decreased growth or photosynthesis reduction or delayed crop development), to reduced soil water uptake and transpiration, and to physical dehydration of the root, stem, or fruit. Stress symptoms may appear at midday, even when the plant is growing in moist soil, or be evident early in the morning or even pre-dawn when soil water is severely depleted. Simple visual indicators of plant water status should be considered valuable irrigation scheduling information. However, visual indicators are often qualitative and subjective and generally occur after a yield reducing plant water status has been reached. The relationship between plant water status and soil water content (or potential) is not universal and depends on the plant (rooting, physiology, and species/variety), soil (physical and chemical properties), and the atmosphere (climatic factors that affect ET_o).

3.2.3.1. Irrigation scheduling feedback loop using plant stress indicators

Plant stress indicators *(PSI)* provides mostly indications, which are useful for irrigation timing (Stegman, 1986), but cannot quantify soil water deficits needed to schedule irrigation water amounts. The required irrigation amount is usually obtained from a conventional soil water budget-based irrigation schedule. *PSI* measured crop water status is used as feedback to adjust *ET* coefficients, and to adjust/modify irrigation timing especially, when "net" irrigation or "effective" precipitation may be uncertain. Frequency of *PSI* measurements is a function of scheduling time steps and irrigation frequencies.

The soil-plant-atmosphere water continuum *(SPAC)* is the physical framework for instrumentation and data interpretation principles. Water moves from the soil (water potential of -0.01 to -1.5 MPa) to the atmosphere (-150 to -500 MPa) through a series of potential gradients and resistances (i.e., an Ohm's Law analogy): in the soil, at the soil-root interface, in the stem and at the leaf-air interface, to mention the major ones. The plant organs used for stress evaluation are located at one of these sections; thus, instantaneous values are influenced by the potential gradients and transpiration fluxes in other parts of the system near the time of the measurement. Cumulative measures, such as fruit and stem growth integrate the plant-water relations over time, but they are still tied to environmental conditions over the observation period. Current models of the *SPAC* involve many difficult to obtain (or define) parameters to enable direct inference of soil water potential or soil water content from plant water status measurements alone.

Soil water is inherently a spatial variable in the field. Under full irrigation, it will depend on the water distribution uniformity and on the variability of soil water holding capacity. Plants are good integrators of soil water potential in their vicinity, but not on larger scales relative to the plant size. Consequently, a single plant may represent a soil area of several m^2 at all the depths, but not the field scale variability (~ hundreds of m^2) or the variability of water status in plant organs. Main stem elongation is a singular value, whereas tissue water potentials, growth, and shrinkage will change with organ age, location on the plant, and exposure to the atmosphere boundary, and irradiance. Plant stress measurements must follow well defined and repeatable organ sampling protocols. Sample size, except remotely sensed parameters, such as canopy temperature or reflectance, will be a statistical function of the observed parameter. The within-plant and soil water spatial variability over the whole field often influence these plant measurements.

To obtain statistically reliable data over a large field, especially with low irrigation distribution uniformity or with variable plant sizes, the required sample size is usually impractical with available time and labor constraints. The usual solution is to designate representative sites based on the grower's or consultant's familiarity with the field. The inference from the sampling site to the whole field will depend on the site selection. Sampling integration with Precision Agriculture methods such as remote sensing or site management might improve site selection and evaluation of site representation for plant water status observations.

Information management becomes a major concern in modern farm management as time and energy to process information is one of the most precious resources of the farm manager or consultant. Data acquisition automation, digital outputs, spatial maps, and automated data processing capabilities of *PSI* instrumentation are important considerations in using *PSI* and turning the measurements into a decision support system *(DSS).* Modern microirrigation controllers are capable of using *PSI* feedback inputs for irrigation scheduling, but the technology has not yet been widely adopted in commercial fields (see also Chapter 7).

3.2.3.2. Plant water potential measurements

Water in the plant tissue is present in two forms – (1) apoplastic water between the cells and cell walls in a dilute solution near atmospheric pressure; and (2) simplastic water in the inner cell solution within the osmotic barrier of the cell membrane. Plant tissue water potential is the difference between the osmotic potential of the inner cell solution (ψ_o), which is created metabolically by concentration of assimilates and ions, and the counter pressure of the cell walls, the turgor pressure (P_t). Leaf water potential (ψ_l), neglecting other minor potentials, can be expressed as

$$\psi_l = P_t - \psi_o \tag{3.35}$$

Water is moving in and out of the tissue by potential gradients. Water moves via the xylem vessels from the roots to the leaves and other plant organs by the apoplastic pathway to the atmosphere, which is the main sink for the water. When the water supply from the roots is adequate and the transpiration rate is small (e.g., pre-dawn conditions), the tissue is saturated, and water uptake is restricted by cell wall expansion. In this case, $P_t = \psi_o$ and $\psi_l = 0$ at which point the plant is at full turgor. On the other extreme, when transpiration is large and water supply is small, $P_t = 0$ and $\psi_l = \psi_o$, and plants will exhibit wilting. Because cell walls are elastic, a wide range of potentials exists between these extreme points of full turgor and wilt.

Tissue water potential is an intensive parameter and gives a momentary snapshot of prevailing plant-water status. It depends on current soil-water potential and transpiration flux induced by current atmospheric demand. Thus, in order to ascertain the soil water conditions for irrigation scheduling, environmental conditions should be well defined.

Leaf water potential (ψ_l) is often measured using the pressure chamber method based on Dixon (1914) and the fundamental work of (Scholander et al., 1965). The pressure chamber or "pressure bomb" has become one of the commonly used *PSI* instruments for research and has made inroads into practical irrigation scheduling. The pressure chamber measures “xylem pressure potential,” which is essentially equivalent to “total water potential” because the “osmotic potential” is usually negligible or small. Briefly, the technique is based on excising a whole leaf, inserting it into a chamber with the petiole extending through a sealed cap, applying gas pressure(typically N), and observing the exudation of vascular sap from the cut petiole, and recording the chamber pressure, which is equivalent to ψ_l. Research with pressure chambers was conducted in the 1970s and 1980s, and the ψ_l thresholds were published for major field crops (Grimes and Yamada, 1982). However, the practical application was restricted because:

1) Immediately after a leaf is excised, water evaporates very rapidly through the stomata causing a considerable ψ_l potential drop in just a matter of seconds. Consequently, strict adherence to measurement procedures must be followed to obtain reproducible data suitable for irrigation scheduling (Meron et al., 1987a). Leaves are often sealed in moist opaque bags after excision to reduce transpiration losses prior to the measurements.
2) Stomatal resistance regulates water loss from the leaves, and thus, internal water potentials. For crops such as cotton that exhibit stomatal closure only at high stress, ψ_l is a good indicator of plant water stress, whereas in other species (e.g., apple), the mid-day stomatal closure under normal conditions will obscure ψ_l changes caused by soil water deficits.
3) The use of ψ_l was introduced into irrigation scheduling assuming the existence of near steady-state solar noon transpiration and day-by-day similarity of climatic conditions, which is typical to Mediterranean climates. Application is limited to solar noon when transpiration is at its peak and environmental conditions change slowly. To interpret

correctly the observed values under less stable climates, the measurements must be normalized to prevailing environmental conditions (Bunce, 1978).

4) The measured ψ_l values depend on operator skill involving the ability to make proper pressure adjustments and endpoint detection. Rapid pressure increases and slow operator response will result in lower ψ_l values.

The ψ_l values when stomatal regulation will begin to reduce transpiration below "well-watered" conditions are listed in Table 3.11 (Slabbers, 1980, See also Phene et al., 1990).

Table 3.11. Critical leaf water potential (ψ_l) at which stomatal regulation of transpiration will begin to reduce transpiration rates for selected crops. Adapted from Slabbers (1980).

Crop	Ψ_l (MPa)
Alfalfa	-1.4
Barley, bean, cotton	-0.9 to -2.4 (average -1.4)
Birdsfoot trefoil	-1.0
Cotton	-1.1 and -1.3
Grass	-1.0
Corn	-1.7, -1.1 to -1.9[†]
Potato	-0.35 to -0.4
Soybean, tomato	-1.0
Sorghum	-0.9 to -1.6[†] (average -1.2), -2.0
Southern pea	-0.8
Sugarbeet	-0.5
Sunflower	-0.75
Wheat	-1.0, -0.7 to -1.9[‡]

[†]depends on growth stage
[‡]depends on leaf position in canopy

Xylem water potential (ψ_x) can be measured with a pressure chamber for leaves that have been enclosed in opaque and water tight envelopes. The leaves are placed in the envelopes when the stomata are closed (e.g., pre-dawn). In fact, the whole leaf acts as a water potential gauge attached to the stem xylem. Xylem water potential in actively transpiring leaves is generally higher than ψ_l, because of the potential drop between the inflow point at the petiole and the stomatal cavities. This drop is termed "leaf resistance". Xylem water potential can be a more reliable and reproducible value because it accounts for the variability between the leaves on the plant, and water losses during measurement (#1 above) or eliminates biases caused by stomatal closure (#2 above) (McCuthan and Shackel, 1992). However, extra labor is required to measure ψ_x because of the additional required step of visiting the site (plant/leaf) to enclose the leaf in the envelope in the morning hours before returning for leaf excision in the early afternoon.

3.2.3.3. Plant size changes from plant-water stress

Plant cells expand their volume by the relaxation of the bonds between the cell wall fibrils and under internal mechanical pressure from the internal cell turgor pressure. The fibrils slip along each other and enable cell wall extension. The process involves the availability of assimilates and hormonal effects, not discussed here, and turgor pressure, which is a function of internal plant water status. Turgor pressure is required for cell expansion so tissue growth is a good integrator of plant water status over time.

Plant tissue volumes will change with their water content. When transpiration flux is greater than water influx from the roots, water flows out and tissue volumes are reduced. In situations of low transpiration, such as at night and/or with ample soil water, plants rehydrate and their cell volumes recover and expand causing turgor pressure increases.

The lack of appropriate instrumentation limits the use of diurnal stem, leaf or fruit volume changes as *PSI* water management tools. The magnitude of daily changes can be in the order of 1 μm for the thickness of a leaf, 2 to 5 μm for a rose stem, 10 to 30 μm for an avocado trunk, 0.1 to 0.6 mm for the diameter of a grapefruit and up to 20 mm for cotton mainstem elongation. For low frequency measurement of fruit growth or mainstem elongation, measuring tape-based devices will suffice. Mechanical precision devices, such as industrial calipers can be used as trunk dendrometers in the 10 μm range, if once- or twice-a-day measurements are desired. However, when diel or diurnal changes must be monitored, a finer resolution is possible only with high-precision electronic recording devices, such as *LVDTs,* (linear variable differential transformers). Accuracy, sensitivity, repeatability, and durability under outdoor conditions with temperature variations are the main requirement for measurements during simultaneous environmental changes.

Maximum daily shrinkage *(MDS)* of trunks and stems or dendrometry has been used as a *PSI* (Goldhamer and Fereres, 2001; 2004). The advantage of dendrometry measurements is that only a single point is required to represent the water status of the whole plant similar to ψ_x. However, the active tissue thickness and elasticity are widely variable among trees and also on different locations on the same tree so that absolute *MDS* limits for stress detection are difficult to establish. Normalization of *MDS* for tissue thickness and elasticity variability is required to establish threshold *MDS* signals that are suitable for irrigation scheduling (Goldhamer and Fereres, 2004).

The other basic problem of using tissue shrinkage in irrigation scheduling feedback, as with other *PSI* methods based on diurnal tissue water content/potential, is normalization to the environmental conditions to separate the influence of atmospheric water demand usually defined in terms of vapor pressure deficit from irrigation related soil water deficits. Other diurnal shrinkage measurements are based on methods using leaf thickness changes or fruit shrinkage (Huguet et al., 1992). Attempts have been made to commercialize irrigation controllers based on electronic shrinkage monitoring devices.

Fruit growth and stem or branch elongations are the most frequently measured parameters because they require simple instrumentation. Fruit size is an important economic quality parameter. In arid climates, irrigation is one of the main tools a producer can use besides thinning to control fruit size. The use of fruit growth as a criterion for irrigation scheduling was introduced by Assaf et al. (1982). Seasonal reference growth curves were used and irrigation amounts were adjusted to follow the target fruit size. Small sections of the crop row are over- and under-irrigated to isolate irrigation effects from climatic and fruit-load factors. The irrigation schedule is adjusted according to growth rates monitored in each regime. Monitoring fruit size manually is labor intensive, and thus, is used infrequently in irrigation scheduling. Continuous electronic monitoring is much faster and is efficient through reduced labor costs, but requires expensive equipment. Main stem elongation measurements have also been used in cotton irrigation scheduling during the early growth stages to regulate the vegetative/reproductive growth ratio (Meron et al., 1987b).

3.2.3.4. Plant stress based on plant temperature

Plant stress measurements with hand-held infrared thermometers *(IRT)* have become increasingly popular in the last 10 to15 years (Hatfield, 1990). Idso et al. (1981) developed an empirical approach for quantifying stress by determining "non-water-stressed baselines" for crops. This is based on linear relationships between the canopy-air temperature difference $(T_c - T_a)$ and the vapor pressure deficit *(VPD)*. Jackson et al. (1981) introduced a theoretical method for calculating the crop water stress index *(CWSI)* that involves the additional terms of net radiation (R_n), aerodynamic resistance (r_a), and crop canopy resistance (r_s) to water vapor transport. Briefly, the air to canopy temperature differences are normalized by the *VPD* between two empirical lines at the wilted baseline *CWSI* = 1 and at the well-watered baseline *CWSI* = 0. Reviews of canopy temperature and crop water stress research were made by Jackson et al. (1988) and Gardner et al. (1992a, 1992b). Major shortcomings of the *CWSI* technique for irrigation scheduling were reported by Stockle and Dugas (1992) that include the difficulty in measuring canopy temperature of row crops in early stages of growth, and that although it can determine when to irrigate, it cannot determine how much water to apply. In addition, canopy temperature measurements are highly sensitive to the view angle of the sensor and its relation to the solar zenith angle (Fuchs, 1990) and azimuth angle (Nielsen et al., 1994). Therefore, standardization and consistency in the procedures are important (Stockle and Dugas, 1992; Gardner et al., 1992b). Despite these shortcomings, irrigation scheduling based on canopy temperature measurements with *IRTs* appears to be promising for some crops (Nielsen and Gardner, 1987; Nielsen, 1990). Clawson and Blad (1982) utilized infrared thermometry for scheduling irrigation for corn in Nebraska. They used canopy temperature variation *(CTV)* rather than *CWSI* in their study. Idso (1982) developed non-water-stressed baselines in Arizona for various crops including corn. Nielsen and Gardner (1987) reported irrigation scheduling of corn with *CWSI* in Colorado and concluded that the *IRT* should become an increasingly important tool in irrigation scheduling by reducing irrigation costs. Braunsworth and Mack (1989) evaluated the relationship between *CWSI* and evapotranspiration *(ET)* and yield of sweet corn in Oregon, and stated that seasonal average *CWSI* values were closely related to the seasonal *ET* deficit and yield deficit. Keener and Kircher (1983) pointed out the limitations of *CWSI* in humid regions with the low evaporative demand and small canopy to air temperature differences. Howell et al. (1984a) demonstrated the usefulness of the *CWSI* for cotton as a *PSI*. In wheat, Howell et al. (1986) evaluated the *CWSI* for irrigation scheduling and as a tool for determining varietal differences to water stress. Minimal yield reductions at a threshold *CWSI* value less than 0.33 were reported for high frequency irrigation of corn (Yazar et al., 1999).

Although the *IRT* instrumentation is inexpensive, can cover large areas quickly, and is easy to use, the *CWSI* method has not became widespread for two main reasons. One, it is difficult to exclude from the field of view of the *IRT* irrelevant spots, such as hot soil and lower leaves, so that the temperature measured does not represent the upper canopy surface. Two, *VPD* alone is insufficient because wind speed and radiation data are also needed for proper normalization of *CWSI (*Choudhury and Idso, 1985). As a result, the baselines cannot be well defined, and the *CWSI* values are difficult to interpret. Normalization of *CWSI* to a well watered canopy reference surface was suggested by (Clawson et al., 1989), but this has not been adopted because of practical obstacles. Many other uses of canopy temperature as *PSI* feedback for irrigation scheduling have been proposed, as well as for site-specific irrigation. The use of *IRTs* and some index of crop water status (Stegman, 1986) can be practical irrigation timing tools.

The canopy time-temperature threshold (*TT*; cumulative time the crop canopy temperature exceeds a predetermined canopy temperature value) has been demonstrated to be even simpler to apply than the *CWSI* (Wanjura et al., 1990) and adapted for automated microirrigation control (Upchurch et at., 1990; Wanjura et al., 1992). A canopy temperature threshold of 28°C has been determined optimum to initiate cotton microirrigations that generally produced the greatest lint yield (Upchurch et al., 1990; Wanjura et al., 1990; Wanjura et al., 1992), whereas initiating irrigation at higher or lower canopy temperatures generally reduced lint yields. The canopy time-temperature threshold *(TT)* concept was based on the Jackson et al. (1981) *CWSI* model by Wanjura et al. (1995) to accumulate time (hours above a threshold canopy temperature set point) before initiating irrigation. Wanjura et al. (1997) included air humidity as a constraint in canopy cooling in the *TT* concept. *TT* times of 2 to 4 h above 28°C were not different from irrigation controls based on a 28°C canopy-threshold temperature alone (Wanjura et al., 1995) indicating the three-day irrigation frequency used with either the *TT* or 28°C canopy-threshold temperature were appropriate for cotton irrigation controls. Wanjura and Upchurch (2000) evaluated the empirical *CWSI*, the theoretical *CWSI*, and *TT* methods across a range of irrigation levels for corn and cotton. Generally, they found more consistent results with the empirical *CWSI* method than the theoretical one, and that corn yields were more consistently correlated with stress using the *TT* method. Evett et al. (1996, 2000b) reported ease of irrigation controls of microirrigation systems for corn and soybean compared with traditional soil water balance irrigation scheduling using the *TT* method.

3.2.3.5. Transpiration measurements by sap flow

The velocity of the transpiration stream within the stem is measured by inducing a short heat pulse and measuring the time of its advance (Cohen et al., 1981; Grainer, 1985) or the time of its dissipation (Weibel and Devos, 1994). These data permit crop transpiration (*T*) to be directly measured and can be used in Eq.3.15 to estimate K_{cb}, and/or K_s factors as

$$T = \left(K_s K_{cb}\right) ET_o \text{ or } \left(K_s K_{cb}\right) = \left(\frac{T}{ET_o}\right) \qquad (3.36\text{ a, b})$$

Transpiration measurements are especially useful in irrigation scheduling for microirrigated vine or tree crops with woody stems. The major limitations of this method are the number of trees or vines that can be economically monitored in a field [~ 4 to 32], the wiring needed to connect sap gauges to a data logger, and the overall time period that a plant can be instrumented without damage.

Steady-state heat flow gauges, *SFG*, (Fig. 3.10) [Sakuratani (1981); Baker and Van Bavel (1987)] permit *T* flow measurements from an energy balance from a low power heating strip (typically a thin heater strip surrounding the plant stem). Heater strips are more applicable for stem diameters less than 50 mm, but can be used successfully on stems as large as 150 mm. However, the larger diameters require more thermocouples and are more expensive. The transpiration flow is computed from measurements of radial heat dissipation and the vertical heat flow. The applied power varies by gauge/heater design between 0.2 to10 W [note, 1 W ≡ 1 J s^{-1}]. The applied power will depend on crop species, gauge design, and transpiration rate. The energy balance equation can be represented as

$$F_t = \frac{(P_{in} - Q_v - Q_r)}{C_{pw}\, dT} \tag{3.37}$$

where F_t is the transpiration flow in g s^{-1}, P_{in} is the heater power input in W, Q_v is the vertical heat flow in W, Q_r is the radial heat flow in W, C_{pw} is the specific heat of water [4.186 J g^{-1} °C^{-1}], and dT is the temperature increase in °C. The temperature differences are usually measured with fine-wire thermocouples arranged as differential thermopiles (thermocouples in series to increase the signal) requiring only precise voltage measurements [~ ± 1 µV]. Van Bavel (1999) describes the theory and application of steady-state heat flow sap gauges. Thermal insulation and radiation shielding are particularly critical for high quality measurements.

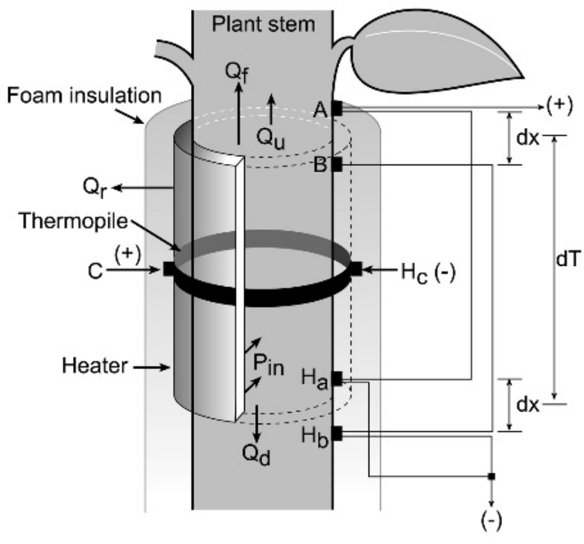

Figure 3.10. Schematic of steady-state heat balance stem sap flow gauge. Drawing courtesy of Kansas State University. Adapted from of Dynamax, Inc., Houston, Texas.

For larger diameter vine or tree trunks (> 150 mm), heat pulse velocity (*HPV*, Cohen et al., 1981) or steady-heat dissipation (*HD*, Granier, 1985) can be utilized to measure tree or vine transpiration. In *HPV*, a heated probe inserted in the sap wood is periodically heated and the temperature rise above and below the heated point determines the velocity of the sap flow (Fig.3.11). In *HD*, as in *SFG* a constant power is applied to a heater element, and the temperature of the sapwood at that point and a lower point determines the water flowrate. The *HD* method from Granier (1985, 1987) is based on liquid velocity heat dissipation theory and defined as

$$K = \frac{\left(\Delta T_m - \Delta T\right)}{\Delta T} \tag{3.38}$$

where K is dimensionless, ΔT is the measured difference in temperature in °C between that of the heated needle, referenced to the lower non-heated needle, placed at a fixed distance below the heated source, and ΔT_m is the value of ΔT in °C when there is no sap flow (zero set value).

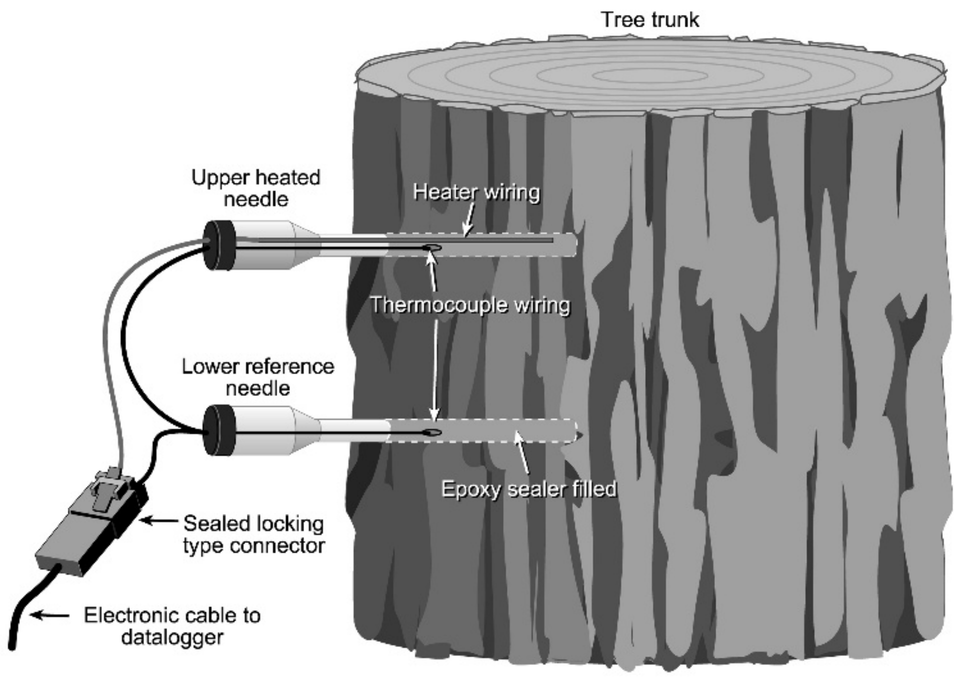

Figure 3.11. Schematic of steady-state heat dissipation stem sap flow gauge. Drawing courtesy of Kansas State University. Adapted from Dynamax, Inc., Houston, Texas.

Granier (1985, 1987) found empirically that the average sap flow velocity V (m s^{-1}) could be related to K by an exponential expression:

$$V = 0.00119\, K^{1.231} \tag{3.39}$$

where V is the sap velocity in m s^{-1}. The sap velocity, V, can be converted to a sap flowrate as

$$F_t = \left(A_s V \right) x\ 10^{-6} \tag{3.40}$$

where F_t is transpiration in g s^{-1} and A_s is the sap conducting area in m^2. Typical midday values for V were reported for forest tree species to vary from 2.8 x 10^{-5} to 2.2 x 10^{-4} m s^{-1} (Granier, 1985; Granier et al., 1996). Both the HPV and HD methods require estimating the sap conducting area, A_s. This area will vary with tree species. The sapwood area can be used as a volumetric calibration factor for the heat velocity, V. Only the sapwood conducts water, and the A_s can be estimated from destructive samples from representative trees or vines, which is not a viable option in most cases for valuable trees, from stem cores from a sample of trees or vines to determine the depth to the sap wood and heartwood (nonconductive tissue), or by estimating A_s from the tree or vine circumference, T_{cir}. Granier et al. (1996) estimated A_s as

$$A_s = -0.0039 + \left(0.59\, T_{cir} \right) \tag{3.41}$$

where T_{cir} is in m indicating about 60% of the stem area is effectively conducting transpiration flows.

Transpiration measurements can be utilized directly in a soil water balance (Eq. 3.36a) or indirectly in an index such as the *CWSI* used with infrared thermal crop temperatures (Jackson et al., 1981). Van Bavel (1999) calculated *CWSI* from transpiration measurements as

$$CWSI = 1 - \left(\frac{T_{crop}}{T_{ref}} \right) \tag{3.42}$$

where T_{crop} is the crop transpiration (L $tree^{-1}$) and T_{ref} is "reference" crop transpiration in L $tree^{-1}$ (i.e., $K_s = 1.0$). In applying Eq. 3.42, one could estimate a "conceptual" T_{ref} or actually measure T_{ref} from a known tree or vine or a set of trees or vines known to be "well supplied" with irrigation.

3.3. SUMMARY

Microirrigation scheduling can employ techniques such as a soil water balance or an ET base, soil water sensing, or plant based water sensing that can be successful in most circumstances. However, each technique has limitations in specific situations. Therefore, two or more scheduling methods are recommended to check and verify field techniques, especially when so many field, soil, plant, and irrigation system performance variations are known to exist. One scheduling method can be used for automatically controlling the microirrigation system, but a secondary method should be used to check and validate crop performance periodically. Often, these sophisticated techniques require specialists trained in irrigation scheduling (crop advisors, irrigation auditors, irrigation engineers, etc.). Typically, university extension specialists, other advisory specialists (USDA-NRCS, water districts, etc.), or manufacturers can provide training on irrigation scheduling for microirrigation systems.

LIST OF TERMS AND SYMBOLS

A	irrigated land area, m^2 or ha depending on usage
A_s	sap conducting area, m^2
ASW	available soil water, mm
a	empirical constant, coefficient, or exponent used in several equations
BPI	Bureau of Plant Industry
b	empirical constant, coefficient, or exponent used in several equations
C_3	type of photosynthetic pathway
C_4	type of photosynthetic pathway
CAM	type of photosynthetic pathway
CER	carbon exchange rate
CO_2	carbon dioxide
C_p	specific heat of moist air [1.013 kJ kg^{-1} °C^{-1}]
C_{pw}	specific heat of water [4.186 J g^{-1} °C^{-1}]
Cu	Christiansen uniformity coefficient, 1 to 100
Cu_d	design coefficient of uniformity, 1 to 100
$Cu*$	Warrick's estimate of Cu, 1 to 100
CTV	canopy temperature variation
Cv	coefficient of variation (σ / x; where σ is the sample standard deviation in flowrate), decimal fraction
Cv_h	total coefficient of flow variability due to hydraulic factors, decimal fraction
Cv_m	manufacturing coefficient of variability, decimal fraction
Cv_t	total coefficient of flow variability, decimal fraction
$CWSI$	crop water stress index
dT	temperature increase of heat flow gauges, °C.
D_{ag}	number of days after germination
D_{max}	number of days from germination until maximum effective rooting
DSS	decision support system
Du	field distribution uniformity of the low quartile of emitter flowrates, 1 to 100
$Du*$	Warrick's estimate of Du, 1 to 100
DUL	drained upper limit, m^3 m^{-3}
Dz	deep percolation below crop rootzone, mm
dz	soil profile sampling interval, mm

E	soil water evaporation, mm or mm d^{-1} depending on usage
E_A	$W_f\,(e^o_s - e_a) / \lambda$, mm/d
EFC	effective full cover, percent
Eia	irrigation application efficiency, decimal fraction
E_{pan}	pan evaporation, mm hr^{-1} or mm d^{-1} depending on usage
E_{pe}	evaporation from Piche atmometer, mm d^{-1}
$EPIC$	Erosion Productivity Impact Calculator
ET	evapotranspiration or crop water use, mm or mm d^{-1} depending on usage
ET_o	reference ET for well-watered grass, mm or mm d^{-1} depending on usage
ET_r	alfalfa reference evapotranspiration, mm or mm d^{-1} depending on usage
Eu	design emission uniformity, 1 to 100
e	solution vapor pressure, kPa,
e_a	mean ambient vapor pressure, kPa
e_o	vapor pressure within the soil of a body of free, pure water, kPa
e^0_s	saturated vapor pressure at the mean daily air temperature, kPa
e_s	mean saturated vapor pressure at the daily maximum and minimum air temperature, kPa
$e_o - e_a$	vapor pressure deficit, kPa
FAO	Food and Agriculture Organization of the United Nations
FDR	frequency domain reflectometry
F_t	transpiration flow, g s^{-1}
f_c	fraction of the soil surface covered by vegetation
f_w	fraction of the soil that is wetted
G	soil heat flux into the soil in MJ m^{-2} d^{-1}
GDD	growing degree days in °C-d,
g	acceleration due to gravity, m s^{-2}
H	water potential in energy per unit mass, m
HD	heat dissipation type
HPV	heat pulse velocity type
HSPA Cu	Hawaiian Sugar Planter's Association Cu, 1 to 100
h_c	crop height, m
I	gross irrigation amount, mm
I_F	irrigation frequency, d

I_M	minimum time required to apply an irrigation, d
I_n	net irrigation amount, mm
IRT	infrared thermometers
K	dimensionless temperature term defined in Eq. 3.38
K_c	single crop coefficient used for varied soil water conditions
$K_{c\ ini}$	single crop coefficient for initial crop growth stage period
$K_{c\ dev}$	single crop coefficient for crop development growth stage period
$K_{c\ max}$	maximum crop coefficient following rain or irrigation,
$K_{c\ mid}$	single crop coefficient for mid-season growth stage period
$K_{c\ end}$	single crop coefficient for end of crop growing season
K_{cb}	basal crop coefficient when the soil surface is visually *dry*
$K_{cb\ ini}$	basal crop coefficient for initial crop growth stage period
$K_{cb\ dev}$	basal crop coefficient for crop development growth stage period
$K_{cb\ mid}$	basal crop coefficient for mid-season growth stage period
$K_{cb\ end}$	basal crop coefficient for end of crop growing season
K_e	crop coefficient for a wet soil surface.
$K_{c\ (Tab)}$	tabular value of K_c or K_{cb} from Tab. 3.3 to Tab. 3.5,
K_p	pan coefficient
K_{SAT}	saturated hydraulic conductivity, mm d^{-1}
$K(\theta)$	soil hydraulic conductivity, mm d^{-1}
L	crop growth stage length, d
L_{ini}	crop growth stage length for initial period, d
L_{dev}	crop growth stage length for crop development period, d
L_{mid}	crop growth stage length for mid-season period, d
L_{end}	crop growth stage length for end of season development period, d
LI	actual crop light interception in the field, decimal fraction
LAI	leaf area index
LLE	lower limit of plant extractable soil water, m^3 m^{-3}
MAD	management allowed depletion, decimal fraction or percent
MDS	maximum daily shrinkage of plant trunks and stems or dendrometry
M_w	molecular mass of water (~ 18x10^{-6} m^3 mol^{-1})
m	empirical factor related to the soil water release curve
N	number of emitters per plant

NM	neutron moderation
$NOAA$	National Oceanic and Atmospheric Administration
$NRCS$	USDA Natural Resources Conservation Service
NWS	National Weather Service
n	number of irrigation sets in a field
P	precipitation, mm
PAW	plant available water that can be extracted from the soil, mm
PAW_c	critical plant available water where soil water deficit begins to reduce transpiration, mm
P_b	barometric pressure, kPa
P_{in}	heater power input, W
P_s	water potential, Pa
PSI	plant stress indicators
P_t	turgor pressure, MPa
Q	system flowrate, $m^3\ s^{-1}$
Q_r	radial heat flow, W
Q_{ro}	runoff depth, mm
Q_v	vertical heat flow, W
q_n	minimum observed emitter flow rate, $L\ h^{-1}$
q_m	maximum observed emitter flow rate, $L\ h^{-1}$
$\overline{q}$	average observed emitter flow rate, $L\ h^{-1}$
R	universal gas constant (~ 8.31 $J\ mol^{-1}\ K^{-1}$)
R_f	root depth development factor, decimal fraction
RH	relative humidity, decimal fraction
RH_{mean}	average relative humidity, percent
RH_{min}	mean value for the daily minimum relative humidity during either the mid or end of season growth stage, percent
R_n	net radiation, $MJ\ m^{-2}\ d^{-1}$
R_{nl}	net long-wave radiation, $MJ\ m^{-2}\ d^{-1}$
R_s	solar irradiance, $MJ\ m^{-2}\ d^{-1}$
r_l	leaf resistance, $s\ m^{-1}$
r_a	atmospheric aerodynamic resistance, $s\ m^{-1}$
r_s	bulk surface resistance term, $s\ m^{-1}$

SAR	sodium adsorption ratio
Sc	system capacity, m s^{-1} or mmd^{-1} depending on usage
SDI	subsurface drip irrigation
SFG	steady-state heat flow gauges
SPAC	soil-plant-atmosphere water continuum
T	crop transpiration, mm or mm d^{-1} depending on usage
T_{ma}	mean daily air temperature,°C
T_K	absolute temperature, K
T_a	ambient air temperature,°C
T_c - T_a	canopy minus air temperature difference,°C
T_{cir}	tree or vine circumference, m
T_{crop}	crop transpiration, L $tree^{-1}$
T_d	air dew point temperature, °C
TDR	time domain reflectometry
Tr	maintenance time required for service, h ha^{-1}
T_{ref}	"reference" crop transpiration, L $tree^{-1}$
TT	time-temperature
ΔT	needle temperature difference for sap flow gauge under transpiring conditions, °C
ΔT_m	minimum needle temperature difference for sap flow gauge under non-transpiring conditions, °C
t	time since the rain or irrigation, d
t_d	time it normally takes a certain soil to become visibly dry, d
U	wind speed, m s^{-1}
U_2	mean daily wind speed in m s^{-1} at 2.0 m over grass
U_z	wind speed in m s^{-1} at elevation z
V	sap flow velocity, m s^{-1}
VPD	vapor pressure deficit, kPa
W_f	empirical wind function in MJ m^{-2} d^{-1} kPa^{-1}
x	individual emitter flowrate, L h^{-1}
x_{lq}	mean emitter flowrate for the lowest 25% (low quarter) of emitters, L h^{-1}
$\overline{x}$	mean of "N" samples of emitter flowrates, L h^{-1}
$Z_{\max}$	maximum anticipated rooting depth, m
Z_{min}	minimum root zone depth, m

Z_r	root zone depth, m,
α	albedo, short-wave reflection
Δ	slope of the saturated vapor pressure curve at the mean air temperature in kPa °C^{-1}
ε	long-wave emissivity
γ	psychrometric constant in kPa °C^{-1}
γ*	adjusted psychrometric constant , $\gamma(1 + r_s / r_a)$, kPa °C^{-1}
λ	latent heat of vaporization in MJ kg^{-1}
ρ	density of air, kg m^{-3}
ρ_b	soil bulk density, kg m^{-3}
ρ_w	density of water, Mg m^{-3} or kg m^{-3} depending on usage
θ	soil water content, mm
θ_{FC}	water content at field capacity, m^3 m^{-3}
θ_g	gravimetric water content, kg kg^{-1}
θ_{SATt}	saturated water content, m^3 m^{-3}
θ_v	volumetric water content, m^3 m^{-3}
θ_{WP}.	wilting point, m^3 m^{-3}
θz	soil water content integrated over the root zone depth, mm
ψ	water potential, J kg^{-1} or MPa depending on usage
ψ_l	plant leaf water potential, MPa
ψ_m	soil matric pressure potential, MPa
ψ_o	osmotic potential expressed in energy per unit volume, Pa
ψ_x	plant xylem water potential, MPa
ζ	drainage rate considered negligible, mm d^{-1}

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

4. SALINITY

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4.1. INTRODUCTION

Microirrigation is frequently the irrigation method of choice where irrigation water supplies are limited or water quality is marginal. Excess salinity is the most common cause of degraded irrigation water quality around the world. The discussion in this chapter is focused on fundamentals and strategies to cope with water or soils that are salt-affected when using microirrigation. Throughout the chapter the advantages and disadvantages of microirrigation in dealing with salinity are discussed.

Microirrigation is often used with saline water because of the system's capability of applying small quantities of water frequently to satisfy crop water requirements and maintaining an adequate wetted soil volume at high water content in the crop's root zone. Thus, salt levels only slightly higher than that of the irrigation water can be achieved. This advantage for crop production with microirrigation, however, is an expense for management. If the system is managed to minimize water use, a zone of soluble salts will accumulate at the edge of the soil wetted area. Any event that interrupts the irrigation supply or increases irrigation water requirements beyond anticipated levels may lead to yield loss because of excess salinity. A second potential problem is rainfall. High rainfall may cause salt accumulated near the soil surface to move into the crop root zone. A third concern is the repositioning of crop rows from one growing season to the next. If the crop was planted midway between emitters for the previous crop, germination failures and/or poor plant stands may occur when seeds are placed in the region of the soil with high salt concentration for the next crop.

As discussed elsewhere in this book, microirrigation systems are quite varied in their design and they are used on a variety of crops. These variations require different management strategies for minimizing deleterious effects from salinity. Emitter placement along the soil surface or beneath the surface will result in different patterns of soil salinity. Likewise, tree crops are typically irrigated with multiple emitters or with microsprinklers beneath each tree canopy, which cause different patterns of salinity.

These and similar potential problems can be overcome or prevented with appropriate management. The discussion in this chapter begins with remarks on the fundamentals governing salinity assessment and management. These fundamentals include quantifying salinity, crop salt tolerance, and leaching. Management practices or system design alternatives to alleviate or minimize the impact of salinity follow the discussion on fundamentals.

4.2. QUANTIFYING SALINITY AND SODICITY

4.2.1. Salinity

Salinity is defined as the concentration of salts in soil or water. There are many ways to represent salinity, the choice varies with discipline. Many of these units and appropriate conversion factors are presented to facilitate comparison and an understanding of the various definitions. Concentration *(C)*, the amount of solute per unit volume, is typically reported in SI metric units as moles per cubic meter of solution (mol/m^3), or as grams per cubic meter (g/m^3), or milligrams per liter (mg/L). The units of g/m^3 and mg/L are numerically equivalent to parts per million (ppm). Traditionally, ion concentration has been expressed as milliequivalents per liter of solution (meq/L). Ion concentration expressed in mol/m^3 can be calculated by dividing its concentration in meq/L by the valence of the ion. To convert from mol/m^3 to g/m^3, multiply by the atomic weight of the ion. For example, calcium (atomic weight of 40 g/mol) at a concentration of 10 mol/m^3 would be equivalent to a concentration of 400 g/m^3. Total salt concentration in units of g/m^3 or mg/L is the sum of the concentrations of each ion present. For units of mol/m^3, it is the sum of either the cations or the anions, but not both.

The electrical conductivity *(EC)* of irrigation water *(EC_i)* is often measured to estimate total salt concentration. A nearly linear relationship exists between the concentration of ions in a solution and the ability of that solution to conduct electricity. For convenience, measurements are reported in SI metric units of decisiemens per meter (dS/m), which has replaced the traditional units of millimhos per centimeter (mmhos/cm). The values are equal numerically. The relationship between salt concentration (g/m^3) and electrical conductivity can be approximated by $C = 640\ EC$. The value of 640 is an average value based on many different single salts or a composite of mixed salts. Actual values may range from 600 to 800 (Tanji, 1990).

Soil salinity must be quantified for use in diagnosis and management. The amount of soluble salts in a soil can be determined or estimated by measurements made on water extracted directly from the soil. The most accepted method of measurement is based on soil samples. Although technological advances have been made in the use of electrical field salinity probes and inductive electromagnetic sensors, soil samples are taken to reference or calibrate the measurements. In the laboratory, soil samples are first saturated with pure water, and a water sample is extracted from the soil paste, typically by vacuum. Analyses (e.g., pH, ion composition or electrical conductivity *(EC_e))* are then made on these extracted samples. When a field soil is relatively wet, soil water samples can be extracted directly from the soil by displacement, absorption, compaction, suction, centrifugation, or pressure membrane extraction techniques. Of these methods, only suction is routinely used in the field where soil solution is extracted by vacuum into a porous ceramic cup buried in the soil. This technique works when the soil matric potential is greater than -30 J/kg.

Knowledge of the concentration of the major specific ions in the soil water over the entire range of field water contents is desirable because of their effects on soil properties. At present, however, field methods are capable of measuring only the total solute concentration. Nevertheless, total solute measurements are extremely valuable because most plants respond to the osmotic potential of the solution, which is directly related to the electrical conductivity of the soil solution.

4.2.2. Sodicity

When the concentration of sodium becomes excessive relative to the concentration of calcium plus magnesium, a soil or water is said to be sodic. As the sodium concentration increases, particularly at low levels of salinity, soil mineral particles will swell and disperse causing water movement into and through the soil to decrease. High sodium concentrations reduce infiltration so that the crop is not adequately supplied with water. Furthermore, the reduction in hydraulic conductivity decreases drainage (Oster et al., 1999). Insufficient drainage can lead to other problems such as anoxia or various root diseases. Excess sodium may also add to cropping difficulties through crusting seed beds, temporary saturation of the surface soil, high pH and the increased potential for disease, weeds, soil erosion, lack of oxygen, and inadequate nutrient availability. In contrast, when calcium and magnesium are the predominant cations adsorbed on the soil exchange complex, the soil tends to be easily tilled with a readily permeable granular structure.

The sodium-adsorption-ratio *(SAR)* of irrigation water is generally a good indicator of the sodium status that will occur in the soil. SAR is defined as:

$$SAR = \frac{C_{Na}}{\left(C_{Ca} + C_{Mg}\right)^{1/2}} \qquad (4.1)$$

where the ion concentrations *(C)* are in mol/m^3. *Na, Ca* and *Mg* refer to sodium, calcium and magnesium. If the units are meq/L, the sum of C_{Ca} + C_{Mg} must be divided by two before taking the square root. For most surface waters used for irrigation, Eq. 4.1 is a suitable indicator of sodicity.

Soil physical conditions and the overall sodicity hazard are dependent upon both *SAR* and salinity. High salinity levels reduce swelling and aggregate breakdown or dispersion, promoting water penetration. High proportions of sodium, however, produce the opposite effect. The approximate boundaries where chemical conditions severely reduce infiltration of water into soil, where slight to moderate reductions occur, and where no reduction is expected in most soils are presented in Fig. 4.1. Regardless of the sodium content, water with an electrical conductivity less than about 0.2 dS/m causes degradation of the soil structure, promotes soil crusting, and reduces water penetration. Rainfall and snowmelt are prime examples of low-salinity waters that reduce water penetration into soils. Both the salinity and the sodium-adsorption-ratio of the applied water must be considered when assessing the potential effects of water quality on soil water penetration (Fig. 4.1).

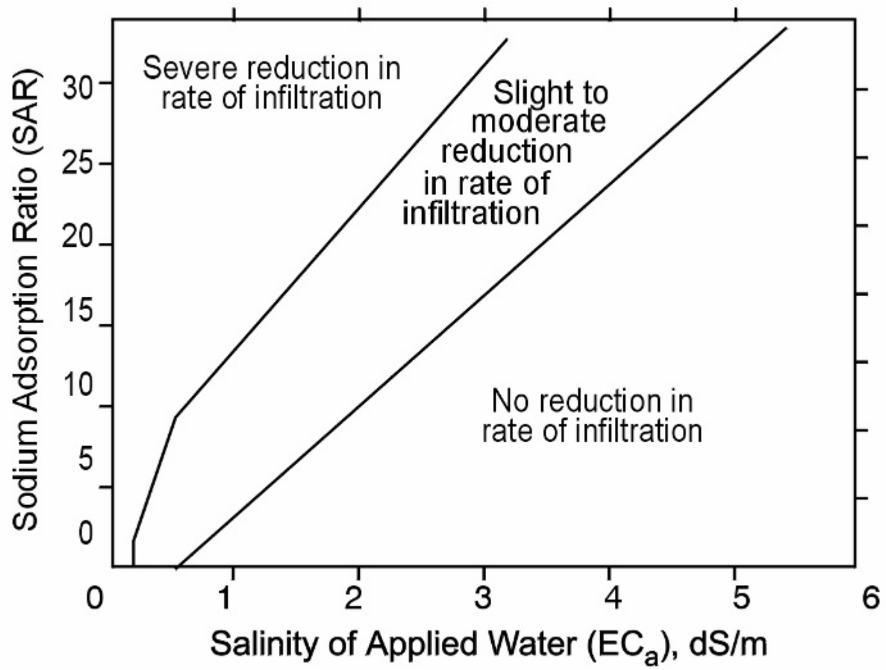

Figure 4.1. Relative rate of water infiltration as affected by salinity and sodium absorption ratio. Adapted from Rhoades, 1977; Oster and Schroer, 1979.

4.3. CROP TOLERANCE

Salt tolerance is generally defined as the degree to which a plant can endure salinity as a stress. The variables associated with this definition include plant species, to a lesser extent the cultivar, salt concentration and composition, and length of exposure to salinity. The site of salt exposure is also a determinant of tolerance. For example, roots are typically the sites of salt exposure in saline soils, but foliage can also be the exposure site when the plant is subjected to salt spray from microsprinklers. Plant exposure to salt may be continuous or intermittent with the plant's response depending on its developmental stage. All of these factors can have significant effects on plant response. Some factors are also strongly dependent upon environmental conditions and other types of stress. Despite the existence of numerous publications on salt tolerance, we still lack a thorough understanding of how plants cope with salinity.

As salinity increases beyond the threshold tolerance value, yield decline is inevitable. Usually at low to moderate salinities, plant growth is reduced with a slight darkening in leaf color. Salt may also influence the rate of plant development by increasing or decreasing the time to crop maturity, depending on crop species and salt concentration (Shannon et al., 1994). In most crops, there may be notable differences in the root/shoot ratio, a response that would not be identifiable in the field. In some crops, salinity changes plant growth habits or increases succulence (Lüttge and Smith, 1984; Shannon et al., 1994). These effects are difficult to detect without comparison with plants grown under identical conditions without salinity. As salt concentrations reach toxic levels, leaves or shoots may exhibit visible symptoms of burning or scorching. Other visible symptoms may be associated with nutrient imbalances caused by competitive interactions between sodium and calcium or potassium, or between chloride and nitrate (Grattan and Grieve, 1992). Interactions between nutrients have also been reported with phosphate, magnesium, and micronutrients, but these observations seem to be specific to certain crops and waters of specific ionic composition.

In the field, the effects of salinity can range from undetectable to total loss of crop. When the soil salinity is minimal or moderate, the plants may appear normal unless they are also grown under nonsaline conditions for comparison. As salinity becomes more severe, plant growth is stunted, leaves may appear darker green or have a blue-green cast, and plants mature earlier. Under severe salinity conditions, bare spots appear in the field and salt may precipitate on the soil surface and in the root zone.

4.3.1. Crop Salt Tolerance

Reliable data to describe salt tolerance can only be obtained from carefully controlled and sufficiently replicated experiments conducted across a range of salinity treatments. Crop yield is the plant component of primary interest (grain, fruit, or biomass). The market acceptability (quality) of the product may also be an important factor. A convenient measure of salinity is the electrical conductivity *(EC)* of a soil or water solution. In field studies, salinity is reported in units of *EC* of a saturated soil paste extract (EC_e) taken from the root zone and averaged over the growing season with depth.

An adequate measure of salt tolerance can be formulated on the basis of a two variable, biphasic model (Maas and Hoffman, 1977). The two variables sought are the crop salt tolerance threshold (*t*) and the slope (*s*) (Fig. 4.2). The crop salt tolerance threshold is the maximum EC_e without significant reduction in yield below a nonsaline control treatment. The threshold is very sensitive to environmental interactions. Its value depends upon both the accuracy of the salinity measurements and the method by which the salinity measurements are integrated over area, depth, and time. Because of this, a high degree of potential error exists in evaluating the slope at salt concentrations near the threshold. Few salinity studies include enough treatments and replications to determine the threshold value precisely. The slope is the percentage of yield decline expected for each unit (EC_e) of soil salinity beyond the threshold value.

Based on this model, the relative yield *(Y)* at any salinity exceeding *t* can be calculated as:

$$Y = 100 - s\left(EC_e - t\right) \tag{4.2}$$

Most crops have a tendency for the slope to "tail-off" at the higher salt concentrations. Salt tolerance at high salinities has little economic importance and measurements made at high salt concentrations may disproportionately skew the salt tolerance curve, which in reality may be curvilinear rather than biphasic. For these reasons, the most reliable value numerically for crop salt tolerance response studies is the value at which yield is reduced by 50 percent (C_{50}). The C_{50}-value may be more informative than the biphasic model when insufficient data are available to provide reliable information on the threshold and slope.

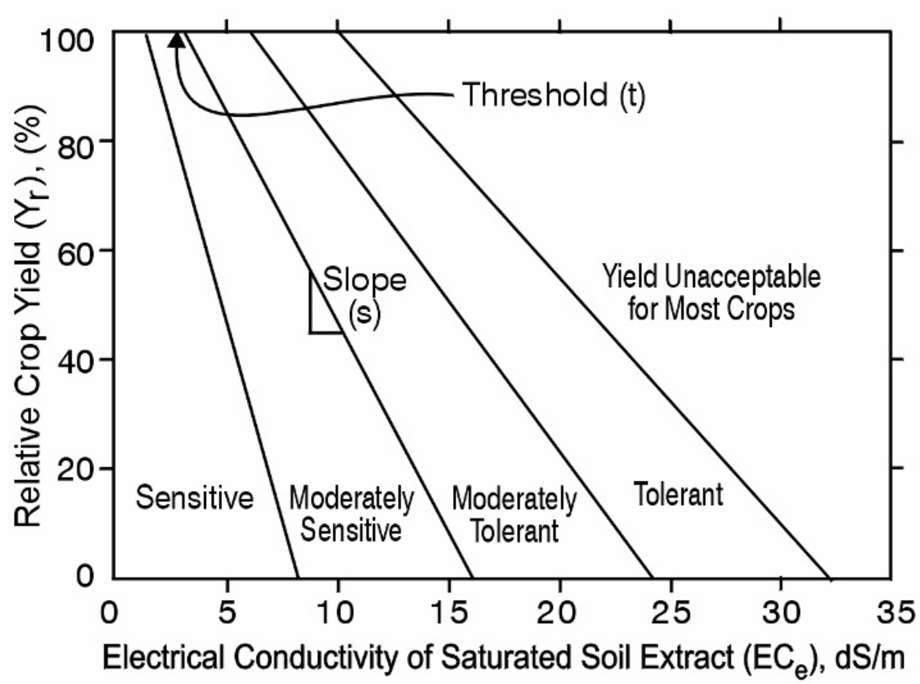

Figure 4.2. Variables in the salt tolerance model and divisions for qualitative ratings for salt tolerance. Adapted from Maas and Hoffman (1977).

Salt tolerance tables have been compiled for 144 crop species, which includes 81 herbaceous crops, 14 woody species and 49 ornamentals (Maas, 1990; Maas and Grattan, 1999). These salt tolerance data are described in terms of yield and soil salinity. A compilation of the salt tolerance for crops commonly irrigated with microirrigation systems is given in Tab. 4.1. While salinity assessments have shown that different crop species vary with respect to *t* and *s* values, reliable genetic screening and selection methods have not been developed to consistently improve crop response and provide more tolerant cultivars. More recently, crop breeding and genetic manipulation using tools such as tissue culture and molecular techniques have been proposed as strategies to deal with excess salinity.

When no direct research exists to determine the *t* and *s* values, crops have been classified with a qualitative scale ranging from sensitive to tolerant (Fig. 4.2) based upon the data available (Francois and Maas, 1994). Salt tolerance values and classifications are extremely useful in predicting the effects of applying a water of a specific salinity on a particular crop. However, a number of mitigating factors may have either positive or negative impacts upon the published salt tolerance values.

Table 4.1. Salt tolerance of crops typically watered by microirrigation. Adapted from Maas and Hoffman (1977).

Crop	Salt tolerance threshold (t)	Percent yield declined (s)	Qualitative salt tolerance rating*
	dS/m	% / (dS/m)	
Almond	1.5	19	S
Apricot	1.6	24	S
Broccoli	2.8	9.2	MS
Cabbage	1.8	9.7	MS
Carrot	1.0	14	S
Corn (grain)	1.7	12	MS
Cotton	7.7	5.2	T
Cucumber	2.5	13	MS
Date palm	4.0	3.6	T
Grape	1.5	9.6	MS
Grapefruit	1.8	16	S
Lettuce	1.9	13	MS
Onion	1.2	16	S
Orange	1.7	16	S
Peach	1.7	21	S
Pepper	1.5	14	MS
Plum	1.5	18	S
Potato	1.7	12	MS
Radish	1.2	13	MS
Strawberry	1.0	33	S
Sugarcane	1.7	5.9	MS
Sweet potato	1.5	11	MS
Tomato	2.5	9.9	MS

* Qualitative salt tolerance ratings are sensitive (S), moderately sensitive (MS), moderately tolerance (MT), and tolerant (T).

4.3.2. Factors Modifying Salt Tolerance

Climate and agricultural management practices may decrease or increase the effects of salinity upon plants. Irrigation management practices that leach salts or maintain lower concentrations of salt in the root zone during growth will reduce detrimental salt effects. Seeding on the slopes of seedbeds or other seed placement techniques that allow the irrigation water to move salts past the seedling root zone improve plant stand or the density of populations. When salt concentrations in the seedbed are not kept low, the resulting reduction in plant stand will decrease yields far more than is predicted by salt tolerance ratings.

Waterlogged soils sometimes accompany salinity in the field and will further exacerbate salinity problems.

Climatic factors such as high temperature, low humidity, high wind speed, and less than optimal light will increase salt damage, whereas factors that reduce transpiration demand will reduce salinity effects. High temperature and low humidity may decrease crop salt tolerance by decreasing the effective threshold value and/or increasing the value of the yield decline slope. Thus, yields will decrease more rapidly with increasing salinity under hot, dry conditions than in a cool, humid environment. Two other environmental factors that can influence the effects of salinity include elevated atmospheric levels of carbon dioxide and ozone. Salinity causes leaf stomata to restrict the volume of air exchanged with the environment. This usually improves plant water use efficiency, but reduces the amount of carbon dioxide that can be taken in and fixed by plant leaves and used for growth. High carbon dioxide concentrations in the air due to the so-called "Greenhouse Effect" may offset the reduction in air exchange. In addition, when pollutants, such as ozone, are present, reductions in air exchange caused by salinity will reduce the volume of pollutants entering the plant, thereby decreasing the adverse effects of ozone (Maas, 1990).

4.3.3. Tolerance to Specific Solutes

Most salt tolerance data collected have been based upon the effects of saline waters containing sodium chloride and calcium chloride and sometimes various amounts of other salt compounds. Many natural waters contain significant amounts of sulfate in addition to chloride. Sulfate salts are typically not as phytotoxic as chloride salts. Thus, plant response to saline waters may be somewhat less than predicted by salt tolerance studies based on only chloride salts. Drainage waters, waters reused from processing or manufacturing operations, or municipal wastes may contain other chemical species, such as boron, selenium, arsenic, heavy metals or other constituents that may be detrimental to plants. Plant species have demonstrated a wide degree of variation in their abilities to accumulate, exclude, or withstand the toxic effects of individual constituents (Flowers and Yeo, 1986; Shannon et al., 1994). Even so, the potential for variability among plant species and cultivars remains as one of the research areas that has not been adequately explored, and will be of increasing importance concomitant with the need to recycle waters for irrigation.

Sodium is known to cause injury in avocado, citrus, grape, and stone fruits at concentrations as low as 5 mol/m^3. High sodium levels have also been shown to cause calcium, potassium, and magnesium deficiencies in plant tissues. Plants generally have some capacity to restrict the uptake of sodium, often between the roots and shoots. This restriction mechanism is 'leaky' and sodium is usually absorbed by the plant in proportion to water transport. Mechanisms exist within trees to sequester sodium in the woody tissues and stems to prevent toxic accumulation in the leaves. When leaf surfaces are wetted by saline irrigation water, sodium may move directly into the leaf, and by-pass the plant's natural sequestration mechanisms. Waxiness usually makes leaves less susceptible to ion accumulation through wetting. Symptoms of sodium toxicity are leaf burn, scorch, or firing. These symptoms are first apparent in older leaves where damage starts at the tips and outer edges and advances inward toward the leaf midrib or towards younger leaves as injury becomes more acute.

Chloride is a major component of most saline soils and waters and can cause toxicity symptoms in sensitive plants (avocado, berry, citrus, grape) at 5 to 10 mol/m^3 based on saturation extracts. Chloride injury results in chlorosis, a yellowing of the leaves that progresses from older to younger leaves. Plants have some capacity to restrict chloride uptake, but less so than sodium.

Boron is an essential micronutrient in plants, but becomes toxic at relatively low concentrations compared with sodium and chloride. The symptoms of boron toxicity are similar to those of chloride, a yellowing or browning of tips and margins of older leaves. Some species, such as eucalyptus, develop interveinal spots as well (Poss et al., 1999). Boron damaged areas typically appear drier than chloride damaged leaf areas. Sensitive crops include citrus, cherry, berry, and grape (0.5 mg/L in saturation extract). More tolerant crops include asparagus and onion (10 mg/L).

Tables describing the tolerance of crops to chloride and boron are available (Maas, 1990). The impact of sodium, selenium, heavy metals, and other contaminants has been studied, but the literature is sparse and only a few crops tested. Some contaminants, such as sodium, reduce crop productivity, whereas selenium that concentrates through the food chain can become toxic to animals.

4.4. LEACHING

Most irrigation waters do not contain enough salt to cause immediate injury to crops using microirrigation. However, the concentration of soluble salts in the soil increases as water is removed by evaporation and transpiration. These processes leave salts behind in the soil. Without leaching (drainage), salt accumulates in the soil with each successive irrigation event. The accumulation of soluble salts in the soil can be controlled by applying irrigation amounts in excess of that needed for evapotranspiration. The portion of the applied water that drains below the crop root zone is termed the leaching fraction *(L)*. Applied water in this context is the amount of irrigation water and precipitation that infiltrates into the soil.

Soil water must leach through the root zone to prevent dissolved salts from increasing to concentrations detrimental to crop production. All soils have a capacity to drain provided a downward hydraulic gradient exists and hydraulic conductivity of the soil is reasonable. Natural drainage in many instances is sufficient to leach salts from the root zone. Soils of fine texture, soils with compacted layers, or soils with layers of low hydraulic conductivity may be so restrictive to downward water movement that the natural drainage capacity is insufficient to provide adequate leaching. In some situations, the hydrogeology may be such that the hydraulic gradient is predominately upward, leading to waterlogging and salination.

When natural drainage is inadequate and a shallow water table is formed, an artificial drainage system will be required to sustain crop productivity. Before installing an artificial drainage system, the natural drainage capacity should be determined. If after applying excess water, the hydraulic gradient and the soil's hydraulic conductivity permit soil water to drain through the root zone, a less extensive artificial system may be required. Alternatively, upward flow from a shallow water table into the root zone can intensify the need for artificial drainage. With either natural or artificial drainage, the water leached below the root zone must go elsewhere. It may take decades or as little as a season for productivity to be reduced, depending on the hydrogeology of the area. Without adequate drainage to an appropriate outlet, agricultural productivity cannot be sustained.

4.4.1. Leaching Requirement

The amount of irrigation water needed to satisfy the crop's water and leaching requirements can be estimated from water and salt balances within the root zone. The major flows of water into the root zone are irrigation, rainfall, and any upward flow from groundwater. Water flows out by evaporation, transpiration, and drainage. Under steady state conditions, the changes in soil water content and salt storage are assumed to be zero. When the total water inflow is less than the evaporation plus transpiration, stored water is extracted by the crop from the root zone and drainage is reduced. With time, the difference between inflows and outflows becomes zero. This results in insufficient downward flow so that salt accumulates and crop growth is eventually suppressed.

In the presence of a shallow water table, deficiencies in irrigation and rainfall amounts may be offset by upward flow from groundwater, but upward flow of soil water can carry salts into the root zone. When upward flow continues and leaching is not adequate, soil salinity will ultimately reduce crop growth and water consumption. Some moderately salt-sensitive crops have been grown successfully in the presence of a saline, shallow water table. Over the long-term, however, a net downward flow of water is required to control salination and sustain crop productivity.

Conditions controlling the water that flows into and out of the root zone rarely prevail long enough for a true steady state to exist. However, it is instructive to consider a simple form of the steady-state equation to understand the relationship between drainage and salinity. The simplified steady-state equation is based upon a number of assumptions and generalizations. First, the upward movement of salt is assumed to be negligible. Second, there is no change in salt storage. Third, the quantities of salt dissolved from soil minerals plus salt added as fertilizer or amendments is essentially equal to the sum of precipitated salts plus salt removed in the harvested crop. Under these conditions, the leaching fraction *(L)* can be represented by:

$$L = \frac{D_d}{D_a} = \frac{C_a}{C_d} = \frac{EC_a}{EC_d} \tag{4.3}$$

where D is depth of water, C is salt concentration, EC is electrical conductivity, and the subscripts d and a designate drainage and applied water (irrigation plus rainfall). This equation applies only to salt constituents that remain dissolved. The conceptual value of this equation is greater than its prediction value for drainage amount or salt concentration because the relationship between the leaching fraction and root-zone salinity is extremely complex.

The minimum leaching fraction that a crop can endure without yield reduction is designated as the leaching requirement (L_r). Several models have been proposed to estimate the crop's leaching requirement. Hoffman and van Genuchten (1983) determined the linearly averaged, mean root zone salinity by solving the continuity equation for one-dimensional vertical flow of water through soil, assuming an exponential soil water uptake function (Raats, 1974). The resulting linearly averaged salt concentration of the root zone given as the concentration of the saturated extract (C_e) is given by Hoffman and van Genuchten (1983). Plants adjust osmotically as soil salinity increases (Maas and Nieman, 1978). Furthermore, salt-tolerance trials are usually designed to maintain leaching fractions of about 0.5. Thus, the osmotic adjustment consistent with no loss of yield can be estimated by the mean soil salinity at 50% leaching. As a first approximation, the leaching requirement can be expressed as a function of the crop salt tolerance threshold value by reducing C_e at any given L by C_e at 50% leaching. Figure 4.3 illustrates this relationship among the salinity of the applied water, the salt-tolerance threshold of the crop, and the leaching requirement. Hoffman (1985) compared calculated leaching requirements from this and other models with experimental results. Of the four models tested, the results of the model depicted in Fig. 4.3 agree well with the measured values throughout the range of L_r of agricultural interest.

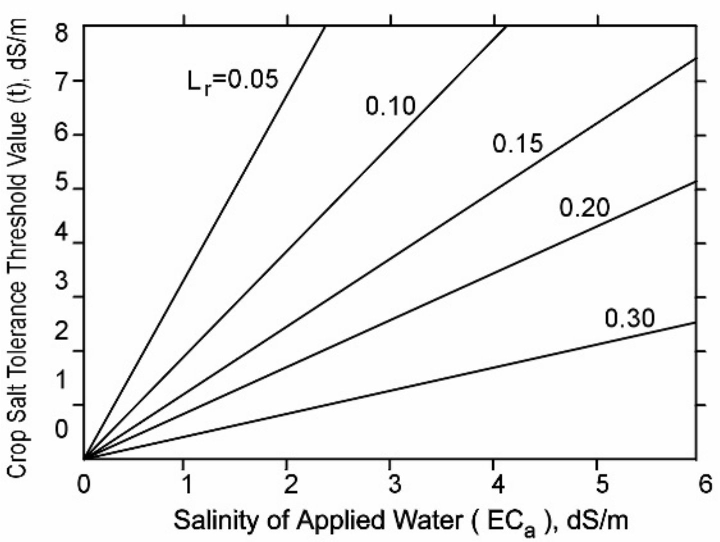

Figure 4.3. Leaching requirement (L_r) as a function of salinity of the applied water and the salt tolerance threshold value for the crop. Adapted from Hoffman and van Genuchten (1983).

The following example illustrates the procedure for estimating the leaching requirement. Assume tomatoes are to be grown in an arid region and irrigated by water with an EC_i of 3 dS/m. The salt-tolerance threshold, *t,* of tomato is 2.5 dS/m. If rainfall is insignificant compared with irrigation and there is no upward flow from a shallow water table, the leaching requirement can be determined directly from Fig. 4.3. In this case, the leaching requirement equals 0.2. To calculate the salinity of the applied water when rainfall is significant, the following equation is useful:

$$C_a = (C_r D_r + C_i D_i)/(D_r + D_i) \tag{4.4}$$

The variable C is salt concentration and D is depth of water. The subscripts *a, r,* and *i,* indicate applied, rain, and irrigation water, respectively. An iterative process must be used to determine L_r because D_i is unknown until L_r is known. As an illustration, assume that the equivalent depth of evaporation and transpiration, D_e+D_t, is 750 mm and rainfall, D_r, is 150 mm. Begin calculations by assuming that D_i is 900 mm and $C_r = 0$. Then, $C_a = C_iD_i/(D_r + D_i) = 3(900)/(150 + 900) = 2.6$ dS/m. With $C_a = 2.6$, L_r for tomato is 0.18 and $D_i = D_e + D_t + D_d = 750 + 0.18\ D_i$. Thus, D_i is 915 mm. This value of D_i is sufficiently close to the assumed value of 900 mm that further iterations are unnecessary.

Accounting for nonuniformity of irrigations in estimating L_r has not been addressed to date. When the leaching requirement is not satisfied, saline soil will develop. With many irrigation systems, one must evaluate whether to apply copious amounts of water to assure that the leaching requirement is met throughout the field or to accept some reduction in yield in parts of the field rather than over irrigate most of the field. Extensive advancements in irrigation technology and management are needed to achieve the goal the leaching requirement precisely. Present irrigation practices are frequently inefficient and inadvertently provide excessive leaching. This is costly, leading to a waste of water, energy, and nutrients, and increasing the need for drainage. Consequently, knowing the leaching requirements of crops and striving to attain them with properly designed and managed irrigation systems is vital. Nevertheless, under the best conditions at present, some excess irrigation water is generally applied to achieve maximum yield. This is less of a problem with well-managed microirrigation because of the inherit capability of the system to apply the desired amount throughout the field.

4.4.2. Impact of Rainfall

Salt movement into the root zone because of rainfall is a concern with microirrigation where salinity is dominant. Salts applied in the irrigation water move with the soil water and accumulate at the periphery of the wetted zone. Accumulations are high midway between water applicators and can be particularly high near the soil surface. Rainwater moving into and through the soil can carry soluble salts back into the crop root zone.

A frequent recommendation to prevent salinity damage from rainfall is to turn on the microirrigation system whenever rain may move salts into the root zone. For example, in Southern California, Valencia orange trees irrigated by a subsurface drip irrigation system with Colorado River water having an electrical conductivity of 1.3 dS/m (800 mg/L of total dissolved salts), were protected during the rainy winter season by irrigating when the soil matric potential dropped to -20 J/kg at a soil depth of 25 cm. Of the annual total of 670 mm of irrigation water, 170 mm was applied during the winter to protect the trees (Nelson and Davis, 1974). In San Diego County, California, the recommended practice for avocado orchards irrigated with Colorado River water is to continue microirrigation in the fall until at least 50 mm of rainfall has occurred over a period of less than 14 days (Oster et al., 1984).

Although these practices for tree crops in Southern California are apparently satisfactory, few studies have been made to quantify how far soluble salts move as a function of the amount of rainfall, or how much, if any, irrigation water must be applied to prevent yield loss, or what are the consequences to yield when irrigation water is not applied. In an attempt to answer some of these questions, a field experiment was conducted to determine whether changes in soil salinity as a consequence of rainfall two to three weeks before harvest influenced lettuce yield (Hoffman et al., 1985). Lettuce was chosen because it is sensitive to soil salinity similar to most tree crops (see Tab. 4.1) and is an important crop grown during the winter when rainfall can be a problem in Mediterranean-type climates. The experiment was conducted in

12 field plots where soil salinity patterns were well established over a period of eight years by a traveling drip system that applied line sources of water. The pattern of soil salinity for the three leaching treatments (0.05, 0.15, and 0.25) before and after a 3-cm depth of rain is illustrated in Fig. 4.4. The patterns of salt accumulation are typical of a line source system, with a pocket of accumulation near the soil surface midway between the water sources and relatively uniform concentrations below a soil depth of 60 cm. This relatively shallow root zone was created by managing the irrigation volume so that the volume of water passing below the 60-cm depth was equivalent to the desired drainage rate. Although the influence of rainfall on soil salinity below 60 cm was negligible, the impact was dramatic near the soil surface (Fig. 4.4). Midway between rows, chloride concentrations were reduced by more than 90% at the soil surface for the 5% leaching treatment compared with a two-thirds reduction for 25% leaching. Even directly beneath the water source, chloride was reduced by two-thirds near the soil surface for all leaching treatments. Chloride, however, did not accumulate in any significant quantities except in the 5 to 20 cm depth interval midway between the rows. With this exception, chloride concentrations above a depth of 90 cm increased very slightly or were reduced.

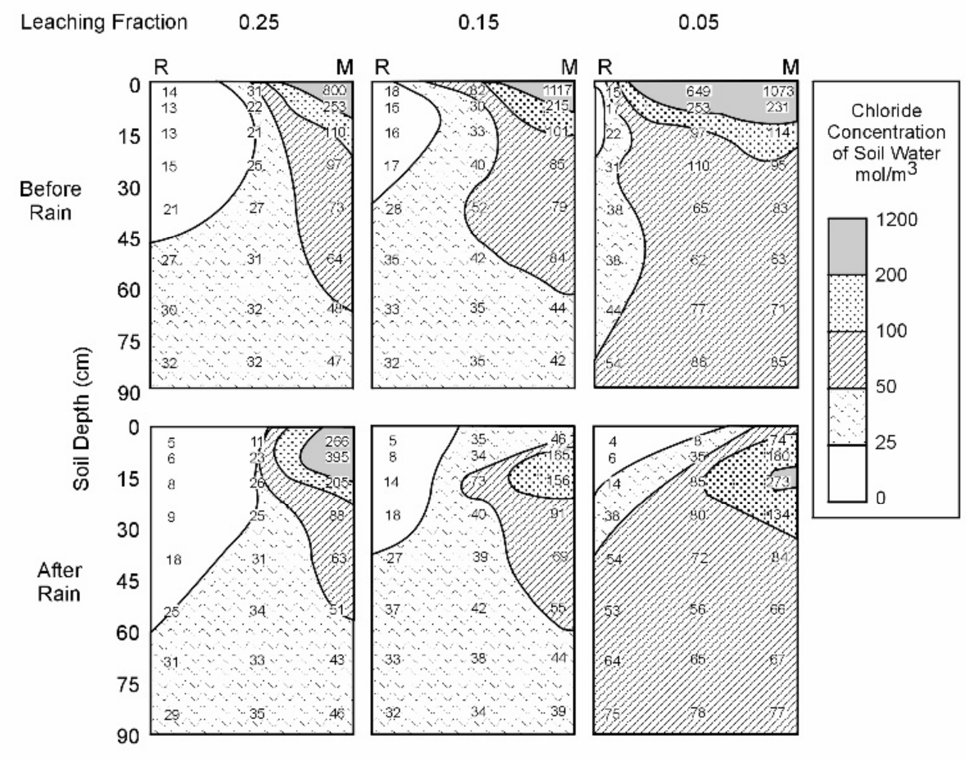

Figure 4.4. Distribution of chloride in the soil water before and after a rainfall depth of 3 cm for three leaching fractions. The notation R indicates plant row and microirrigation source and M denotes midway between the microirrigation sources. Adapted from Hoffman et al. (1985).

For all three leaching treatments, large quantities of chloride were leached below the root zone or were diluted in the increased volume of water stored in the soil profile because of the 3-cm rainfall. Even with the high levels of chloride near the soil surface in the 5% leaching treatment before the rain, the increased soil water content and continued leaching resulted in minor changes in the patterns of soil salinity. Changes in salt concentration had no influence on lettuce yield.

4.5. INFLUENCES OF IRRIGATION SYSTEM AND WATER SOURCE ON SOIL SALINITY

Microirrigation has several advantages compared with alternative irrigation methods when the irrigation water is saline. Except for low growing crops irrigated with microsprinklers or sprayers, microirrigation avoids wetting of the leaves with saline water. Because microirrigation is normally applied frequently, there is a continuous leaching of the soil volume from which the plant extracts water. Leaching can also be provided intermittently, between growing seasons, and by seasonal rainfall when soil salinity in the root zone is maintained below detrimental levels.

Traditionally, the goal of irrigated crop production has been to maximize yield. To maximize yields, salinity must be controlled at low levels by leaching. Management goals to alleviate excess salinity are mediated by costs of water, drainage, and amendments to soils and waters. When water quality is impaired, quantity is limited, or drainage is restricted, the hazardous effects of salinity on crop growth and dangers of either insufficient or excessive leaching are serious concerns. However, crops can be grown successfully with saline waters provided suitable irrigation and cropping strategies are practiced (Rhoades, 1988). Precise management and methods are required for water application and distribution when the salinity hazard is great. Water requirements needed for crop use and leaching should be accurately assessed and provided in a timely manner. Crop water requirements have been developed for nonsaline situations (Erie et al., 1982). With saline water, growth and consumptive water use may be reduced. However, preliminary evidence indicates that some crop water coefficients may be applicable over a range of salinities because the water unused by the crop is available to offset the increase in the leaching requirement (Letey and Dinar, 1986).

Crop water production functions relating yield to irrigation application in saline situations are needed to develop optimum irrigation management strategies. Simulated functions have only been developed for a limited number of crops (Letey and Dinar, 1986). The greater the salinity of the irrigation water, the greater is the need for adequate irrigation and drainage. Computer simulation models have been developed based upon the available data to serve as management and decision-support tools. Two approaches are available for predicting water uptake/use/depletion in the presence of salinity. One approach is mechanistic based on the physics of water transfer through soil and roots (Nimah and Hanks, 1973). Another is an empirical approach based upon crop behavior as expressed by a set of values related to *t* and *s* (van Genuchten, 1987). The mechanistic model has the potential of predicting salinity effects for different environments. Cardon and Letey (1992a, 1992b) found that salinity dependent reductions in water uptake calculated using the mechanistic model were too low, whereas their empirical model conformed more closely to experimental data. Another model, that still needs to be validated with field data, showed that osmotic potential alone could not explain reduced growth in lysimeter-grown wheat and sorghum unless the effects of salinity on root permeability were taken into consideration (Majeed et al., 1994). Other soil-water-plant models have been useful for the evaluation of management strategies in which two or more waters with different qualities are available for irrigations, for example, Childs and Hanks (1975) and Wagenet and Hutson (1987).

4.5.1. Influence of Irrigation Method

The distribution pattern of soil salinity depends on the variability of soil properties, differences in water management, and the design of the irrigation system. The soil salinity profile that develops as water is transpired or evaporated depends, in part, on the water distribution pattern specific for the irrigation method. Distinctly different salinity profiles develop for different irrigation methods. Each irrigation method (flood, furrow, sprinkler, and microirrigation) has its own advantages and disadvantages for salinity management.

Field flooding in most instances is a very inefficient system because of inadequate surface leveling and should not be used where salinity is a problem. Flooding within borders usually results in excessive water penetration near the border levees, at the inlet end, and at the lower end of the strips. When surface drainage is prevented, and there is inadequate water penetration midway down the strip, detrimental salt accumulation may occur. Similarly, when insufficient amounts of water are supplied at one end of a basin, the far end may have excessive salt accumulation. The basin method has the potential for more uniform water applications than other flooding methods provided the irrigation flowrate is adequate and the basins are leveled, sized properly, and have uniform soils.

With furrow irrigation, salts tend to accumulate in the seedbeds because leaching occurs primarily below the wetted furrows. When the surface soil is mixed between successive crops and the irrigation water is not too saline, the increase in salt over several growing seasons may not be serious. When excess salt accumulates and rainfall is inadequate to provide leaching, another irrigation method may be required or the application of special agronomic techniques (e.g., planting on the side slopes of the beds, planting in the furrows, etc.) can be helpful. In furrow and flood methods, the length of the area irrigated, irrigation application rate, soil characteristics, slope of the land, and time of application are the factors that govern the depth and uniformity of application. Proper balance among these factors is beneficial for controlling salinity.

Sprinkler irrigation unavoidably causes wetting of the crop foliage unless below-canopy sprinkling is possible. Microsprinklers and spray jets may also wet low-structured crop canopies. Salts can be absorbed directly into wetted leaves. Thus, some crops experience foliar injury and yield reductions that may not occur when systems that do not wet the foliage are used with the same water (Maas, 1985). In tree and vine crops, sprinkling below the canopy can minimize the extent that leaves are wetted. However, even with under-canopy sprinklers, severe damage of the lower leaves can occur (Harding et al., 1958). The extent of foliar injury depends upon the concentration of salt in the leaves, frequency of irrigation, weather conditions, and water stress. For example, salt concentrations that cause severe leaf injury and necrosis after a day or two of hot, dry weather may not cause any problems when the weather is cool and humid. Because foliar injury is related more to frequency of sprinkling than the duration, infrequent, heavy irrigations should be applied rather than frequent, light irrigations (Francois and Clark, 1979). Slowly rotating sprinklers that allow drying between cycles should be avoided because this increases the wetting-drying frequency. Sprinkling should be done at night or in the early morning when evaporation is lowest. Approximate concentrations of chloride and sodium in sprinkled waters that cause foliar injury for some crops are listed in Tab. 4.2.

Flooding and sprinkler irrigation systems that wet the entire soil surface create a profile that at steady state increases salinity with soil depth to the bottom of the root zone, when moderate leaching is applied, application is uniform, and no shallow, saline groundwater is present. A typical soil salinity profile for sprinkling is illustrated in Fig 4.5. When irrigations are infrequent, the salt concentration in the soil solution increases with time between irrigations, particularly near the soil surface. In the presence of a shallow, saline water table and, particularly, with inappropriate irrigation management techniques, salts will accumulate near the soil surface. Frequently, this situation leads to a severe salinity problem.

Table 4.2. Relative susceptibility of crops to foliar injury from saline sprinkling water. After Maas (1990).

Na or Cl concentrations (mol/m^3) causing foliar injury			
<5	5 - 10	10 - 20	>20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugarbeet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

Microirrigation systems that apply water from point sources have the advantage of providing high leaching near the emitters. Also, high soil water contents at salinity levels approximating the irrigation water can be maintained in the root zone by frequent small water applications. Plant roots tend to proliferate in the leached zone of high soil water content near the water sources. This allows water of relatively high salt content to be used successfully in many cases. Fine soil textures that restrict water movement, the redistribution of water required to germinate seeds, and the accumulation of salts at the soil surface between emitters are management concerns.

The salinity profile under line water sources on the soil surface, such as furrows and either porous or closely spaced, multi-emitter microirrigation systems, has lateral and downward components (Fig. 4.5). The typical cross-sectional profile has an isolated pocket of accumulated salts at the soil surface midway between the line sources of water and a second, deep zone of accumulation, with the concentration depending on the amount of leaching. A leached zone occurs directly beneath the line source. Its size depends on the irrigation rate, the amount and frequency of irrigations, and the crop's water extraction pattern.

The distribution from point irrigation sources, such as micro-basins and drip systems with widely spaced emitters, increases radially from the water source in all directions below the soil surface (Fig. 4.5), whereas the salt distribution from line sources increases laterally and downward. As the rate of water application increases, the shape of the salinity distribution changes. The mathematical model of Bresler (1975) predicts that the salinity distribution in uniform, isotropic sand changes from elliptical with the maximum movement vertical to a more circular form as the rate of water movement decreases. In isotropic and layered soils, the horizontal rate of water movement is greater than the vertical, resulting in relatively shallow salt accumulations. For tree crops irrigated with several drip emitters per tree, the wetting patterns may overlap, thereby reducing the level of salt accumulation midway between the emitters under the tree.

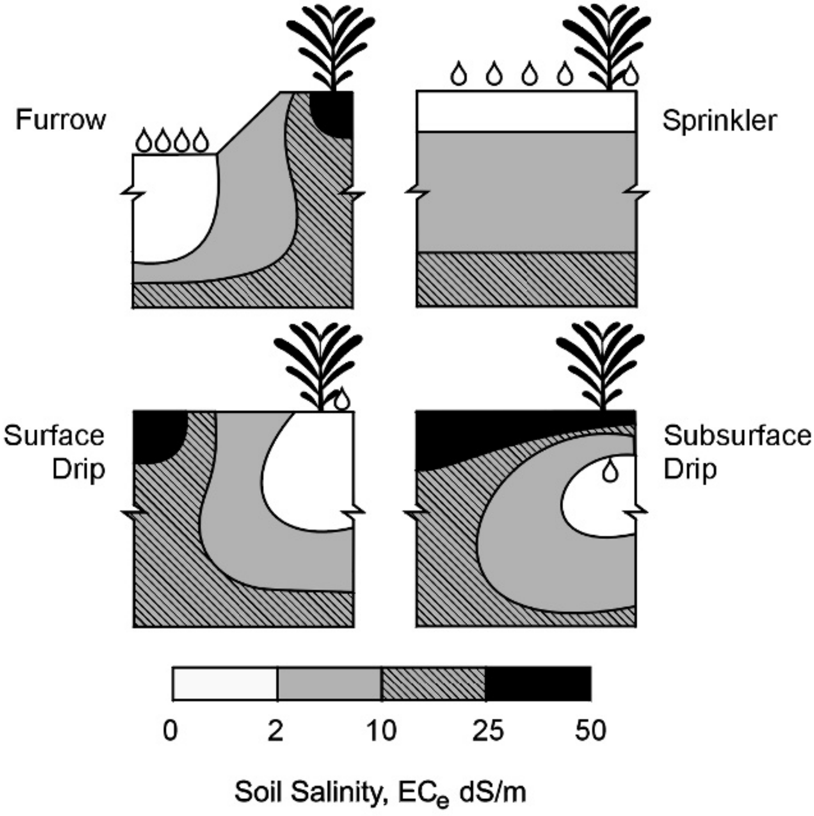

Figure 4.5. Influence of irrigation method on the distribution of salinity within the soil profile.

The continuous upward water movement from a subsurface microirrigation system results in salt accumulation near the soil surface as water is lost by evapotranspiration. Subsurface microirrigation systems provide no means of leaching these shallow accumulations. Where salinity is a hazard, leaching of these shallow accumulations of salt may be required from rainfall or another irrigation method.

4.5.2. Reuse and Conjunctive Use of Waters

Various strategies for using waters of different salinities have been proposed. It has been demonstrated that cycling waters of different qualities can be successful for irrigating crops during different growth stages or used in crop rotations with salt tolerant and sensitive crops (Rhoades, 1987; 1990). The feasibility for using high quality water with saline water depends on both supply and availability of mixing and delivery systems. When nonsaline waters are available for irrigations during critical crop growth stages, growers can take advantage of the fact that many crops are most salt-sensitive during the seedling stage and much more tolerant during later growth stages.

Plant salt tolerance varies with phenological growth stage so that irrigation can be managed to circumvent salt damage. For example, providing high quality water or minimizing salt accumulation by increasing irrigation frequency can reduce salinity effects at salt-sensitive growth stages. For some crops, saline water applied during the later stages of development will improve yield quality by increasing the content of sugars or soluble solids in the fruit. The timely application of saline water during fruit development has been used as a strategy to improve sugar content in melons or soluble solid content in tomatoes (Shannon and Francois, 1978). In response to some moderate levels of salt and drought stress, fruit trees sometime exhibit significant increase in fruit set and yield, but usually at a cost in subsequent years due to reduced biomass production. Other disadvantages of irrigating with saline water may be the delaying of crop maturity, decreased shipping quality, or reduced product shelf life. Francois and Clark (1980) delayed fruit maturation in ‘Valencia’ oranges by increasing salt stress without affecting fruit quality. Their results also indicated that salinity had no effect on total soluble solids (TSS), but Bielorai and colleagues (1988) found slight increases in TSS and sugar content of ‘Shamouti’ oranges when the chloride concentration of the irrigation water was 450 mg L^{-1}. In general, the literature is inconsistent on this subject and the effects of salinity on TSS and sugar content in citrus fruit appears inconclusive (Maas, 1993).

4.5.2.1. Reuse

Agricultural drainage water or other saline water sources can be safely reused when the characteristics of the water, soil, and crop are known and can be properly managed. Growers must have access to a wide range of management tools and technologies, and be more attentive of changing crop conditions when using saline water. Poor quality irrigation water requires the selection of salt-tolerant crops, improvements in water management, and maintenance of soil structure and permeability (tilth, hydraulic conductivity). When sensitive crop growth stages are excluded, the mean salinity averaged over time is a good measure to equate against the salt tolerance tables; and, the arithmetic mean salinity within the rooting depth integrated over the time of exposure is an effective approximation for estimating crop response.

One of the purposes of microirrigation is to increase the efficiency of water application, and thus to minimize runoff. Microirrigation reduces the need for water reuse, (e.g., tail water collection). However, the need for leaching to control salination may result in the requirement to collect, contain, and reuse drainage water. In addition, drainage water could be available for reuse from rainfall/runoff events or from nearby, less efficient, irrigation systems. When drainage water is mixed with surface water sources, the practice is termed “conjunctive use.”

High concentrations of specific constituents can be a major degradation factor when using drainage waters for irrigation. Waters with low concentrations of many constituents provide plants with many of the essential nutrients needed for growth. However, as salinity increases, a constituent may become toxic or interfere with the uptake of other nutrients. In soils, the accumulation of ions increases the osmotic potential against which plants extract water. It can also degrade soil structure. To establish the maximum benefit from degraded water and to help dispose of drainage waters, strategies for water reuse have evolved. Water reuse must be balanced against both short- and long-term needs, with consideration for both local and off-site effects. Water reuse for agricultural crops has distinct economic incentives with a number of crops known to be highly tolerant to salinity. However, as salinity increases in the irrigation water, there is a greater need to manage carefully irrigation and drainage practices and monitor a number of factors that must be considered to assure sustainability of the system. In some instances, hydrogeological conditions prohibit suitable leaching and groundwater pumps are used to lower water tables. Application of pumped groundwater in conjunction with surface-supplied irrigation water has been accepted as the most economical and environmentally acceptable means of reusing drainage water provided that the groundwater is sufficiently low in total salinity and toxic ions. This strategy can potentially increase groundwater salinity over time. The long-term sustainability of a conjunctive use surface or subsurface irrigation system will depend upon land and groundwater management on a regional scale; and at the local level, on groundwater pumping depth and water distribution (Prendergast et al., 1994).

4.5.2.2. Blending

Blending is the process of mixing two or more water sources before irrigation. Unless the water sources have low salt concentrations, blending saline water with high quality water is usually not a recommended alternative (Rhoades, 1989; 1990). An exception may be when saline water is needed to blend with high quality water to maintain soil permeability.

4.5.2.3. Cycling

Cyclic use involves alternate irrigations from two or more water sources. High and low quality water may be alternately used as the crop matures to avoid salt-sensitive growth stages, or simply to reduce the time weighted average salinity in the root zone. For cyclic use strategies, factors that should be considered include the effects of changes in salinity during the growing season, the average salinity distribution in the root zone, the interactions with climatic variables, and the effects of different soil types. After crop establishment, the salinity in the root zone averaged over time and soil profile depth may be considered as the effective salinity exposure (Shalhevet, 1994). This means that in most cases, once crops are established, there probably will be little measurable difference in a field situation as a result of applying 4 and 10 dS/m water in alternate irrigations applied over a crop cycle versus using a water of 7 dS/m in each irrigation event. This is the result of compensating factors in both soils and plants. Research efforts are underway to determine whether certain advantages can be obtained by either the application of high quality water during sensitive growth stages or the use of low quality water immediately prior to or during reproductive stages. To date, this technology has been developed for only a limited number of situations.

4.5.3. Environmental Consequences

In irrigated agriculture, salinity becomes a problem in two major ways. First, salt is imported with the irrigation water. Second, during the normal dissolution processes that occur in the soil, salt concentration increases, and its composition changes. As soil water evaporates and plants transpire water, salts are concentrated in soils, often with detrimental effects on both soils and crops. The total amount of salt imported through irrigation is often not fully comprehended. By using Colorado River water at Parker Dam, Arizona as an example, the salinity of the water is about 1 dS/m or about 640 mg/L. To irrigate citrus, an annual consumptive water use is about 1 m, with water containing 6.4 Mg/ha of salt. This does not take into account the additional water needed for leaching, dissolution of salts that are present in the soil, and fertilizer additions.

The build-up of salts in the root zone results in yield loss and, possibly, the breakdown of soil structure. The field solution to the problem is to leach the salt from the root zone, a process that requires adequate drainage and the use of even more water to meet the leaching requirement.

When saline drainage water is collected in evaporation ponds, its constituents, especially heavy metals, can accumulate to toxic levels. Trace elements are a concern because they are toxic at very low concentrations. Some elements, such as selenium are bioconcentrated in the food chain becoming more toxic in organic forms.

4.6. SALINITY MANAGEMENT PRACTICES

4.6.1. Soil Salinity Distribution

The distribution of soil salinity under tree crops with microirrigation can be complex because of enlargement of the crop root zone with time and the addition of emitters as the trees grow. An example of this complexity has been reported by Nightingale et al. (1991). Their study was conducted to determine the impact of the volume of saline water applied to almond trees with a microirrigation system and the amount and distribution of the components of soil salinity. Irrigation water with an electrical conductivity of 1.5 dS/m was applied to provide 50, 100, and 150% of the crop's computed evapotranspiration to prevent water stress. As frequently done commercially, emitters were added to the system as the trees grew beginning with drippers close to the trunk when the trees were first planted. The emitter pattern shown in Fig. 4.6 was used for four years (1984-87) prior to the soil salinity values reported here. The components of the irrigation water of greatest concern were boron, sodium and chloride with concentrations of 0.87, 191, and 118 mg/L, respectively. Irrigation amounts for the third year were 14.0, 26.9, and 40.3 m^3/tree or depths equivalent to 377, 723, and 1083 mm. Rainfall during the irrigation season was negligible.

The average distributions of chloride, sodium, and boron through the soil profile to a depth of 1.5 m are given in Fig. 4.7. Values are reported from directly beneath the drip irrigation lateral out perpendicular for a distance of 1.6 m. The leaching requirement for almond with this water is 0.17 (Hoffman et al., 1990). Thus, the salt distributions for 50% ET indicate concentrations when irrigation is inadequate to prevent salt damage. Based on chloride concentrations, the leaching fraction was 0.05. The leaching fraction for the 100% ET treatment water applications was calculated to be 0.13. Chloride concentrations for the 100%

ET treatment are high because the leaching requirement was not met. The calculated leaching fraction was 0.34 for the 150% ET treatment, and therefore, water applications were more than adequate to prevent salinity damage to the almond trees.

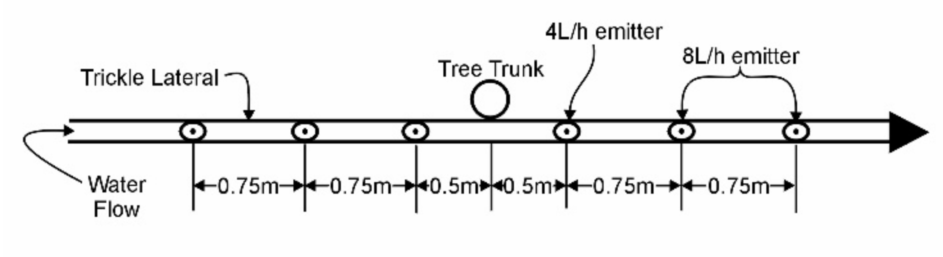

Figure 4.6. Location of the microirrigation emitters in relationship to an almond tree for the results shown in Fig. 4.7. Adapted from Nightingale et al. (1991).

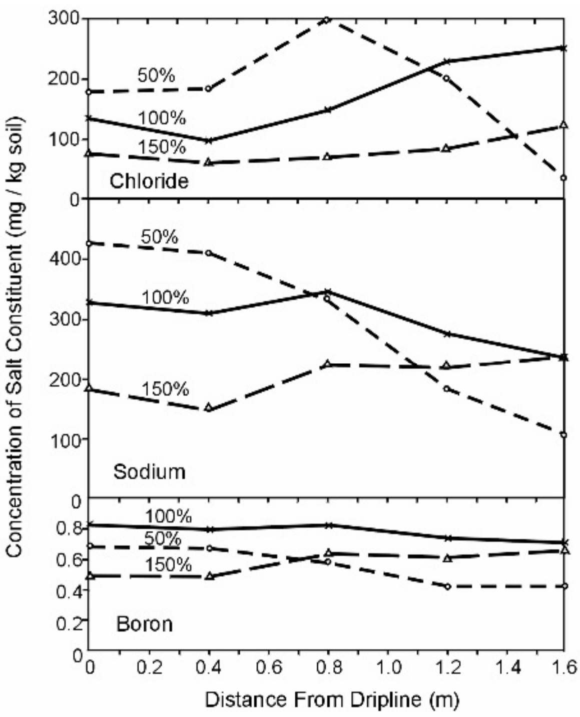

Figure 4.7. Concentration of chloride, sodium, and boron in the soil profile of an almond orchard as a function of distances perpendicular to a linear array of microirrigation emitters as shown in Fig. 4.6 as a percentage of the calculated evapotranspiration. Adapted from Nightingale et al. (1991).

4.6.2. Crop Considerations

Agromanagement techniques that minimize or prevent salinity effects include leaching, deep plowing, amendment and fertilizer applications, drainage, field-leveling operations, and irrigation technologies. Other management options include the use of drip or sprinkler irrigation to improve water application efficiency and alterations in seed bed formation and seed placement to avoid salts accumulated near the soil surface (Rhoades, 1993). Some strategies that have not been adequately researched involve manipulation of population densities to improve plant stand and application of nonsaline or more saline water dependent upon variable salt tolerance with growth stage.

4.6.2.1. Crop selection

Crop species differ in salt tolerance as a result of their genetic composition. Differences in salt tolerances within cultivars of a crop species are smaller than differences among species. Thus, crop substitution, or the replacement of salt-sensitive crops with more tolerant ones, has been practiced from the dawn of irrigated agriculture and is still probably one of the easiest and most practiced strategies for dealing with salinity. When high-quality waters are unavailable for irrigation and leaching, control of high salinity in soils traditionally has been through crop substitution and agromanagement. Thus, barley may be substituted for wheat, cotton for corn, sugar beet for lettuce, etc. Unfortunately, high-valued vegetable crops grown under microirrigation, generally are more salt sensitive than most field crops. Also, harvest quality usually has a more dramatic impact on marketable yields of horticultural crops than field crops.

4.6.2.2. Other management techniques

A number of cultivation and management methods are available and can offset yield loss when saline water is used for crop production. Some simple methods include using more vigorous cultivars, using screening processes to select seed of larger size and higher seed weight, increasing population densities to offset smaller plant size, and reductions in tiller number, and placing seed on sloped or modified seed beds so that salts drawn to the surface by evaporation accumulate away from the seeds. Another method of ameliorating the effects of irrigating with moderately saline drainage water is to reduce fertilizer applications in concert with the nutrient composition of the water and soils. Because recycled waters often contain some nutrients, the amount of applied fertilizers can be reduced. On the other hand, because ion interaction and competition reactions affect plant nutrient uptake, additions of calcium, potassium or some other element may be required for improving crop growth depending on the composition of reused waters.

4.6.3. Infiltration

The infiltration of water into the soil is essential for good crop production. Under irrigated conditions, soils can become less permeable when soil aggregate stability is disrupted by sodicity. Soil clay minerals that are expandable consist of stacked platelet-like structures with negative charges that attract cations. The strength of the electrical charges of the cations associated with the platelets is responsible for the separation between the platelets such that the further the separation, the more ‘swelling’ occurs. As soils swell, they become less permeable to water. Sodium ions are less strongly attracted to clays than calcium. The loose association of sodium ions for the clay platelet causes the platelets to separate further, and thus, more swelling occurs as sodium replaces calcium in the soil. As the platelets are forced apart, water flows into the spaces and pushes the platelets further apart, resulting in dispersion of the platelets. The dispersed clay platelets can block soil pores, further reducing infiltration.

Water with low salinity can move into the interplatelet space more easily than high salinity water. Thus, in sodic clay soils, rainfall can result in swelling and dispersion and, consequently, poor infiltration. At any given salinity, infiltration will decrease as SAR increases. However at any SAR value, infiltration will increase as salinity increases (Fig. 4.1).

An example of this problem has been observed on the east side of the San Joaquin Valley of California. When a vineyard was converted from furrow irrigation to an in-line emitter system placed above the soil on the trellis supporting the vines, the plants wilted. The soil had a relatively low infiltration rate because of the soil texture. Under furrow irrigation, enough of the soil surface was wetted during an irrigation to accommodate sufficient water infiltrating to satisfy crop water requirements. The microirrigation system did not wet sufficient soil volume and the infiltration rate of the smaller soil surface area did not satisfy crop water requirements.

4.6.4. Reclamation of Salt-Affected Soils

Soils may be naturally saline or become salinized because of irrigation mismanagement or inadequate drainage. Such soils require reclamation before irrigated agriculture can be profitable. Leaching is the only proven method of reclaiming salt-affected soils. Sodic soils normally require the addition of an amendment or tillage or both to promote the leaching process. Soils high in boron are particularly difficult to reclaim because of the tenacity by which boron is held in the soil. Growing very salt tolerant plants during the reclamation process can accelerate leaching. The addition of root channels and crop residue enhances water movement through the soil profile and thereby aids leaching. Reclaiming saline soils by harvesting plants with the salts they have taken up is not practical. Similarly, flushing water over the soil surface to remove visible crusts of salt is not effective. Adequate drainage and suitable disposal of the leaching water are absolute prerequisites for reclamation.

4.6.4.1. Saline soils

The amount of water required for salt removal from a saline soil depends on the initial level of salinity, soil physical characteristics, technique of applying water, and soil water content. Leaching by continuous flooding is the fastest method, but it requires larger quantities of water than leaching by sprinkler or by intermittent flooding. Intermittent flooding or sprinkling, though slower, is more efficient and will require less water, than continuous ponding, particularly on finer textured soils

The relationship between the ratio of the remaining concentration *(C)* to the initial salt concentration (C_o) and the ratio of the depth of water leaching though the profile (d_L) to the total depth of soil to be reclaimed (d_S), when water is ponded continuously on the soil surface can be described by

$$K = (C/C_O) \bullet (d_L/d_S) \tag{4.5}$$

where K is a constant that depends on soil type. Equation 4.5 defines the curves in Fig. 4.8 for organic (peat) soils when K = 0.45, for fine textured (clay loam) soils when K = 0.3, and for course textured (sandy loam) soils when K = 0.1. Equation 4.5 is valid when *(d_L/d_S)* exceeds K. The results of nine field leaching experiments are summarized in Fig. 4.8 (Hoffman, 1986).

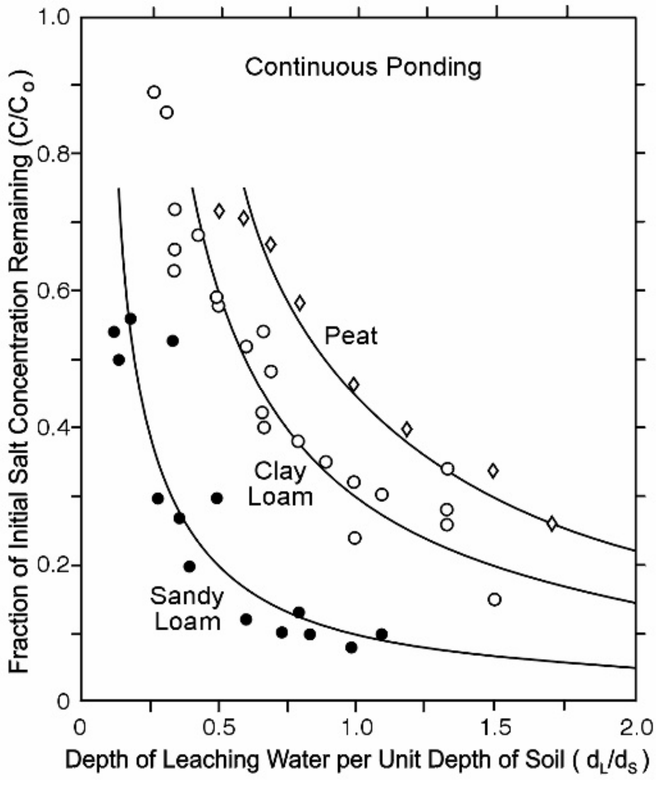

Figure 4.8. Relationship between the fraction of the initial level of soil salinity remaining and the depth of the leaching water applied by continuous ponding per unit depth of soil for three soil types. Adapted from Hoffman (1980).

The amount of water required for leaching soluble salts can be reduced by intermittent applications of ponded water or by sprinkling, particularly for fine textured soils. The results of three leaching trials by intermittent ponding where no water table was present are summarized in Fig. 4.9. Agreement among experiments is excellent considering the variety of soil textures and the depth of water applied each cycle (50 to 150 mm) with corresponding ponding intervals varying from weekly to monthly. In the case of intermittent ponding, K in Eq. 4.5 is approximately 0.1 for all soil types. For fine textured soils, only about one-third as much water is required with intermittent ponding than continuous ponding to remove about 70% of the soluble salts initially present.

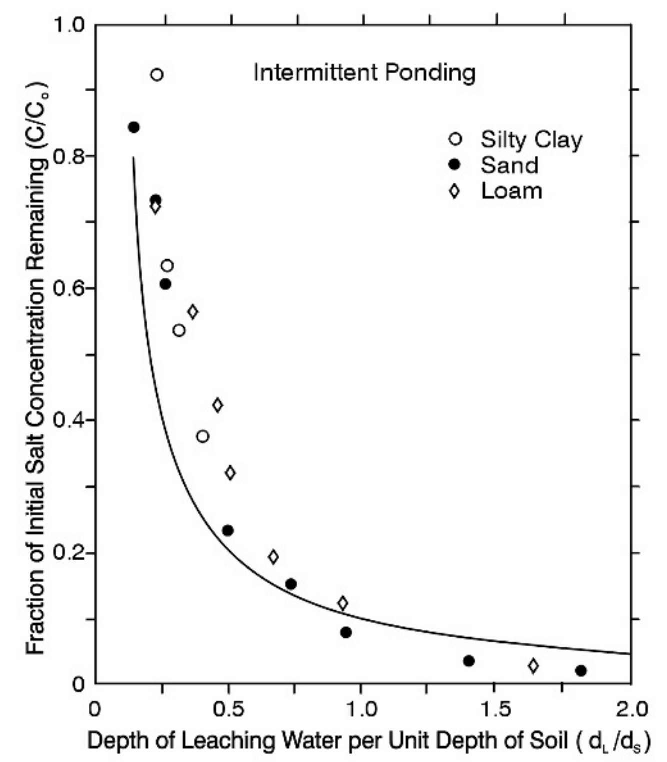

Figure 4.9. Relationship between the fraction of the initial level of soil salinity remaining and the depth of the leaching water applied by intermittent ponding per unit depth of soil Adapted from Hoffman (1980).

Reclamation by flooding may be relatively inefficient when tile or open drains are present. Most of the leaching water flow will take place through the soil near the drains, whereas leaching midway between the drains is low. The regions between drains should be leached by basins separated from the regions above the drains. Alternatively, leaching with sprinklers should improve efficiency (Luthin et al., 1969).

4.6.4.2. Sodic soils

The reclamation of sodic soils is very difficult, if not impossible, without the use of chemical amendments to replace exchangeable sodium in the soil with calcium. Properties of typical amendments are given in Tab. 4.3. In a calcareous soil, (a soil containing lime), the addition of acids or acid forming materials may dissolve sufficient lime to provide exchangeable calcium. Gypsum, however, is the preferred additive because of its low cost, good solubility, and availability.

Table 4.3. Chemical properties of various amendments for reclaiming sodic soil. (adapted from Hoffman and Shalhavet, (in press)).

Amendment	Chemical composition	Physical description	Solubility in cold water (Kg/m^3)	Amount equivalent to 1 Kg of 100% gypsum (Kg)
Gypsum	$CaSO_4 \cdot 2H_2O$	White mineral	2.4	1.0
Sulfur	S_8	Yellow solid/powder	0	0.2
Sulfuric acid	H_2SO_4	Corrosive liquid	Very high	0.6
Lime sulfur	9% Ca+24% S	Yellow-brown solution	Very high	0.8
Calcium carbonate	$CaCO_3$	White mineral	0.014	0.6
Calcium chloride	$CaCl_2 \cdot 2H_2O$	White salt	977	0.9
Ferrous sulfate	$FeSO4 \cdot 7H_2O$	Blue-green salt	156	1.6
Pyrite	FeS_2	Yellow-black mineral	0.005	0.5
Ferric sulfate	$Fe_2(SO_4) \cdot 9H_2O$	Yellow-brown salt	4400	0.6
Aluminum sulfate	$Al_2(SO_4)_3 \cdot 18H_2O$	Corrosive granules	869	1.3

The gypsum requirement *(GR)* to reclaim a sodic soil depends on the amount of exchangeable sodium (Na) to be replaced by calcium. This can be calculated from the relationship

$$GR = 0.86 d_s \rho_b \bullet (CEC) \bullet (E_{Na_i} - E_{NA_f}) \tag{4.6}$$

where d_S is the depth of soil to be reclaimed (m); ρ_b is the soil bulk density (Mg/m^3); *CEC* is the cation exchange capacity of the soil (mol/kg*);* E_{Na_i} and E_{Na_f} are the initial and desired final exchangeable sodium fractions (Keren and Miyamoto, 1990). According to this equation, about 10 Mg/ha of gypsum will replace 30 mol/kg of Na to a depth of 0.3 m for a soil having a bulk density of 1.32 Mg/m^3. Typically, a 1-cm depth of water per hectare will dissolve about 0.25 Mg of gypsum. Thus, a 40-cm depth of water will be required to reclaim the soil in the preceding example to a depth of 30 cm. It is difficult to reclaim a deep sodic soil profile in a single leaching operation. The usual procedure is to partially reclaim the soil during the first year, then plant a shallow-rooted crop and continue the reclamation process in the succeeding years until the profile is reclaimed (Keren and Miyamoto, 1990).

When a soil is both saline and sodic, the initial removal of salts may create sodic conditions and reduce soil permeability. The equivalent dilution method, which is based on the principle that divalent cations tend to replace monovalent cations on the exchange complex as a result of the dilution of the soil solution, was proposed to overcome this problem (Reeve and Doering, 1966). In this method, waters of high salt content are used to leach the excess sodium. Subsequent applications are made with higher quality waters to leach the salts.

4.6.4.3. Boron leaching

As with other salts, excess boron must be removed. More water is needed to leach boron than other salts because it is tightly adsorbed on soil particles. In a procedure similar to leaching soluble salts, the relationship between (C/C_o) and (d_L/d_S) for boron can be approximated by using K=0.6 in Eq. 4.5. Furthermore, periodic leachings may be required to remove additional boron released over time from the soil particles (Oster et al., 1984).

4.7. SUMMARY AND CONCLUSIONS

The principles that govern the impact of salt-degraded waters and soils on crop productivity are reviewed. A more detailed coverage of the topic is presented by Tanji (1990). The type of irrigation system does not impact the principles. There are, however, a number of design and management aspects with microirrigation that are unique. Many of these aspects are presented in this chapter.

One of the most important advantages of microirrigation is in dealing with hazardous salinity conditions. Microirrigation can be used to apply frequent, small amounts of irrigation to match evapotranspiration and leaching requirement. However, as this matching of water input and requirement is achieved, any misjudgment or system failure that occurs can initiate a relatively rapid response to crop salt stress. This occurs because of the lack of a soil water reservoir to compensate for inadequate water applications.

Notwithstanding this concern, microirrigation affords the opportunity to use more saline water than perhaps possible with other irrigation methods. This is possible because of the continuous maintenance of roots with an optimal soil water content zone that is relatively stable in size. Thus, roots do not experience fluctuations of wet and dry conditions or low and high salt concentrations.

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Microirrigation for Crop Production
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5. General System Design Principles

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5.1. OVERVIEW OF THE DESIGN PROCESS

Microirrigation systems are designed to transport water from a source through a delivery network of pipes and emission water devices to a crop. The general goal of a microirrigation system design is to provide irrigation water uniformly and efficiently to a crop to help meet the evapotranspiration needs and to maintain a favorable root zone water balance. Associated goals are to increase fruit or fiber production or to maintain plant visual quality. Other water delivery goals may be to protect plants and/or fruits and flowers from extreme temperature conditions (hot or cold), to apply crop or soil chemicals (fertilizers, pesticides, etc.), or to dispose wastewater, which can be an important resource. Thus, the ultimate design will vary from one system to another. System goals need to be established with defined objectives, system constraints, and a desired set of outcomes to be used as a common theme throughout the design process. This will help with the selection and placement of specific components, sizing and layout of the distribution system, and the development of appropriate operational guidelines and procedures. It is assumed that the reader has some background in fluid dynamics and an understanding of irrigation systems. Therefore, most of the discussion will focus on the design processes specifically related to microirrigation systems in terms of sources of water, system hydraulics, and microirrigation components.

5.1.1. Initial Assessment

The water delivery system must provide water to the crop in a timely, efficient, and economical manner. Several constraints and system characteristics influence this process and can be grouped into the following categories and related characteristics:

- Land / Field - The total irrigated area; field shape(s) and dimensions; slope(s); and soil profile characteristics of texture, porosity, water holding capacity, and depth.
- Crop(s) - Type of crop(s), evapotranspiration requirements, growth and development characteristics; and cultural characteristics (spacing/orientation, tillage, and field structural characteristics such as bedding, plastic mulch, trellises, etc.)
- Water Source - Available quantity (flow and volume) and timeliness, quality (pH, EC, Fe, S, Mg, Ca, Na, algae or other suspended solids, etc.), and physical location with respect to the irrigated area.

System properties in the preceding categories are assessed and then used to determine crop water requirements, the capacity of the soil to retain and release water for the crop, and the number and size of the irrigated zones. One or more constraints may exist within the preceding characteristics that may limit the "size" of the overall system. Thus, a preliminary analysis is performed using a mass balance approach.

$$(Q_{sys})(T_c)=(2.778)(A)(I_{gr}) \tag{5.1}$$

[Note: Constants, such as 2.778 in Eq. 5.1 are specific to the unit of the variables as listed and used in that equation].

The product of the design irrigation system volumetric flowrate (Q_{sys}, L/s) and the system operating time per irrigation cycle (T_c, h) is balanced with the irrigated area (A, ha) and the gross irrigation depth per irrigation cycle (I_{gr}, mm). Gross irrigation depth needs to include the net irrigation depth, additional water for leaching (if necessary), and water to compensate for transmission and application efficiency losses. One or more of the mass balance parameters may be fixed with a maximum and/or minimum value while others may be desired estimates. For example, the water supply may be limited in flowrate capacity (Q_{sys}) or total volume per irrigation event ($Q_{sys} \bullet T_c$). With that information the other values of Eq. 5.1 will need to be adjusted to maintain a mass (volume) balance. Examples 5.1 and 5.2 demonstrate Eq. 5.1.

Example 5.1.

A 25-ha irrigated crop is to have a gross daily water application depth of 6.0 mm. The water is to be applied to the crop in a 7.0 h time period. What is the required system flowrate?

Equation 5.1 is rearranged to solve for Q_{sys} using the known parameters of:

T_c = 7.0 h; A = 25 ha; and I_{gr} = 6.0 mm.

$$Q_{sys} = \frac{(2.778)(25\,ha)(6\,mm)}{7.0\,hr} = 59.5\,\frac{L}{s}$$

Therefore, the required system flowrate is 59.5 L/s.

Example 5.2.

A water supply has a peak available flowrate of 30.0 L/s. How much area can be irrigated daily if the maximum daily operating time for the irrigation system is 16.0 h and the gross peak daily irrigation depth is 8.0 mm?

Equation 5.1 is rearranged to solve for A using the known parameters of:

Q_{sys} = 30.0 L/s; T_c = 16.0 h; and I_{gr} = 8.0 mm.

$$A = \frac{(30\,L/s)(16.0\,h)}{(2.778)(8\,mm)} = 21.6\,ha$$

Therefore, the maximum area is: A = 21.6 ha that can be irrigated daily.

5.1.2. Microirrigation Layout and Components

A sketch of an example microirrigation system field layout with three zones is shown in Fig. 5.1. In this example, the water supply and control head (see Fig. 5.2) are located in the center of the field. Many other arrangements and locations are possible. The control head will generally contain the pump station and associated controls, system valves, pressure gauges, and water treatment equipment (filters and chemical injection systems). If the water source contains large particles or sand, an initial screening or sand separator filter may be included. Flowmeters and pressure gauges are very important for general system management and to assess whether line breaks or clogging have occurred. In addition, multiple pressure gauges are often used to monitor pressure drops across chemical injection stations and filtration systems (Fig. 5.2). Backflow prevention systems are needed when chemicals are injected into the irrigation system. Local laws and regulations regarding chemigation and backflow prevention requirements should be followed. The mainline pipes extend from the control head to the zone stations that may include pressure regulators along with manual or automatic control valves.

Water flows from the zone station into a manifold (Fig. 5.3) and then into one or more lateral lines through a header pipe and connection. Depending on field slopes and pipe system designs, some header assemblies will require individual pressure regulation. A wide range of assemblies and connection systems are available. A more detailed discussion on the hydraulics and design of these pipe networks is presented in Section 5.3 of this chapter.

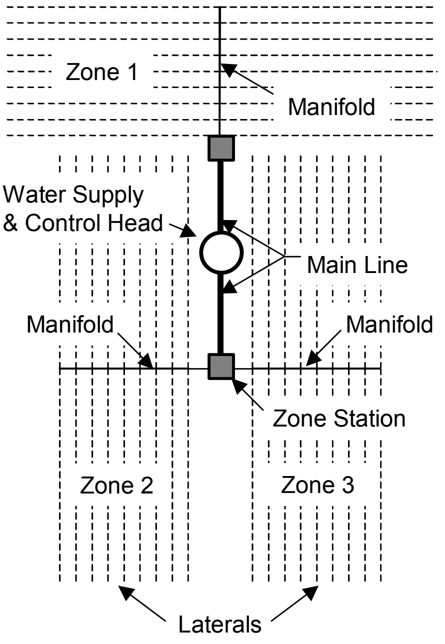
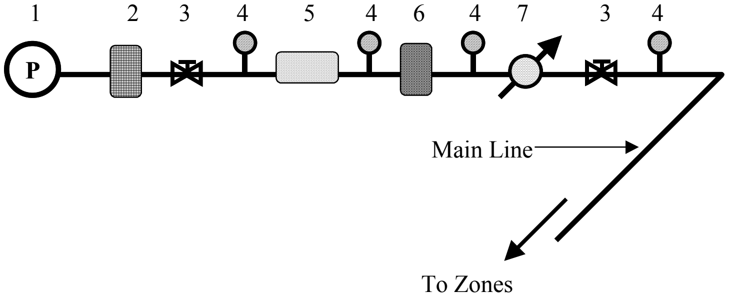


Figure 5.1. General field layout of a microirrigation system with three field zones.



1. Pump or Pressurized Water Supply
2. Initial Filter for Large Particles & Sand (if needed)
3. Flow Control Valve
4. Pressure Gauge
5. Chemical Injection Station – Backflow Prevention
6. Main Filter Station
7. Flowmeter

Figure 5.2. Example arrangement of the water supply and control head for a microirrigation system.

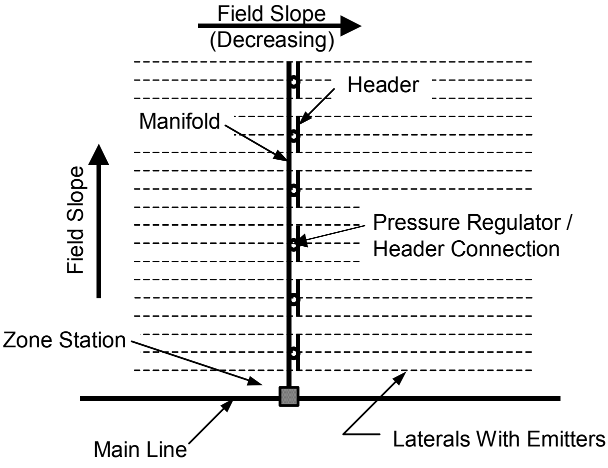


Figure 5.3. Example layout of a microirrigation zone. In this case, the supply manifold is positioned slightly upslope from the field center to create shorter upslope lateral line runs.

5.1.3. The Design Process

Because the design process can produce several system arrangements and outcomes, it is difficult to describe it with a single set of rules. Using the available data, the designer will need to develop one or more acceptable starting scenarios. The initial steps of the design process are outlined below and in the associated flow chart shown in Fig. 5.4.

Preliminary Steps of the Microirrigation System Design Process:

1. Meet with the site owner/operator to assess the desired outcomes and uses of the irrigation system.
2. Assess the general site characteristics with particular reference to the general landscape, irrigated field, crop(s), and water supply.
3. Develop an initial “rough draft” of design scenarios based on the results of Step 2 and a mass balance analysis (Eq. 5.1). Determine a desired pump location if one does not currently exist. If the entire field does not need to be irrigated simultaneously, divide the field into an appropriate number of zones. Position lateral lines along the contour or other desired orientation, and layout manifold and mainline pipes.
4. Assess the physical, economical, and cultural constraints associated with the water supply, the field, and production system. Evaluate the rough draft scenarios based on that assessment.
5. If more information is needed, go back to Step 1 and reassess the site characteristics.
6. If one or more rough draft scenarios are reasonable and/or acceptable, proceed to Step 8. For example, draft scenarios may differ based upon the sizes and shapes of zones, or lateral line lengths and orientation.

7. If the current system scenario can be modified to accommodate the additional constraints, return to Step 1. If not, proceed to Step 10.
8. Present and thoroughly explain the rough draft design scenario(s) to the owner/operator.
9. If any of the proposed design scenarios are acceptable to the owner/operator proceed to Step 11.
10. If other microirrigation system scenarios exist proceed back to Step 1 to reassess the site and system characteristics. If not, then stop.
11. Continue with the formal design process.

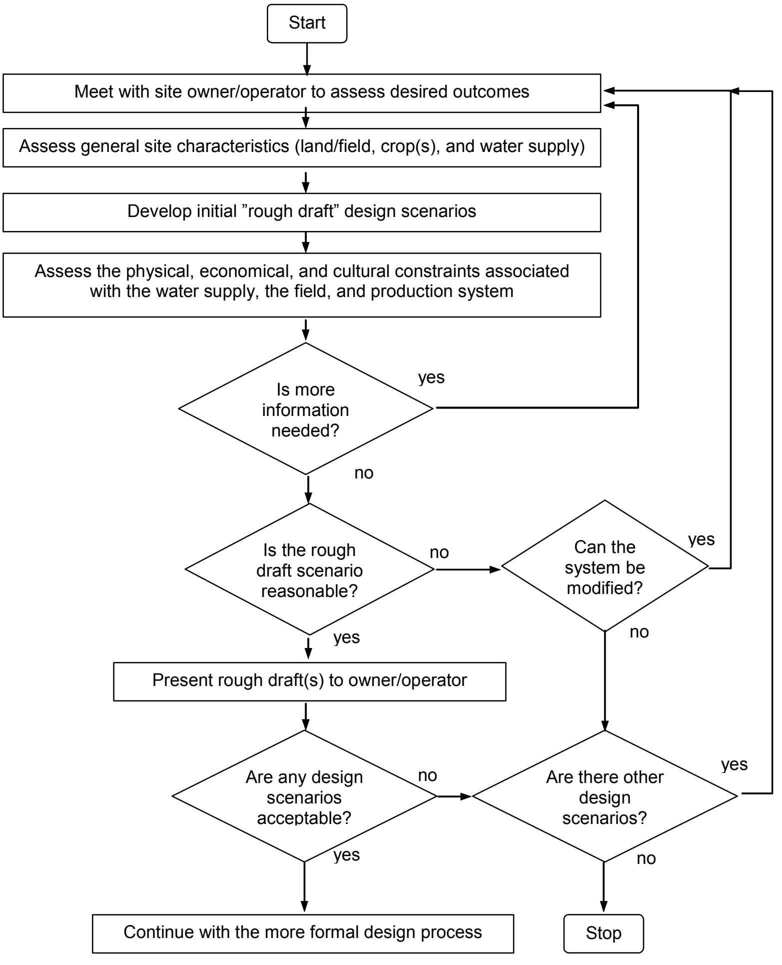


Figure 5.4. Flow chart describing the initial steps of the design process. Courtesy of Kansas State University.

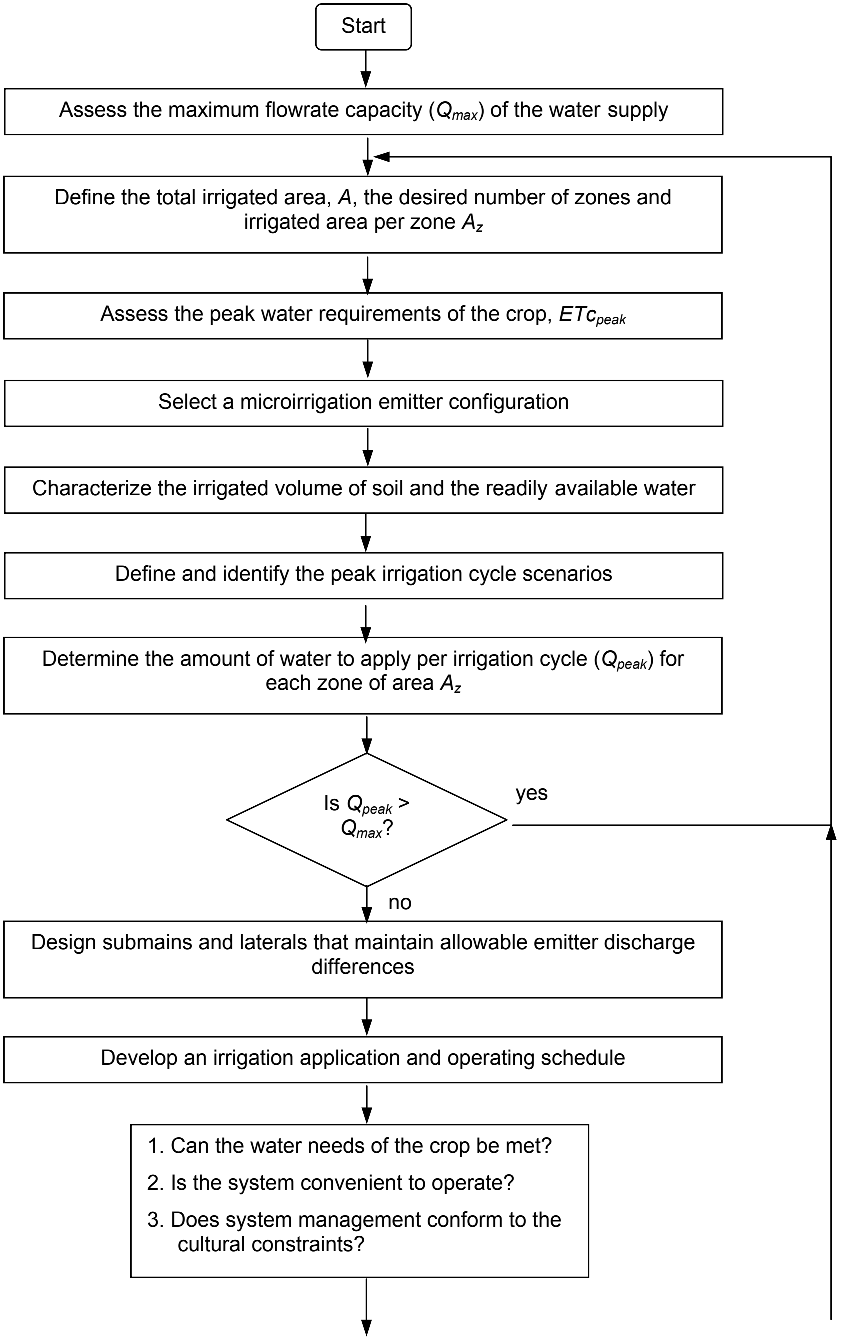
The next stage of the design process focuses on sizing, selecting, and synthesizing the individual components into a working system that satisfies the constraints of the problem, addresses the established objectives, and meets the desired goal. This part of the process mixes artful creativity with the designer's knowledge of the system hydraulics, the characteristics of the microirrigation emitters, and biological and physical aspects of the production system. An outline of the next series of steps in the design process is provided and is associated with the flow chart (Fig. 5.5).

Steps for the General Microirrigation System Design Process

1. Assess and quantify the maximum flowrate capacity (Q_{max}) of the water supply system.
2. Define the total irrigated area, A, the desired number of zones, and the irrigated area per zone A_z.
3. Assess and quantify the daily peak water requirements of the most water demanding crop, ETc_{peak}, and the net daily irrigation requirement. Some systems may be used for multiple crops and should be designed for the crop with the highest peak demand.
4. Select a microirrigation emitter configuration with respect to the type of emission device (dripper, spray jet, bubbler, etc.) and emission device spacing that economically conforms to the cropping and production system constraints. Refer to Chapters 12, 13, 14, and 15 for details with respect to specific system applications.
5. Characterize the irrigated volume of soil based upon the emitter water distribution characteristics. Then, determine the amount of water that would be readily available at the desired upper level of water content (generally the field capacity of the soil). Define an acceptable management allowed deficit (MAD) value for the soil and crop system to determine the amount of readily available water to the crop.
6. Based on the results of Steps 3, 4, and 5, define and identify the peak irrigation cycle scenarios. Some soil and crop systems may have a limited root-zone reservoir for water and will require multiple irrigation cycles per day while other systems may be irrigated once every 2, 3, or more days.
7. Determine the amount of water to apply per irrigation cycle for each zone:

$$Q_{peak} = \frac{2.78 \bullet (A_z)(I_{net})}{(E_a)(T_c)} \tag{5.2}$$

   where the peak total flowrate for the system, Q_{peak} (L/s), is determined from the irrigated area per zone (A_z, ha) as defined in Step 2, the peak daily crop water use or net irrigation requirement (I_{net}, mm) from Step 3, the application efficiency of the irrigation system (E_a), and the irrigation operation time per cycle (T_c, h). The net irrigation requirement (I_{net}) must be adjusted for the number of days between cycles, the number of cycles per day, and/or for salinity leaching requirements.
8. If the required peak system flowrate exceeds the maximum available flowrate capacity ($Q_{peak} > Q_{max}$), repeat Steps 2 through 7 by adjusting the variables (A_z and T_c) of Eq. 5.2 as appropriate to satisfy the criteria of $Q_{peak} \le Q_{max}$.
9. Layout and design a submain and lateral pipeline system that will maintain emitter discharge rate differences within allowable limits.
10. Develop an irrigation application and operating schedule.


Start
Assess the maximum flowrate capacity (Q_{max}) of the water supply
Define the total irrigated area, A, the desired number of zones and irrigated area per zone A_z
Assess the peak water requirements of the crop, ETc_{peak}
Select a microirrigation emitter configuration
Characterize the irrigated volume of soil and the readily available water
Define and identify the peak irrigation cycle scenarios
Determine the amount of water to apply per irrigation cycle (Q_{peak}) for each zone of area A_z
Is Q_{peak} > Q_{max}?
yes
no
Design submains and laterals that maintain allowable emitter discharge differences
Develop an irrigation application and operating schedule
1. Can the water needs of the crop be met?
2. Is the system convenient to operate?
3. Does system management conform to the cultural constraints?

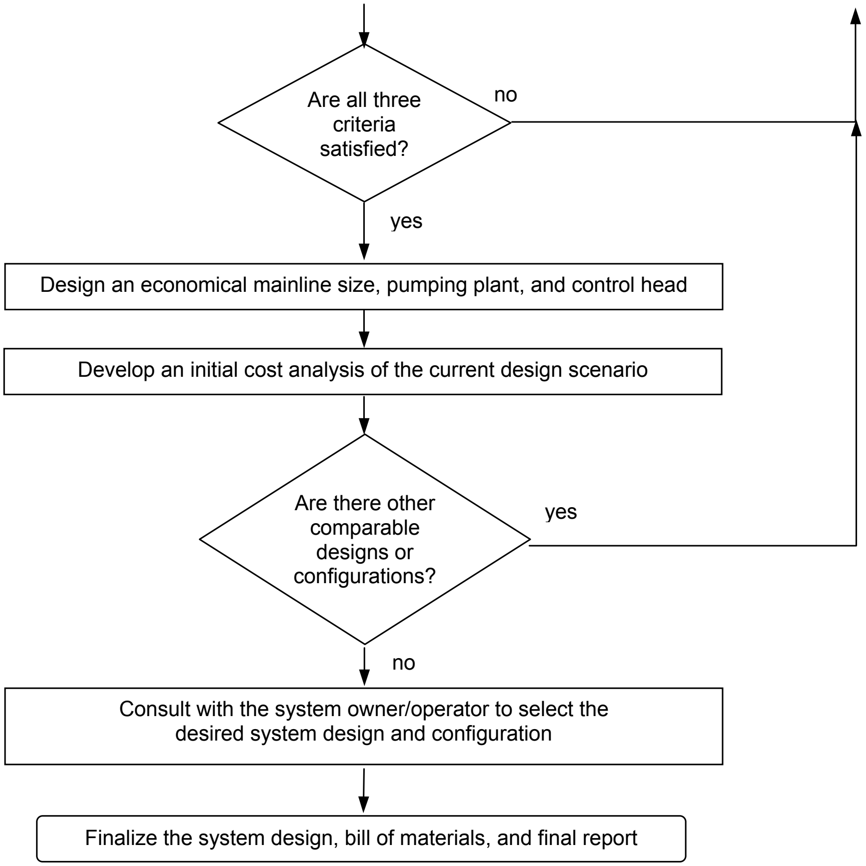


Figure 5.5. Flow chart of the general steps in the design process. Courtesy of Kansas State University.

11. Assess whether the system is convenient to operate and conforms to the cultural constraints of the overall crop production and field system. If not, return to Step 2.
12. Design an economical size for the mainline pipe system, submain pipes, header pipes, manifolds, the pumping plant, and control head components (filters, injectors, valves, and controllers).
13. Develop an initial cost analysis of the current design scenario.
14. Assess whether other potentially acceptable system designs and configurations exist. If yes, return to Step 2.
15. Present the desired system design and configuration to the system owner/operator and discuss options or final plans.
16. Finalize the system design and specifications, develop a bill of materials, and create a final product report.

The remainder of this chapter provides additional discussion and detail on the calculations and decisions related to the design process steps. Sample calculations and examples are provided to demonstrate the presented concepts and methods.

5.2. SOURCES OF WATER

A common objective of all microirrigation systems is to transport water from a source to the irrigated field. The water source may be groundwater, surface water such as a canal or pond, or recycled water such as a municipal wastewater treatment system or livestock wastewater lagoon.

5.2.1. Water Quantity and Quality

As discussed in Section 5.1, system designs need to include an assessment of the quantity of water available from the source for use (total quantity and capacity or rate), and the amount needed or that must be used for the desired goal. The total quantity of available water will depend on applicable laws or allocation procedures and the size of the source. Water limitations, use restrictions, ownership, and uncertainty in water supply amounts will influence the total irrigated area, the irrigation scheduling decision process, and perhaps the choice of components and "permanency" of the system. A limited water supply may be used to adequately irrigate a limited irrigated area or may be used to "deficit" irrigate a larger area. Some microirrigation systems are designed for long-term use (>10 years) on a single site, whereas other systems may have some "portability" included into the design in order to accommodate uncertainty in a local water source or land-lease agreements. These situations are not necessarily the norm, but can provide some unique and challenging design scenarios.

The quality of the water source must be assessed as to how physical, biological and/or chemical constituents in the water may affect or interact with components of the delivery system (pump, pipes, valves, and emitters), the soil, and crop. Proper water treatment and amendment practices must be used to avoid clogging of the microirrigation emitters (see Chapter 11). Water quality from both groundwater and surface water sources can range from excellent to very poor, and typical quality concerns include suspended solids, dissolved solids, and biological organisms. Poor well screening and/or well development problems can result in undesirable quantities of suspended sand, silt, or clay particles. Surface water sources may have suspended particles of silt and/or clay, aquatic plants, small fish, algae, larvae, or other organic debris. In most instances, these physical constituents can be controlled with proper filtration.

Dissolved solids such as calcium, iron, or manganese can precipitate under certain conditions and subsequently clog emitters. Biological organisms include slimes (associated with iron and/or hydrogen sulfide), fungi, and algae. Chemical treatment of the water is often necessary in addition to filtration to prevent emitter clogging and/or to reclaim clogged emitters. A more detailed discussion on maintenance criteria and procedures to prevent and reclaim clogged emitters is provided in Chapter 11. Severe instances of several of the preceding water quality problems may require expensive remediation components and/or management practices to ensure proper and continual operation of the microirrigation system. Because such conditions may result in a financially impractical design, or poor system performance or failure, a thorough assessment of the quality of the water source must be performed prior to completion of the final design.

5.2.2. Groundwater

A substantial portion of the freshwater used in irrigation is supplied by groundwater sources (aquifers) that are accessed through wells. Depths to the water bearing formations can range from a few meters to several hundred meters. In deep, confined aquifers the water may be under pressure such that it will naturally rise within the well to a position (piezometric surface) substantially higher than the upper confining layer of the aquifer. In the unconfined well, this would be the water table or static water surface. As water is withdrawn from the well, the piezometric surface or water table (of the respective aquifer) will decline in elevation at the well. The amount of water level decline is known as the drawdown and is used to determine the level of the pumping water surface, which will be discussed later in the Section 5.3. Drawdown may range from 1 m to well over 10 m and is influenced by aquifer hydraulic properties, the radius of the well, and the rate of water withdrawal.

Some aquifer sources have excellent water quality and require little or no treatment other than filtration. Other aquifer sources may contain biological organisms originating from contaminated wells and other water sources, or may contain certain dissolved elements that can result in clogging through precipitation. The water from these sources may require elaborate treatment systems that are designed to minimize emitter clogging.

Thus, the primary aquifer considerations from the microirrigation design viewpoint include well yield (or rate of water withdrawal), the elevation of the piezometric surface or water table, the expected drawdown, and the quality of the water. In many aquifers, these remain relatively stable, but each of these parameters can change. In some shallow aquifers or those with low recharge rates, changes can occur within a growing season. Such aquifers with varying conditions need careful assessment in the design process to determine their impact on system components and management.

5.2.3. Surface Water

Surface water sources for microirrigation systems include natural or man-made ponds, lakes, lagoons, rivers, canals, and small streams. As with groundwater sources, the quantity, rate of supply, and quality are the primary concerns for system design. Small ponds and/or lagoons may have restrictions in the total volume of available water and also may have other constraints such as a minimum required level of base storage, when the water may be withdrawn, or the rapidity of water replenishment. Some small streams may have minimum base flow requirements that must be satisfied, and small canals may be hydraulically restrictive with respect to water supply rates. Water delivery schedules on canal supply systems may not be practical for use with some microirrigation systems.

Water quality concerns are generally greater with surface water sources than with groundwater sources. Surface water may have suspended materials, such as silt or clay particles, algae, larvae, or organic and inorganic debris. These elements must be removed by filtration. Microbiological organisms may obtain their energy from constituents in the water that cannot be filtered. Livestock and municipal water treatment lagoons are generally nutrient-enriched water sources. Those nutrients or other dissolved elements can provide a food source for microbiological organisms that can grow, accumulate, and clog emitters. These biological organisms can generally be controlled with chlorination or other biological control methods (Chapter 11).

Recycled water sources from municipal wastewater, livestock wastewater lagoons, and industry wastewater sources should be thoroughly assessed for their physical, chemical, and biological constituents. Key concerns include pH, salts, nitrogen, and phosphorus. Some “contaminated” water sources may contain heavy metals or organic compounds that are of concern when applied to agricultural crops and fields. Water application and/or loading rates may need to be assessed with respect to the concentrations of certain key compounds in the water. Allowable water application amounts may not be sufficient to meet peak or design crop water demands and supplemental “clean” water sources may be needed to augment the water supply. The reader is referred to Chapter 9 for a more thorough discussion of use of recycled water through microirrigation systems.

5.3. SYSTEM HYDRAULICS

5.3.1. Hydraulic Principles

The water flowing in microirrigation systems has energy due to position (elevation), internal pressure, and velocity. The goal of the microirrigation system is to move water from the source to the irrigated field and ultimately the root zone of the irrigated plants. Thus, the design must include a hydraulic mass and energy analysis of the system for proper sizing of components and to ensure uniform distribution of water. As previously discussed, the microirrigation system may include a pump, filter station, chemical injection system, a network of mainlines, submains, and manifold pipelines, and then lateral lines with microirrigation emitters (Figs. 5.1, 5.2, and 5.3). The conservation of mass principle is used to analyze the velocity and volumetric discharge or flowrate characteristics of the hydraulic network. At any location within the system with a single inlet and outlet, the volumetric flowrate (Q, L/s) is related to the average flow velocity (v, m/s) and cross-sectional area of flow (a, mm^2) as:

$$Q = \frac{(a)(v)}{1000} \tag{5.3}$$

Equation 5.3 will be used throughout the hydraulic analysis of the system to ensure that safe flow velocities are maintained. Water hammer is a hydraulic condition that can occur within pipelines when high flow velocities exist with sudden changes in flow direction, rapid closing of valves, and/or rapid starting or stopping of pumps. These conditions can result in high surge pressures within the pipe system due to the momentum of flowing water. Resulting high surge pressures can damage pipelines or other system components. This can result in major problems such as personal injury or system failure during critical crop growth periods. To minimize excessive surge pressures, a maximum flow velocity of 1.5 m/s is recommended (ASAE S376.2, 2000) for most pipeline sections within the system. While some designers may allow flow velocities up to 2.0 m/s, other surge pressure and water hammer precautions must be designed into the system. Additionally, a minimum flow velocity of 0.3 m/s is recommended to ensure that suspended materials can be properly flushed. Flow velocities at the ends of laterals and manifolds will approach zero and suspended particles will tend to settle in those lines. Flush valves and a flushing cycle can be used to remove these particles with a minimum flushing velocity of 0.3 m/s (ASAE EP405.1, 2000) or as specified by the manufacturer of certain microirrigation components.

Example 5.3

Find the smallest safe inside diameter (ID) for a circular pipeline that needs to convey 25 L/s. A maximum "safe" flow velocity of 1.5 m/s is assumed.

Rearranging Eq. 5.3 for area, a, yields: $a = \frac{1000(Q)}{v}$

From the given information: Q = 25 L/s; and v = 1.5 m/s (assumed)

Thus, the smallest "safe" cross sectional area is:

$$a = \frac{1000\,(25\ L/s)}{1.5\ m/s} = 16{,}667\ mm^2$$

The corresponding inside diameter, D, is:

$$D = \left(\frac{4}{\pi}\,a\right)^{0.5} = \left(\frac{4}{\pi}\,(16{,}667\ mm^2)\right)^{0.5} = 146\ mm$$

Therefore, the smallest "safe" inside diameter for the pipeline is 146 mm. The actual ID depends upon commercially available pipes such as 155 mm for a SDR26 PVC pipe.

Another aspect of higher flow velocities is the associated increased friction head loss to be discussed in a later section. Thus, larger pipe sizes will reduce flow velocities and will in turn result in reduced surge pressures, reduced water hammer problems, and reduced pipeline friction (energy) losses. However, larger pipe sizes can substantially add to the overall cost of the system. The designer must balance all of these constraints to achieve an economical system that applies water uniformly and is safe to operate.

5.3.1.1. Total head

As water flows through the hydraulic system, the energy varies due to changes in flow velocity, elevation, water pressure, pump inputs, or internal friction within the hydraulic network and associated components. The system design must include an energy analysis to properly size all components to ensure that the desired water discharge rates are uniformly achieved throughout the system without excessive static or dynamic (surge) pressures. The goal of the hydraulic design is to provide a system that is reliable, uniform, economically functional, and safe.

The total energy of water is typically expressed in units of pressure (kPa) or equivalent height of a column of water (m). The latter unit is more common and is generally referred to as meters of (water) head, pressure head or just "head". While any consistent energy units may be used, this discussion will use units of meters of water head. An energy balance is used to analyze the head of the water at any position within the microirrigation hydraulic network. For example, two locations in a pipe system, A(upstream) and B (downstream), each has an associated total head , H_A and H_B , respectively. If a pump exists between locations A and B, then the head added to the system from the pump (H_P) must be considered. As water flows from location A to location B, head is "lost" due to friction (H_F) within the hydraulic network. The energy balance using these terms is shown by Eq. 5.4.

$$H_A + H_P = H_B + H_{F_{A-B}} \tag{5.4}$$

The head (or level) at any location "A" or "B" is defined as the sum of the velocity head, pressure head, and elevation head components. In this discussion water will be flowing from location A to location B. The friction head term ($H_{F\ A\text{-}B}$) includes pipeline friction head losses and minor friction head losses (minor losses) associated with water flowing through valves, fittings, or other components of the system. For location A with average pipeline flow velocity, v_A (m/s), pressure head, h_A (m), and elevation, z_A (m), the total energy head, H_A, is:

$$H_A = \frac{v_A^2}{2\,g} + h_A + z_A \tag{5.5}$$

where g is the acceleration due to gravity (9.81 m/s^2). Inserting Eq. 5.5 and a similar relationship developed for H_B (using v_A, h_A, and z_A) into 5.4 results in the following general energy equation, which is a form of the Bernoulli equation:

$$\frac{v_A^2}{2\,g} + h_A + z_A + H_P = \frac{v_B^2}{2\,g} + h_B + z_B + H_{F_{A-B}} \tag{5.6}$$

As previously discussed, flow velocities within pipelines should be maintained at 1.5 m/s or less to minimize excessive surge pressures and water hammer. Even with a flow velocity of 2.0 m/s, the associated velocity head is 0.20 m and is much smaller than the other energy head terms. The velocity head term can become substantial and should be considered when high nozzle discharge velocities are part of an analysis, but this situation is not encountered in most microirrigation system designs. Under most hydraulic analysis scenarios, the velocity head term (v^2 / 2 g) is often very small compared with the other energy terms in Eq. 5.6, and can be neglected.

Pressure head (h) is the energy associated with internal or static pressure of the water with respect to atmospheric pressure. The pressure head term is zero for free or open water surfaces such as ponds, rivers, or the water surface in wells. Some microirrigation systems may be supplied by a "precharged" or pressurized water source in which the input pressure to the system is specified. Sometimes the input pressure of such systems varies with the associated flow and a separate discharge pressure/flow analysis or measurement may be required for the pressurized source. In general, the desired downstream or operating pressure is specified at a certain location which is then used as one of the analysis locations (*A, B, …*).

The elevation head of all locations, (*A, B, …*) is the elevation (m) of each location with respect to a common, fixed datum. For uniform and mild sloped systems the analysis simply considers the elevation of the water source and of the distal end of the system. However, multiple energy head analyses must be performed for nonuniform sloped fields with substantial elevation changes.

Elevation head gains due to field depressions may exceed acceptable limits or elevation head losses due to field ridges may result in poor system performance.

5.3.1.2. Pump energy requirements

The head added to the system from a pump (H_P) is also referred to as the total dynamic head. The pump has two primary purposes: (1) to move water (Q), and (2) to add head or energy (H_P) to the water. In the initial design analysis, pump discharge head is often the primary unknown variable in Eq. 5.6 and all other terms are defined using other information or relationships. In many situations, the pump only needs to provide energy to (1) overcome elevation gains from the water source to the distribution network; (2) add pressure to the system to operate the microirrigation emitters; and (3) overcome pressure losses in the system due to friction. Rearranging Eq. 5.6 for this scenario and neglecting velocity head differences yields:

$$H_P = (z_B - z_A) + (h_B - h_A) + H_{F_{A-B}} \tag{5.7}$$

Example 5.4.

A pump needs to move water from a pond into a microirrigation system. The elevation of the pond water surface is at 78.0 m (location A) and the elevation of the inlet to the microirrigation lateral network is at 83.7 m (location B). It is desired to have an operating pressure of 150 kPa (H_B = 15.3 m) at location B. The friction losses between locations A and B are estimated to be 7.4 m. From Eq. 5.7 the total dynamic head for the pump is:

Hp = (83.7 m – 78.0 m) + (15.3 m – 0.0 m) + 7.4 m = 28.4 m

These results indicate that the pump needs to provide 28.4 m of head into the system.

Once the total dynamic head, H_P (m), is defined, it is then combined with the volumetric flowrate, Q, (L/s), to define the power associated with the flowing water. This power is often referred to as the water power (WP, kW) and is determined from:

$$WP = \frac{(Q)(H_P)}{102} \tag{5.8}$$

Example 5.5.

If the flowrate in Example 5.4 is 25.0 L/s, find the associated water power (WP) that must be provided by the pump.

From Eq. 5.8:

$$WP = \frac{Q \bullet H_P}{102} = \frac{(25.0\ L/s)\ (28.4\ m)}{102} = 7.0\,kW$$

The pump must provide 7.0 kW of "water power" into the system.

The power required to drive the pump is called brake power, *BP* (kW), and is related to the water power, *WP* (kW), and pump efficiency, E_P, as:

$$BP = \frac{WP}{E_P} \tag{5.9}$$

The brake power is also known as the shaft power input to the pump that must be provided by the prime mover or power unit (electric motor or internal combustion engine) and energy transmission devices (gears, belts, shafts, etc.). Water slipping around pump impellers and internal pump friction contribute to the "inefficiency" of the pump and is a dynamic characteristic that generally changes with pump speed and/or discharge. Pump manufacturers provide these relationships in the form of pump curves for their various pump designs and operating conditions. While values of E_P can range from less than 50% to over 80%, an initial value of 70% may be assumed until a specific value is obtained. Electric motors and internal combustion engines will also have an efficiency factor associated with the conversion of the input energy (electrical power, natural gas, diesel fuel, etc.) into output power (brake power). The efficiency of properly loaded electrical motors can range from 85% to over 90%, whereas internal combustion engines typically have fuel conversion efficiencies of less than 40%.

Example 5.6.

Find the required brake power input for a pump with an efficiency of 70% that can provide a flowrate of 25.0 L/s with a total dynamic head of 28.4 m (Example 5.5).

Use WP = 7.0 kW (Example 5.5) and $E_P = 0.70$

Using Eq. 5.9,

$$BP = \frac{7.0\ kW}{0.70} = 10.0\ kW$$

Therefore, the required brake power input from the power unit to the pump must be 10.0 kW.

5.3.1.3. Total friction head

Friction head losses (H_F) occur due to water flowing through pipes, fittings, and other components of the irrigation system. The magnitude of this energy loss depends on the velocity of the flowing water (v), the "roughness" of the flow path through pipes, fittings, and components, and the number of flow directional changes through fittings and components. Because flow velocity (v) is related to (Eq. 5.3) the volumetric flowrate (Q) and the cross-sectional area of flow (a), proper selection of pipe and component size or diameter (D) directly impacts the total head loss and subsequently total energy requirements of the system. In addition, excessive energy losses within mainlines, submains, header, and/or lateral pipe sections can result in substantial variations in operating pressure and non-uniform application of water throughout the hydraulic network.

The total friction head loss (H_F) is equal to the sum of the friction head loss associated with each component of the hydraulic network between any two positions of the analysis. This is summarized by Eq. 5.10 as:

$$H_F = H_f + H_m \tag{5.10}$$

where H_F is the total friction head loss (m) between the two locations in the hydraulic analysis, H_f is the total friction head associated with water flowing through the pipes of the network and H_m is the sum of the minor friction losses associated with water flowing through pipe fittings (couplers, elbows, tees, etc.), valves, filters, or other components directly in line with the hydraulic network (flowmeters, injectors, hydraulic pumps, etc.).

The total friction head loss associated with the various components of Eq. 5.10 is unique to the specific components and flow regimes of the analysis. Variations in system flowrates or alterations (additions or deletions) of the associated components will change the total friction head loss. Thus, all flow and design scenarios must be separately analyzed to ensure that an acceptable hydraulic balance is achieved.

5.3.1.3.1. Pipeline friction head loss

The Hazen-Williams equation is the most commonly used formula for calculating friction head loss in irrigation laterals. The general form of this relationship for continuous pipe sections with one inlet and one outlet is:

$$J = \frac{100\ (h_f)}{L} = \left(1.212 \bullet 10^{12}\right)\left(\frac{Q}{C}\right)^{1.852} (D^{-4.87}) \tag{5.11}$$

where J is the head loss gradient in the pipe (m/100 m), h_f is the pipeline friction head loss (m), L is the pipeline length (m), $1.212 \bullet 10^{12}$ is a conversion constant for S.I. units, Q is the pipeline flowrate (L/s), C is the Hazen-Williams friction coefficient for the pipe material, and D is the inside diameter of the pipe (mm). The friction coefficient (C) varies from 100 for old steel pipe to 135 for newer steel pipe to 150 for smooth plastic pipe. The inside diameter of the pipe must be used in all computations. Equation 5.11 can be rearranged to solve directly for the friction head loss as:

$$h_f = L\left(1.212 \bullet 10^{10}\right)\left(\frac{Q}{C}\right)^{1.852} (D^{-4.87}) \tag{5.12}$$

Tables 5.1a and 5.1b, 5.2a and 5.2b, and 5.3 provide values of v and J for various flowrates (Q) and pipe sizes for SDR 41 PVC, SDR 26 PVC, and polyethylene plastic pipe, respectively.

Example 5.7.

Find the pipeline friction head loss for a 200 m long plastic pipe (C = 150) that has an inside diameter of 160.1 mm and is to convey a water flowrate of 25.0 L/s.

From the given information: L = 200 m; Q = 25.0 L/s; C = 150; and D = 160.1 mm

Using Eq. 5.12,

$$h_f = (200)\left(1.212 \bullet 10^{10}\right)\left(\frac{25.0}{150}\right)^{1.852}\left(160.1\right)^{-4.87} = 1.61\ m$$

The friction head loss in that section of pipe is estimated to be 1.61 m. This does not include any friction loss associated with valves, fittings, or other components on that section of pipe. Approximately, the same friction loss value can be obtained from Tab. 5.1b for the 168 mm O.D. pipe [h_f = (0.81 m/100 m)·200 m = 1.62 m].

A similar computational approach for head loss has been proposed by Watters and Keller (1978) for smooth plastic (PVC and polyethylene) pipes. For pipes with inside diameters less than 125 mm:

$$h_f = L\left(7.89 \bullet 10^{5}\right) Q^{1.75}\ D^{-4.75} \tag{5.13}$$

For pipes with inside diameters larger than 125 mm:

$$h_f = L\left(9.58 \bullet 10^{5}\right) Q^{1.83}\ D^{-4.83} \tag{5.14}$$

where h_f and L are in m, Q has units of L/s, and D is in mm as previously defined.

Example 5.8:

Repeat example 5.7 using Eq. 5.14

$$h_f = (200) \bullet \left(9.58 \bullet 10^{5}\right) \bullet (25.0)^{1.83} \bullet (160.1)^{-4.83} = 1.56\ m$$

The computed value of h_f = 1.56 m is very close to the result in Example 5.7.

The Darcy-Weisbach (D-W) equation is another approach that may be used and is better for computing head loss in small diameter flow pathways such as microirrigation lines and emitters. This equation has the form:

$$h_f = 1000 \ (F_f) \frac{L}{D} \frac{v^2}{2\,g} \tag{5.15}$$

where F_f is the D-W friction factor, and other terms and units are as previously defined. The D-W friction factor (F_f) can be estimated from the Reynolds number (Ry) using the Blasius Equation for small diameter, smooth pipes with Ry values between 2000 and 100,000.

$$F_f = (0.316)\,(Ry^{-0.25}) \tag{5.16}$$

The dimensionless Reynolds number for 21°C water can be found from:

$$Ry = \left(1.30 \bullet 10^6\right) \bullet \left(\frac{Q}{D}\right) \tag{5.17}$$

where Q and D are in L/s and mm as previously defined. The D-W equation will be used in the emitter hydraulics section. Additional detail on this approach is available from Keller and Bliesner (1990).

5.3.1.3.2. Multiple outlet pipes

When pipeline flowrates change due to diverging flows, the associated friction loss also changes, thus requiring a separate head loss analysis. However, multiple outlet pipes such as manifolds, headers, and laterals typically have uniformly spaced and uniformly discharging outlets. When both of these conditions exist, Eq. 5.12 can be modified using the Christiansen multiple outlet reduction factor, F, as:

$$h_f = (F)(L)\left(1.212 \bullet 10^{10}\right)\left(\frac{Q}{C}\right)^{1.852} (D^{-4.87}) \tag{5.18}$$

where all terms are as previously defined. The multiple outlet reduction factor (F) is obtained using the velocity exponent from Eq. 5.18 (m = 1.852) and the number (N) of evenly spaced and equal discharging outlets. Mathematical relationships presented by Christiansen (1942) were developed for the case when the first outlet is positioned at one full space off of the supply line (Fig. 5.6A) or by Jensen and Fratini (1957) for the case when the first outlet is positioned at one-half space off of the supply line (Fig. 5.6B). Table 5.4 summarizes the F-value results of those relationships for Fig. 5.6A and 5.6B.

Table 5.1a. Average flow velocity (v) and head loss gradient factors (J) for SDR 41 PVC thermoplastic pipe for various flowrates (Q) and smaller pipe sizes.

PVC Class 100 IPS plastic pipe; SDR = 41				C = 150				
	OD	ID	OD	ID	OD	ID	OD	ID
Diameter (mm)	33.4	31.8	48.3	45.9	60.3	57.4	88.9	84.6
Nom. size (in.)	1	1	1.5	1.5	2	2	3	3
Q	v	J	v	J	v	J	v	J
L/s	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m
0.10	0.13	0.08	0.06	0.01				
0.20	0.25	0.28	0.12	0.05				
0.30	0.38	0.59	0.18	0.10	0.12	0.03	0.05	0.01
0.40	0.50	1.00	0.24	0.17	0.15	0.06	0.07	0.01
0.50	0.63	1.52	0.30	0.25	0.19	0.09	0.09	0.01
0.60	0.76	2.13	0.36	0.35	0.23	0.12	0.11	0.02
0.70	0.88	2.83	0.42	0.47	0.27	0.16	0.12	0.02
0.80	1.01	3.62	0.48	0.60	0.31	0.20	0.14	0.03
1.00	1.26	5.48	0.60	0.91	0.39	0.31	0.18	0.05
1.20	1.51	7.68	0.73	1.28	0.46	0.43	0.21	0.07
1.40	1.77	10.21	0.85	1.70	0.54	0.57	0.25	0.09
1.60	2.02	13.08	0.97	2.18	0.62	0.73	0.28	0.11
1.80	2.27	16.26	1.09	2.71	0.70	0.91	0.32	0.14
2.00	2.52	19.77	1.21	3.29	0.77	1.11	0.36	0.17
2.50			1.51	4.98	0.97	1.68	0.45	0.25
3.00			1.81	6.98	1.16	2.35	0.53	0.36
3.50			2.11	9.28	1.35	3.13	0.62	0.47
4.00			2.42	11.89	1.55	4.01	0.71	0.61
4.50			2.72	14.79	1.74	4.99	0.80	0.75
5.00					1.93	6.06	0.89	0.92
5.50					2.13	7.23	0.98	1.09
6.00					2.32	8.50	1.07	1.29
8.00							1.42	2.19
10.00							1.78	3.31
12.00							2.14	4.64
14.00							2.49	6.17
16.00							2.85	7.91

Pipe dimensions of Outside Diameter (OD) and Inside Diameter (ID) are shown in mm, Nominal size is in inches, and Velocity is shown in meters per second (m/s).

Head loss gradient (J) is calculated using the Hazen-Williams formula and is expressed as meters of head loss per 100 meters of pipe (m/100 m).

** Velocities over 1.5 m/s are not recommended (shaded areas).

Table 5.1b. Average flow velocity (v) and head loss gradient factors (J) for SDR 41 PVC thermoplastic pipe for various flowrates (Q) and larger pipe sizes.

PVC Class 100 IPS plastic pipe; SDR = 41				C = 150				
	OD	ID	OD	ID	OD	ID	OD	ID
Diameter (mm)	114.3	108.7	168.3	160.1	219.1	208.4	273.1	259.7
Nom. size (in.)	4	4	6	6	8	8	10	10
Q	v	J	v	J	v	J	v	J
L/s	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m
1.00	0.11	0.01						
1.20	0.13	0.02						
1.40	0.15	0.03						
1.60	0.17	0.03						
1.80	0.19	0.04	0.09	0.01				
2.00	0.22	0.05	0.10	0.01				
2.50	0.27	0.07	0.12	0.01				
3.00	0.32	0.10	0.15	0.02				
3.50	0.38	0.14	0.17	0.02	0.10	0.01		
4.00	0.43	0.18	0.20	0.03	0.12	0.01		
4.50	0.48	0.22	0.22	0.03	0.13	0.01		
5.00	0.54	0.27	0.25	0.04	0.15	0.01		
5.50	0.59	0.32	0.27	0.05	0.16	0.01		
6.00	0.65	0.38	0.30	0.06	0.18	0.02	0.11	0.01
8.00	0.86	0.64	0.40	0.10	0.23	0.03	0.15	0.01
10.00	1.08	0.97	0.50	0.15	0.29	0.04	0.19	0.01
12.00	1.29	1.36	0.60	0.21	0.35	0.06	0.23	0.02
14.00	1.51	1.82	0.70	0.28	0.41	0.08	0.26	0.03
16.00	1.72	2.33	0.80	0.35	0.47	0.10	0.30	0.03
18.00	1.94	2.89	0.89	0.44	0.53	0.12	0.34	0.04
20.00	2.15	3.52	0.99	0.53	0.59	0.15	0.38	0.05
25.00	2.69	5.31	1.24	0.81	0.73	0.22	0.47	0.08
30.00			1.49	1.13	0.88	0.31	0.57	0.11
35.00			1.74	1.51	1.03	0.42	0.66	0.14
40.00			1.99	1.93	1.17	0.53	0.75	0.18
45.00			2.24	2.40	1.32	0.66	0.85	0.23
50.00			2.48	2.92	1.47	0.81	0.94	0.28
60.00			2.98	4.09	1.76	1.13	1.13	0.39
70.00					2.05	1.51	1.32	0.51
80.00					2.35	1.93	1.51	0.66
90.00					2.64	2.40	1.70	0.82
100.00							1.89	1.00
120.00							2.26	1.40
140.00							2.64	1.86

Pipe dimensions of Outside Diameter (OD) and Inside Diameter (ID) are shown in mm, Nominal size is in inches, and Velocity is shown in meters per second (m/s).

Head loss gradient (J) is calculated using the Hazen-Williams formula and is expressed as meters of head loss per 100 meters of pipe (m/100 m).

** Velocities over 1.5 m/s are not recommended (shaded areas).

Table 5.2a. Average flow velocity (v) and head loss gradient factors (J) for SDR 26 PVC thermoplastic pipe for various flowrates (Q) and smaller pipe sizes.

PVC Class 160 IPS plastic pipe; SDR = 26				C = 150				
	OD	ID	OD	ID	OD	ID	OD	ID
Diameter (mm)	33.4	30.8	48.3	44.5	60.3	55.7	88.9	82.1
Nom. size (in.)	1	1	1.5	1.5	2	2	3	3
Q	v	J	v	J	v	J	v	J
L/s	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m
0.10	0.13	0.09	0.06	0.01				
0.20	0.27	0.32	0.13	0.05				
0.30	0.40	0.68	0.19	0.11	0.12	0.04	0.06	0.01
0.40	0.54	1.16	0.26	0.19	0.16	0.07	0.08	0.01
0.50	0.67	1.76	0.32	0.29	0.21	0.10	0.09	0.01
0.60	0.80	2.46	0.38	0.41	0.25	0.14	0.11	0.02
0.70	0.94	3.27	0.45	0.55	0.29	0.18	0.13	0.03
0.80	1.07	4.19	0.51	0.70	0.33	0.24	0.15	0.04
1.00	1.34	6.34	0.64	1.06	0.41	0.36	0.19	0.05
1.20	1.61	8.88	0.77	1.48	0.49	0.50	0.23	0.08
1.40	1.88	11.82	0.90	1.97	0.57	0.66	0.26	0.10
1.60	2.14	15.14	1.03	2.52	0.66	0.85	0.30	0.13
1.80	2.41	18.82	1.15	3.14	0.74	1.06	0.34	0.16
2.00	2.68	22.88	1.28	3.81	0.82	1.29	0.38	0.19
2.50			1.60	5.76	1.03	1.94	0.47	0.29
3.00			1.92	8.08	1.23	2.72	0.57	0.41
3.50			2.25	10.75	1.44	3.62	0.66	0.55
4.00			2.57	13.76	1.64	4.64	0.76	0.70
4.50			2.89	17.11	1.85	5.77	0.85	0.87
5.00					2.05	7.02	0.95	1.06
5.50					2.26	8.37	1.04	1.27
6.00					2.46	9.84	1.13	1.49
8.00							1.51	2.54
10.00							1.89	3.83
12.00							2.27	5.37
14.00							2.65	7.15
16.00							3.03	9.15

Pipe dimensions of Outside Diameter (OD) and Inside Diameter (ID) are shown in mm, Nominal size is in inches, and Velocity is shown in meters per second (m/s).

Head loss gradient (J) is calculated using the Hazen-Williams formula and is expressed as meters of head loss per 100 meters of pipe (m/100 m).

** Velocities over 1.5 m/s are not recommended (shaded areas).

Table 5.2b. Average flow velocity (v) and head loss gradient factors (J) for SDR 26 PVC thermoplastic pipe for various flowrates (Q) and larger pipe sizes.

PVC Class 160 IPS plastic pipe; SDR = 26				C = 150				
	OD	ID	OD	ID	OD	ID	OD	ID
Diameter (mm)	114.3	105.5	168.3	155.3	219.1	202.2	273.1	252.0
Nom. size (in.)	4	4	6	6	8	8	10	10
Q	v	J	v	J	v	J	v	J
L/s	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m	m/s	m/100 m
1.00	0.11	0.02						
1.20	0.14	0.02						
1.40	0.16	0.03						
1.60	0.18	0.04	0.08	0.01				
1.80	0.21	0.05	0.09	0.01				
2.00	0.23	0.06	0.11	0.01				
2.50	0.29	0.09	0.13	0.01				
3.00	0.34	0.12	0.16	0.02				
3.50	0.40	0.16	0.18	0.02	0.11	0.01		
4.00	0.46	0.21	0.21	0.03	0.12	0.01		
4.50	0.51	0.26	0.24	0.04	0.14	0.01		
5.00	0.57	0.31	0.26	0.05	0.16	0.01		
5.50	0.63	0.37	0.29	0.06	0.17	0.02	0.11	0.01
6.00	0.69	0.44	0.32	0.07	0.19	0.02	0.12	0.01
8.00	0.92	0.75	0.42	0.11	0.25	0.03	0.16	0.01
10.00	1.14	1.13	0.53	0.17	0.31	0.05	0.20	0.02
12.00	1.37	1.58	0.63	0.24	0.37	0.07	0.24	0.02
14.00	1.60	2.10	0.74	0.32	0.44	0.09	0.28	0.03
16.00	1.83	2.69	0.84	0.41	0.50	0.11	0.32	0.04
18.00	2.06	3.35	0.95	0.51	0.56	0.14	0.36	0.05
20.00	2.29	4.07	1.06	0.62	0.62	0.17	0.40	0.06
25.00	2.86	6.15	1.32	0.94	0.78	0.26	0.50	0.09
30.00			1.58	1.31	0.93	0.36	0.60	0.12
35.00			1.85	1.74	1.09	0.48	0.70	0.17
40.00			2.11	2.23	1.25	0.62	0.80	0.21
45.00			2.37	2.78	1.40	0.77	0.90	0.26
50.00			2.64	3.38	1.56	0.93	1.00	0.32
60.00			3.17	4.73	1.87	1.31	1.20	0.45
70.00					2.18	1.74	1.40	0.60
80.00					2.49	2.23	1.60	0.76
90.00					2.80	2.77	1.80	0.95
100.00							2.00	1.15
120.00							2.41	1.62
140.00							2.81	2.15

Pipe dimensions of Outside Diameter (OD) and Inside Diameter (ID) are shown in mm, Nominal size is in inches, and Velocity is shown in meters per second (m/s).

Head loss gradient (J) is calculated using the Hazen-Williams formula and is expressed as meters of head loss per 100 meters of pipe (m/100 m).

** Velocities over 1.5 m/s are not recommended (shaded areas).

Table 5.3. Average flow velocity (v) and head loss gradient factors (J) for polyethylene pipe for various flowrates (Q) and smaller pipe sizes.

Polyethylene plastic pipe		C = 150									
Diameter (mm)		ID 15.8		ID 20.9		ID 26.6		ID 35.1		ID 40.9	
Nom. size (in.)		0.5		0.75		1.00		1.25		1.5	
Q L/min	Q L/s	v m/s	J m/100m	v m/s	J m/100 m	v m/s	J m/100 m	V m/s	J m/100m	v m/s	J m/100m
2	0.03	0.17	0.30	0.10	0.08						
4	0.07	0.34	1.09	0.19	0.28						
6	0.10	0.51	2.31	0.29	0.59	0.18	0.18	0.10	0.05	0.08	0.02
8	0.13	0.68	3.94	0.39	1.00	0.24	0.31	0.14	0.08	0.10	0.04
10	0.17	0.85	5.96	0.48	1.51	0.30	0.47	0.17	0.12	0.13	0.06
12	0.20	1.02	8.35	0.58	2.12	0.36	0.65	0.21	0.17	0.15	0.08
14	0.23	1.19	11.11	0.68	2.82	0.42	0.87	0.24	0.23	0.18	0.11
16	0.27	1.36	14.22	0.78	3.62	0.48	1.12	0.28	0.29	0.20	0.14
18	0.30	1.53	17.69	0.87	4.50	0.54	1.39	0.31	0.36	0.23	0.17
20	0.33	1.70	21.50	0.97	5.47	0.60	1.69	0.34	0.44	0.25	0.21
22	0.37	1.87	25.65	1.07	6.52	0.66	2.01	0.38	0.53	0.28	0.25
24	0.40	2.04	30.14	1.16	7.66	0.72	2.36	0.41	0.62	0.30	0.29
26	0.43	2.21	34.95	1.26	8.89	0.78	2.74	0.45	0.72	0.33	0.34
28	0.47	2.38	40.09	1.36	10.19	0.84	3.15	0.48	0.82	0.36	0.39
30	0.50			1.45	11.58	0.90	3.57	0.52	0.93	0.38	0.44
35	0.58			1.70	15.41	1.05	4.75	0.60	1.24	0.44	0.59
40	0.67			1.94	19.73	1.20	6.09	0.69	1.59	0.51	0.76
45	0.75			2.18	24.54	1.35	7.57	0.78	1.98	0.57	0.94
50	0.83			2.42	29.83	1.49	9.20	0.86	2.40	0.63	1.14
60	1.00					1.79	12.90	1.03	3.37	0.76	1.60
70	1.17					2.09	17.17	1.21	4.48	0.89	2.13
80	1.33					2.39	21.98	1.38	5.74	1.01	2.73
90	1.50							1.55	7.14	1.14	3.39
100	1.67							1.72	8.68	1.27	4.12
125	2.08							2.15	13.12	1.59	6.23
150	2.50									1.90	8.74
175	2.92									2.22	11.62

Pipe Inside Diameter (ID) are shown in mm, Nominal size is in inches, and Velocity is in m/s.

Head loss gradient (J) is calculated using the Hazen-Williams formula and is expressed as meters of head loss per 100 meters of pipe (m/100 m).

** Velocities over 1.5 m/s are not recommended (shaded areas).

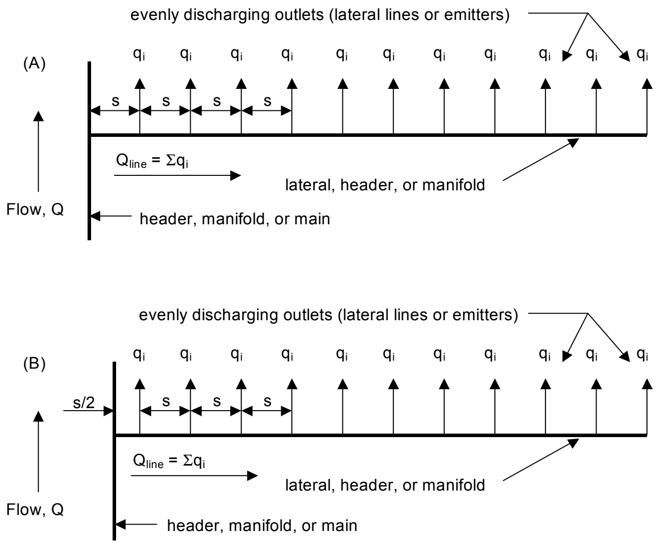


Figure 5.6. Discharging outlet orientation for the multiple outlet factor, F. (A) The first outlet is a full space from the pipe inlet (column A in Tab. 5.4); and (B) the first outlet is one-half space from the pipe inlet (column B in Tab. 5.4).

Table 5.4. Multiple outlet correction factor *F* for various outlet numbers and two outlet configurations. Column A values are used when the first outlet is a full space from the pipe inlet (Fig. 5.6A), and column B values are used when the first outlet is a half space from the pipe inlet (Fig. 5.6B).

Number of outlets	*F* A Full space	*F* B Half space	Number of outlets	*F* A Full space	*F* B Half space
1	1.00	1.00	8	0.42	0.38
2	0.64	0.52	9	0.41	0.37
3	0.53	0.44	10 - 11	0.40	0.37
4	0.49	0.41	12 - 14	0.39	0.37
5	0.46	0.40	15 - 20	0.38	0.36
6	0.44	0.39	21 - 35	0.37	0.36
7	0.43	0.38	>35	0.36	0.36

Example 5.9.

A 114 mm O.D., SDR 41 PVC (I.D. = 108.7 mm) manifold pipe (C = 150) is 90 m long and has lateral line connections every 6.0 m. The total flowrate to each lateral line is 0.80 L/s. Compute the average friction head loss through the manifold when the first lateral connection is one full space off of the mainline pipe. (Similar to Fig. 5.6A).

The number of lateral outlets is:

$$N = \frac{Manifold\ Length}{Lateral\ Spacing} = \frac{90\ m}{6.0\ m} = 15\ outlets$$

The total manifold flowrate is:

$$Q_m = (15\ outlets) \bullet (0.80\ L/s\ \ per\ outlet) = 12.0\ L/s$$

From Tab. 5.4 (use col. A), F = 0.38 for 15 outlets. Using Eq. 5.18, the manifold friction head loss is:

$$h_f = (0.38)(90)\ (1.212 \bullet 10^{10}) \left(\frac{12.0}{150}\right)^{1.852} (108.7)^{-4.87} = 0.47\ m$$

Therefore, $h_f = 0.47$ m.

Friction head loss gradient values (J) from the tables may also be used with the friction factor, F. From Tab. 5.1b, J = 1.36 m/100 m, and the friction head loss is computed as:

$$h_f = (0.38)(90m)\ (1.36m/100m) = 0.47\ m$$

Either of these approaches is acceptable and both produce a friction head loss of about 0.5 m.

5.3.1.3.3. Fitting, valve and component losses

The friction head loss through pipe fittings, valves and other components must be computed and included in the analysis of the hydraulic network. These head loss computations should be performed for all system components (screens, couplers, elbows, tees, valves, filters, etc.) that are in the flow path between the water entrance *(A)* and final discharge or distal *(B)* positions of the energy balance analysis. Many manufacturers of valves, filters and other components will provide tables and charts that quantify the friction head loss for the range of acceptable flowrates through that specific component. For many common components (fittings and valves) the friction head loss is related to the velocity head by:

$$h_f = (k_f)\frac{v^2}{2\,g} \tag{5.19}$$

where k_f is the fitting or valve friction factor (dimensionless), and other terms are as previously defined. The velocity head may be computed or estimated using Tab. 5.5. Table 5.6 summarizes values of k_f for several common fittings and valves.

Table 5.5. Values of the velocity head ($v^2/2g$, m) for various flowrates (Q, L/s) and diameters of the flow area (D, mm).

Flow	Diameter of flow area (mm)									
Q (L/s)	15	20	25	40	50	75	100	150	200	250
0.2	0.07									
0.3	0.15	0.05								
0.4	0.26	0.08								
0.5	0.41	0.13	0.05							
0.6	0.59	0.19	0.08							
0.8	1.04	0.33	0.14							
1.0	1.63	0.52	0.21							
1.2		0.74	0.30	0.05						
1.5		1.16	0.48	0.07						
2		2.07	0.85	0.13	0.05					
3			1.90	0.29	0.12					
4				0.52	0.21					
5				0.81	0.33	0.07				
6				1.16	0.48	0.09				
8				2.07	0.85	0.17	0.05			
10					1.32	0.26	0.08			
12					1.90	0.38	0.12			
15						0.59	0.19			
20						1.04	0.33	0.07		
25						1.63	0.52	0.10		
30							0.74	0.15	0.05	
40							1.32	0.26	0.08	
50							2.07	0.41	0.13	0.05
60								0.59	0.19	0.08
80								1.04	0.33	0.14
100								1.63	0.52	0.21
125									0.81	0.33
150									1.16	0.48

A flow velocity of 2.0 m/s results in a velocity head of approximately 0.20 m, but higher velocity head values may occur through fittings and valves that have smaller nominal sizes than the associated pipe. For example, a 75 mm nominal size valve may be installed on a 100 mm nominal size pipe, thus resulting in a higher flow velocity and velocity head through the valve. This practice is sometimes used to reduce component costs and/or may be necessary for proper operation of the specific component under the flow regimes of the system. When a fitting or valve has a smaller nominal diameter than the associated pipe, use the highest velocity head that corresponds to the highest flow velocity section of that component. Furthermore, k_f values that correspond to the same velocity head may be summed to define an overall k_f value for that section of the system.

Table 5.6. Friction factors k_f for various system fittings and valves for use with Eq. 5.19.

Fitting or valve	Screwed fittings (mm)				Flanged fittings (mm)				
	25	50	75	100	100	125	150	200	250
Elbows									
Regular 90	1.50	1.00	0.80	0.70	0.31	0.30	0.29	0.27	0.25
Long radius 90	0.75	0.42	0.30	0.25	0.22	0.20	0.18	0.16	0.14
Regular 45	0.34	0.30	0.29	0.28	0.18	0.18	0.17	0.17	0.16
Tees									
Line flow	0.90	0.90	0.90	0.90	0.15	0.13	0.12	0.10	0.09
Branch flow	1.90	1.40	1.20	1.10	0.70	0.66	0.62	0.58	0.54
Valves									
Globe	8.70	7.00	6.00	5.60	6.30	6.00	5.90	5.80	5.80
Gate	0.25	0.17	0.14	0.12	0.16	0.13	0.11	0.08	0.06
Swing check	3.00	2.30	2.10	2.00	2.00	2.00	2.00	2.00	2.00
Angle	4.70	2.00	1.40	1.00	2.10	2.10	2.10	2.10	2.10
Foot	0.80	For all diameters							
Basket strainer		1.50	1.30	1.10	1.10	0.95	0.85	0.75	0.65
Couplings/Unions	0.08	0.05	0.04	0.04					
Sudden reduction	Dr = ratio of smaller to larger pipe				For $0.25<Dr<1.0$; $k_f = 0.45 + 0.10*Dr - 0.54*Dr^2$				
Sudden enlargement	Dr = ratio of smaller to larger pipe				$k_f = (1 - Dr^2)^2$; use velocity of smaller pipe				
Inlets/Entrances									
Bell-mouth	0.05	For all diameters							
Square edged	0.50	For all diameters							
Inward projecting	1.00	For all diameters							

Source: Engineering Data Book, First Edition. 1978. Hydraulic Institute, Cleveland, OH.

Example 5.10.

Estimate the valve and fitting related friction head loss values associated with 12 L/s of water flowing through a 100 mm diameter pipeline with the components listed below. Valves and fittings are listed with their nominal size, the k_f values are from Tab. 5.6, and the velocity head values are from Tab. 5.5. The resultant friction head loss values, h are listed in the right hand column.

Valve/Fitting	*Diameter, mm (Nominal, in.)*	k_f	$v^2 / 2g$ *(m)*	*No. of units*	h_f *(m)*
Swing check valve	*100 (4 in.)*	*2.00*	*0.12*	*1*	*0.24*
Sudden reduction[1]	*100—75 (4 in. – 3 in.)*	*0.22*	*0.38*	*1*	*0.08*
Globe valve	*75 (3 in.)*	*6.00*	*0.38*	*1*	*2.28*
Sudden enlargement[1]	*75—100 (3 in. – 4 in.)*	*0.19*	*0.38*	*1*	*0.07*
Elbows, 45 regular	*100 (4 in.)*	*0.28*	*0.12*	*2*	*0.07*
Elbows, 90 regular	*100 (4 in.)*	*0.70*	*0.12*	*4*	*0.34*
Total h_f					*3.08 m*

[1] *Velocity heads for the smaller pipe diameters are used.*

5.3.1.3.4. Emitter connection losses

Microirrigation emitters that are not formed as an integral part of the lateral (as with some collapsible drip irrigation emitting hoses) may be attached to the laterals with an in-line, on-line, or on-line-riser connection. These connections create additional local friction head losses. Karmeli and Keller (1975) present a modified version of Eq. 5.18 that substitutes the "equivalent" length (*LE*) of pipe for the actual length of pipe (*L*). The emitter connections that create additional friction head loss are related to an equivalent length of pipe (L_f) that would result in the same amount of friction head loss. Similar procedures have been used for valves and other fittings. Thus, the modified form of Eq. 5.18 for microirrigation laterals is:

$$h_{fl} = (F)\frac{LE}{100}(J) \tag{5.20}$$

where h_{fl} is the friction head loss (m) in the microirrigation lateral, *LE* is the equivalent length (m) of the lateral due to the additional friction loss from the inserted or attached microirrigation emitter connections, and the multiple outlet factor, *F*, and head loss gradient, *J*, are as previously defined in Tab. 5.4 and Eq. 5.11, respectively. The equivalent length of the lateral is based upon the following relationship:

$$LE = (n_e)(L_e + L_f) \tag{5.21}$$

where n_e defines the number of emitters on the lateral, L_e is the length of pipe (m) between emitters, and L_f is the equivalent length of pipe (m) that is equal to the friction loss created by the water flowing past each emitter connection.

Emitter related equivalent length (L_f) values may range from 1.00 to 3.00 m for in-line, insert-type emitter connections, from 0.05 to 0.40 m for in-line, protruding barb connections, and from 0.30 to 1.00 m for on-line smooth connections that do not restrict or alter flow. In-line protruding barb connections (Fig. 5.7) are very common in many microirrigation systems. Pitts et al. (1986) used protruding barb equivalent length data from Watters and Keller (1978) to create an equivalent length relationship based on the diameter of the barb and the diameter of the lateral line. The emitter related equivalent length can be estimated from:

$$L_f = (3.5)(D_b)(D_l^{-1.86}) \tag{5.22}$$

where L_f is the equivalent length of pipe (m) associated with the friction loss from the protruding barb connection, D_b is the outside diameter (mm) of the barb, and D_l is the inside diameter (mm) of the lateral. Barb diameters (D_b) range from 3.8 to 7.6 mm for many common microirrigation emitters (Fig. 5.7).

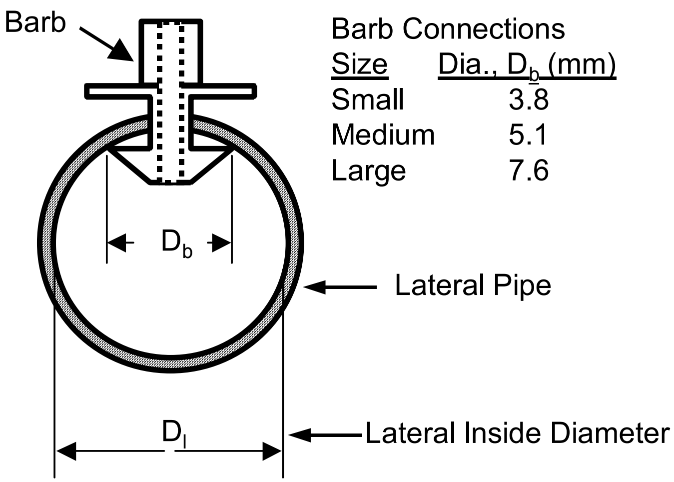


Figure 5.7. Schematic of a punched barb connection with relative barb sizes.

Example 5.11.

A 20.9 mm inside diameter polyethylene lateral supplies water to spray-jet emitters that are used to irrigate trees. The lateral is 150 m long and has one spray-jet every 5 m. The spray-jets have a 7.5 mm diameter barb that is punched (protrudes) into the polyethylene lateral. The average water discharge rate from each spray-jet is 40 L/ h. Find the estimated lateral line friction head loss.

The number of emitter connections is:

$$n_e = \frac{150\ m}{5\ m} = 30$$

From Tab. 5.4, F = 0.37 with the first emitter one full space off of the manifold. Using Eq. 5.22 with D_b = 7.5 mm and D_l = 21 mm

$$L_f = (3.5)(7.5)(21)^{-1.86} = 0.09\ m$$

The equivalent lateral length (LE) from Eq. 5.21 is:

$$LE = (30)(5.0 + 0.09\ m) = 153\ m$$

The lateral flowrate is:

$$Q_l = (30)(40\ L/h) = 1200\ L/h = 0.33\ L/s$$

The friction loss gradient (J) for a 20.9 mm lateral with 0.33 L/s of flow is 5.47 m/100 m (Tab. 5.3). The lateral friction head loss from Eq. 5.20 is:

$$h_{fl} = (0.37)\left(\frac{153}{100}\right)(5.47) = 3.1\ m$$

Whether this level of friction loss is acceptable will depend on the slope of the lateral, the operating pressure and the discharge characteristics of the emitters.

5.3.2. Emitter Hydraulics

Microirrigation emitters are the small water-dispensing devices that are designed to dissipate pressure and constantly discharge a small, uniform flow of water. Some general discussion on emitter types and characteristics was provided in Chapter 1. This section will provide more detail on the flow and discharge characteristics of microirrigation emitters and how that information is used in the synthesis and design of the system.

Emitter hydraulics can be analyzed using the continuity equation (Eq. 5.3) with the Darcy-Weisbach equation (Eq. 5.15) (Karmelli and Keller, 1975; Boswell, 1990; Keller and Bliesner, 1990). Equation 5.3 is rewritten with terms for emitter discharge q_e (L/h), based on the average flow velocity (v_e, m/s) and cross sectional area of the flow path (a_e, mm^2) as:

$$q_e = 3.6(a_e)(v_e) \tag{5.23}$$

Then, rearranging Eq. 5.15 to solve for emitter flow path water velocity:

$$v_e = \left[\frac{D_e}{1000(F_f)(l_e)}(2)(g)(h_e)\right]^{0.5} \tag{5.24}$$

where D_e is the inside diameter of the flow path, F_f is the friction factor, l_e is the length of the flow path, g is gravity, and h_e is the operating head across the emitter. Thus, Eqs. 5.23 and 5.24 can be combined as:

$$q_e = 3.6(a_e)\left[\frac{D_e}{1000(F_f)(l_e)}(2)(g)(h_e)\right]^{0.5} \tag{5.25}$$

or

$$q_e = 3.6(a_e)(C_e)[2(g)(h_e)]^{0.5} \tag{5.26}$$

where Eq. 5.26 is a general discharge equation and C_e is a hydraulic discharge coefficient that ranges from 0.6 to 1.0 (Boswell, 1990; Keller and Bliesner, 1990). Emitter hydraulic designs are quite varied and can result in laminar flow, turbulent flow, orifice flow, or pressure compensating flow. These classifications are associated with the way flow occurs in the emitter and will change the characteristics of C_e as well as the exponent of Eq. 5.26. An emitter discharge exponent *(x)* is defined and using Eq. 5.26 an emitter discharge coefficient (k_e) is:

$$k_e = 3.6(a_e)(C_e)[2(g)]^x \tag{5.27}$$

The resulting relationship between emitter water discharge (q_e) and operating head (h_e) or operating pressure (p_e), is then generalized by Eqs. 5.28 and 5.29 as:

$$q_e = (k_e)(h_e^{\,x}) \tag{5.28}$$

or

$$q_e = (k_e)(p_e^{\,x}) \tag{5.29}$$

where k_e is the emitter discharge coefficient and x is the emitter discharge exponent. The units for q_e are typically L/h with h_e in units of meters of head and p_e in units of kPa of water pressure. The units of k_e are specific to the units of p_e or h_e and q_e, whereas the emitter exponent (x) is dimensionless and typically varies between 0 and 1. Equations 5.28 and 5.29 assume consistent flow path conditions over the recommended operating pressure range for the emitters. The emitter discharge coefficient (k_e) includes dimensional characteristics of the emitter flow path. When variations in emitter flow path shape (expansions or contractions) occur due to pressure changes, Eqs. 5.28 or 5.29 may not be appropriate or may be limited to a specified operational range (i.e. pressure compensating emitters discussed below).

The three types of emitter discharge relationship are shown in Fig. 5.8. When "x" is equal to 1.0 (or very close), the emitter discharge-head (or pressure) relationship is linear and the emitter is considered to be non-compensating. This occurs with laminar flow emission devices. Some "long flow path" emitters have x-values of 0.7 to 0.8. When x is equal to 0.5, then orifice or turbulent flow is occurring. This is similar to the discharge from many standard sprinklers. As the value of x decreases below 0.5, pressure-compensating flow starts to occur. When operated within the manufacturer's specified ranges, a fully pressure-compensating emitter has an x-value of 0.0.

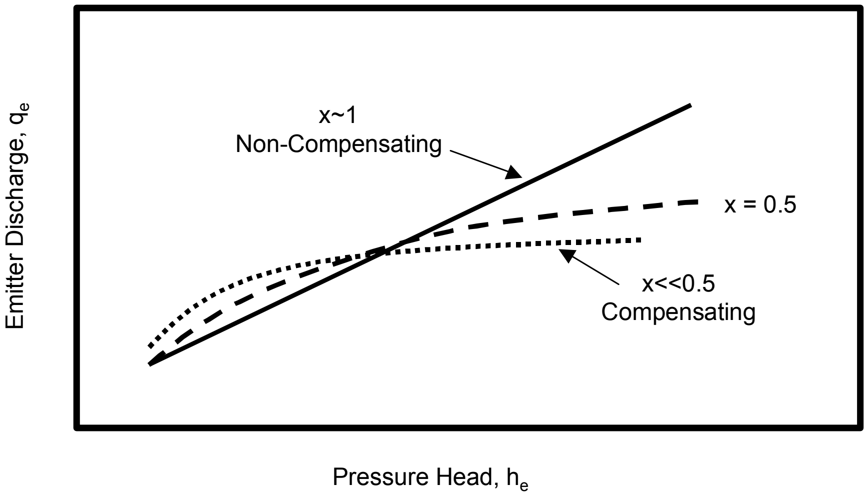


Figure 5.8. Example of emitter discharge relationships for non-compensating flow (x=1), orifice flow (x=0.5), and pressure compensating flow (x<<0.5).

For design purposes, manufacturers may provide specific values of k_e and x for different microirrigation emitter products. However, these values can also be determined using regression analysis approaches with measured or published data on the variation of q_e with corresponding values of h_e or p_e. A simple graphical analysis approach may also be used in which k_e is the y-axis intercept of the logarithmic relationship between emitter discharge and operating head or pressure (Fig. 5.9) and the exponent (x) is the slope of that relationship. Thus, by using two representative points of that relationship:

$$x = \frac{\log\left(\frac{q_1}{q_2}\right)}{\log\left(\frac{p_1}{p_2}\right)} \tag{5.30}$$

and

$$k_e = \frac{q_e}{{p_e}^x} \tag{5.31}$$

where q_1, q_2 represent the respective emitter flowrates for two different and representative emitter operating pressures, p_1 and p_2. In a similar manner, pressure heads, h, could be used instead of pressures, p.

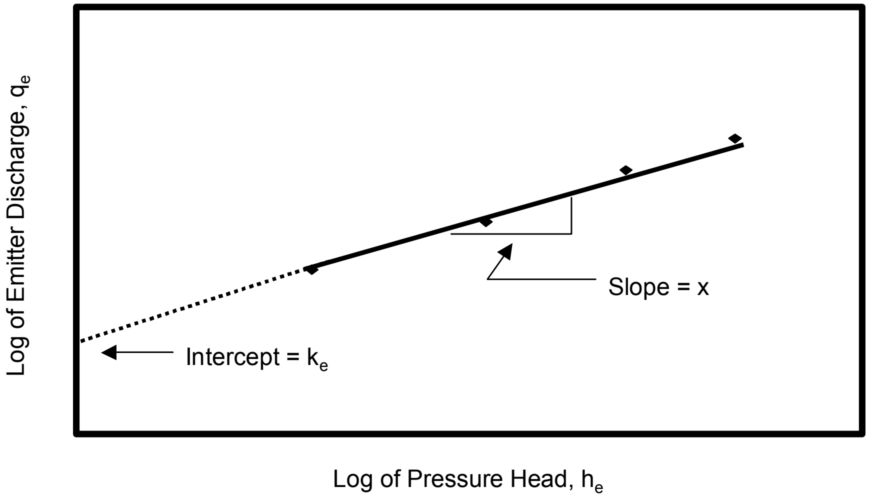


Figure 5.9. Logarithmic relationship between emitter discharge and pressure head. The slope of the relationship is the emitter discharge exponent "x" and the intercept is the emitter discharge coefficient k_e.

Example 5.12.

The following pressure and flowrate data were obtained for an emitter.

p (kPa)	*35*	*70*	*105*	*140*	*175*	*210*
q_e *(L/ h)*	*1.06*	*1.44*	*1.67*	*1.93*	*2.20*	*2.35*

Determine the emitter discharge coefficient and exponent using a regression analysis and also using Eqs. 5.30 and 5.31.

Figure 5.10 shows the graphical representation of the data along with the power series regression formula from a spreadsheet statistical analysis where $k_e = 0.216$, $x = 0.446$, and $r^2 = 0.997$.

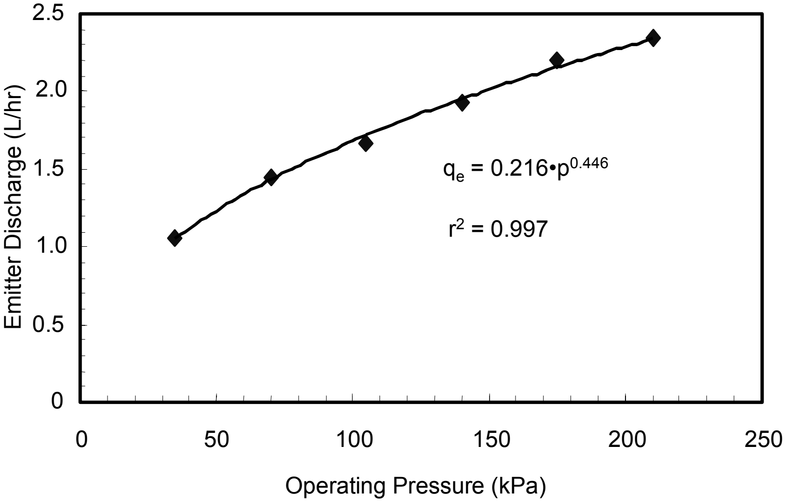


Figure 5.10. Graphical representation of the emitter discharge data from Example 5.12 along with the power series regression formula and regression correlation.

Using the 70 and 140 kPa data points with Eqs. 5.30 and 5.31 yields:

$$x = \frac{\log\left(\frac{1.44}{1.93}\right)}{\log\left(\frac{70}{140}\right)} = 0.423$$

and

$$k_e = \frac{1.44}{70^{0.423}} = 0.239$$

This second analysis results in $k_e = 0.239$ and $x = 0.423$, which vary by 10.6% and 5.2%, respectively, from the power series regression analysis results. It is important to remember that the power series analysis had a very high correlation coefficient (r^2) and utilized all six sets of data points in the analysis while the second analysis utilized just two sets of data points. If a linear regression analysis is possible, it can provide better results.

Lower emitter discharge exponents are advantageous in that they allow for greater pressure variations for a given emitter discharge variation (Fig. 5.11).

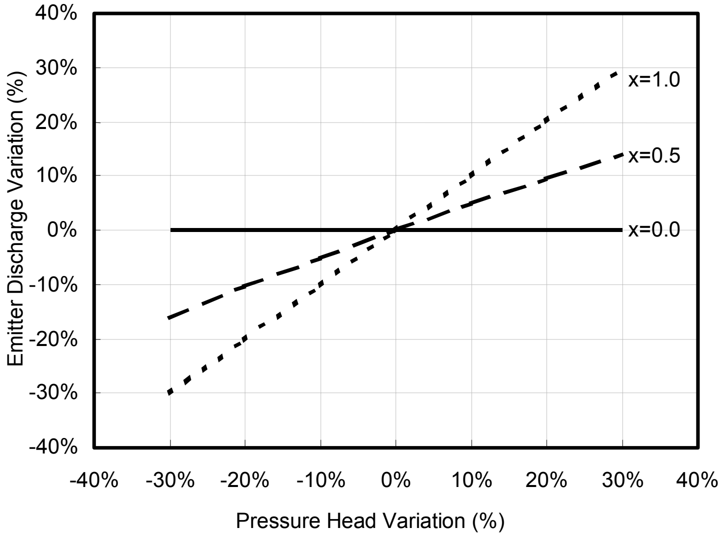


Figure 5.11. Effect of emitter exponent, x, on emitter discharge variation with respect to pressure head variations for the exponent classifications of non-pressure compensating flow (x=1.0), orifice flow (x=0.5), and fully pressure compensating flow (x=0.0).

5.3.3. Microirrigation Lateral Lines

Microirrigation lateral lines convey water from the headers or manifolds to the emitters. The combination of laterals and manifold pipe constitute a hydraulic subunit. The design process is used to size the diameters and lengths of the lateral lines and manifold within a subunit in order to achieve an acceptable level of emitter discharge variation. A general recommendation is to design the system to have 50% of the subunit pressure head variation (Δh_s) occur in the lateral lines (Δh_l) and the other 50% to occur within the manifold (Δh_m) (Karmelli and Keller, 1975; and Keller and Bliesner, 1990).

Emitter discharge rates (of non-pressure compensating emitters) vary along the length of the lateral due to internal pressure changes associated with friction head losses and/or elevation head fluctuations. Because many operating heads are in the lower ranges of 4 to 14 m, elevation changes and internal lateral line friction head loss can have a substantial effect on the lateral line operating head. The location of the maximum and minimum emitter discharge rates is dependent on the lateral diameter and flow related friction characteristics, emitter discharge rate characteristics, and orientation of the lateral (level, upward slope, or downward slope). Furthermore, manufacturing processes associated with the emitters result in hydraulic discharge differences known as manufacturer's variation. These factors need to be considered in the design of the laterals along with the flow variations that will occur due to pressure head changes.

The total head at any location along a lateral can be defined using the general energy equation (Eq. 5.5). Total head (*H*) along the lateral will change with length (*L*) and this change can be expressed as:

$$\frac{dH}{dL} = \frac{d\left(v^2/2g\right)}{dL} + \frac{dh}{dL} + \frac{dz}{dL} \tag{5.32}$$

As was previously discussed with the velocity head term, lateral line flow velocities are very low and the resultant velocity head differences will be very small and can be neglected. Thus, Eq. 5.32 can be rewritten as:

$$\frac{dH}{dL} = \frac{dh}{dL} + \frac{dz}{dL} \tag{5.33}$$

where dH/dL is the slope of the energy grade line. This term will be negative in a flowing pipe due to the internal friction loss with respect to lateral line length. The slope of the lateral is represented by the dz/dL term. The term, dz/dL, is positive for upward slope lateral orientations, negative when the lateral is positioned on a downward slope, and zero when the lateral is on flat ground. The pressure variation (dh/dL) along the lateral is expressed as:

$$\frac{dh}{dL} = \frac{dH}{dL} - \frac{dz}{dL} \tag{5.34}$$

When laterals are laid on a zero slope or upward slope orientation (Case I for both orientations), dh/dL will be negative and pressure head will consistently decrease with lateral line length. The greatest pressure and maximum emitter flowrate (q_{max}) occurs at the lateral inlet and the lowest pressure and minimum emitter flowrate (q_{min}) occurs at the distal end. For zero slope conditions ($dz/dL = 0$), pressure head changes are only due to friction head loss and the ratio of the change in pressure head (Δh) to the change in total energy head (ΔH) can be expressed using a dimensionless energy gradient relationship (Wu et al., 1986). When the Hazen-Williams friction head loss formula is used, the pressure head loss ratio (R_i) is expressed as:

$$R_i = \frac{\Delta h}{\Delta H} = 1 - \left(1 - \left(L_i/L\right)\right)^{2.852} \tag{5.35}$$

where the pressure head loss ratio, R_i, represents the fraction of the total pressure drop that occurs at a location L_i along a lateral of length L. This relationship is graphically displayed in Fig. 5.12A and shows that the majority of the friction head loss in a level (zero slope) lateral occurs in the first half of the lateral.

When laterals are laid on a downward slope (Case II), dz/dL is negative and pressure head will initially decrease with lateral line length (at a rate less than the uphill case) until a minimum value is reached, and then will increase due to elevation head gains that are greater than friction head losses. Depending on the slope, elevation head gains can closely match or even exceed friction head losses so that the distal end pressure head of the lateral exceeds the inlet end pressure head. This is shown for a hypothetical case (Fig. 5.12B) where the minimum pressure head occurs at $L_i/L = 0.30$, the maximum pressure head occurs at L_i=L, and demonstrates that the location of p_{max} and p_{min} and subsequently q_{max} and q_{min} is not as predictable as in Case I.

For a lateral on a uniform slope, the pressure head (h_i) at a position L_i can be determined using the inlet pressure (at $L_i = 0$; $h_i = h_o$), the slope (S, positive, + for upward sloped laterals and negative, -, for downward sloping laterals), and the pressure head loss ratio R_i, from:

$$h_i = h_o - (S)(L_i) - (R_i)(h_f) \tag{5.36}$$

For level, constant-diameter laterals, approximately 75% of the pressure head loss occurs at a lateral position of L_i/L equal to 0.40 (Keller and Bliesner, 1990). Similarly, Eq. 5.35 yields a value of 0.767 for R_i when a value of L_i/L equal to 0.40 is used. These relationships can be used as general rules during the initial design process of constant-diameter laterals. However, elevation effects must be considered for upward and downward sloping laterals. The following general relationship (Keller and Bliesner, 1990) can be used to estimate the lateral inlet pressure head (h_o) for constant diameter laterals.

$$h_o = h_a + (0.5)(S)(L) + (0.75)(h_f) \tag{5.37}$$

where h_a represents the average lateral pressure head, and S (positive, +, for upward sloped laterals and negative, -, for downward sloping laterals), L and h_f are as previously defined.

Even though emitter discharge rates vary along the lateral, the variation should be small and the multiple outlet analysis (Eq. 5.18) can be used for computing h_f (using $F = 0.36$, for 15 or more outlets) and will be adapted to the lateral line friction head loss analysis. The preceding procedures using Eqs. 5.35 and 5.36 can be easily programmed for computer analysis and graphical output of the pressure head distribution (see Example 5.15 later in this section). Such a procedure can be used to observe the pressure head distribution along a lateral. Equation 5.37 can be used to estimate lateral inlet pressure heads based upon desired average pressure heads, field slopes, and friction loss characteristics.

Zazueta et al. (1984) and Zazueta and Smajstrla (1995) derived an expression for the location of the minimum pressure in a downward sloping lateral (or manifold). This relationship is specific for use with Hazen-Williams and multiple outlet based analyses:

$$\frac{L_m}{L} = 1 - \left(\frac{\Delta z}{h_f}\right)^{0.54} \tag{5.38}$$

where, L_m is the distance from the inlet of the lateral to the location of the minimum pressure (m), Δz is the elevation difference (the absolute value of $S \bullet L$) along the length of the lateral, L (m), and h_f is the friction head loss (m) for the lateral pipe size without considering outlets (Eq. 5.12). The minimum head (h_{min}) in the lateral at that location (L_m) is given by:

$$h_{min} = h_o - (S)(L_m) - \frac{h_f}{2.852}\left(1 - \left(1 - \frac{L_m}{L}\right)^{2.852}\right) \tag{5.39}$$

where all terms are as previously defined, S (m/m) is negative for a downward slope, h_o is the inlet head (m), and h_f is the friction head loss (m) for the lateral pipe size without considering outlets.

As previously indicated, flow variation within laterals occur due to pressure head variations and manufacturing variations of the individual emitters. Both of these processes will be discussed and related as to how they can be used in the design process. Lateral emitter flow variation (q_{var}) can be determined from the maximum emitter flowrate (q_{max}) and the minimum emitter flowrate (q_{min}) along the lateral as:

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \tag{5.40}$$

Emitter flow variation of 10% or less is generally desirable, acceptable when between 10% and 20%, and unacceptable when greater than 20%. The emitter flowrate relationship (Eq. 5.28) can be used with Eq. 5.40 to express the emitter flow variation in terms of the maximum and minimum lateral pressure heads as:

$$q_{var} = 1 - \left(\frac{h_{min}}{h_{max}}\right)^x = 1 - (1 - h_{var})^x \tag{5.41}$$

where

$$h_{var} = \frac{h_{max} - h_{min}}{h_{max}} = 1 - \frac{h_{min}}{h_{max}} \tag{5.42}$$

in which h_{var} is the lateral pressure head variation, and h_{max} and h_{min} are the maximum and minimum lateral pressure heads, respectively. Equation 5.41 can also be rearranged to determine the pressure head ratio based upon an acceptable flow variation as:

$$\frac{h_{min}}{h_{max}} = (1 - q_{var})^{1/x} \tag{5.43}$$

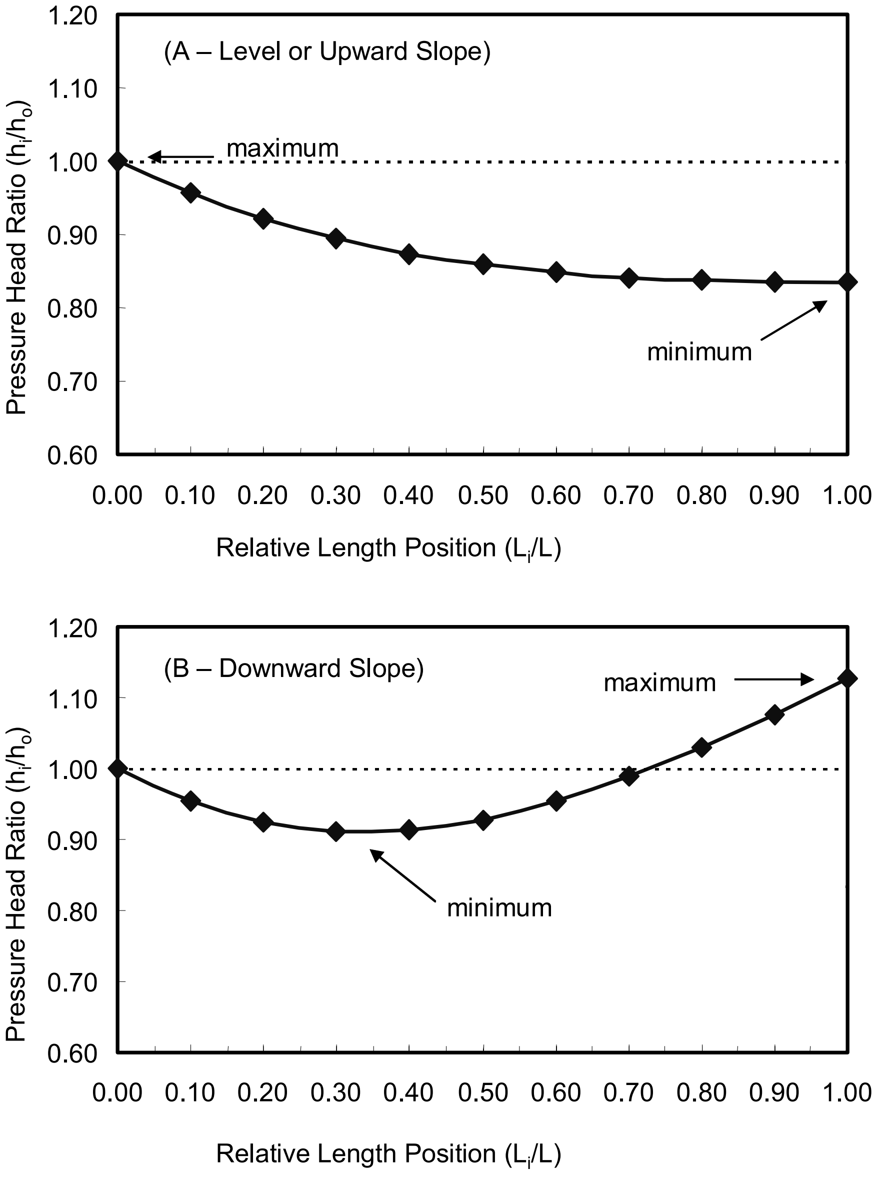


Figure 5.12. Pressure head ratio (h_i/h_o) with respect to relative lateral position (L_i/L) for (A) Case I: a level (zero) or upward sloped lateral; and (B) Case II: a downward sloped lateral. Note: Actual location of minimum values will depend on land slope and lateral friction loss characteristics.

Example 5.13.

For an emitter with an exponent of x = 0.446, calculate the emitter flow variation for a pressure head variation of 15%. Also calculate the allowable pressure head ratio for an emitter flow variation, q_{var}, of 10%.

Using Eq. 5.41 with the allowable pressure head variation of 15%

$$q_{var} = 1 - (1 - 0.15)^{0.446} = 0.070 = 7.0\%$$

and using Eq. 5.43 with the allowable emitter flow variation of 10%

$$\frac{h_{min}}{h_{max}} = (1 - 0.10)^{1/0.446} = (0.90)^{2.24} = 0.79$$

Therefore, a pressure head variation of 15% results in an emitter flow variation of 7.0%, and a 10% flow variation can allow a 79% pressure head ratio or a 21% pressure head variation.

Flow variation among emitters and within a given lateral and subunit design will also occur due to the manufacturing variability of the flowrate from the emitters. The influence of manufacturing variability can be evaluated using the design emission uniformity *(EU)* formula developed by Karmeli and Keller (1975). The design emission uniformity within a subunit is evaluated using the manufacturer's coefficient of variation (C_v), the minimum emitter discharge rate (q_{min}) within the subunit, the average (or design) emitter discharge rate (q_a) for the subunit, and the number of emitters per plant (n_p) or 1, whichever is greater as:

$$EU = 100 \left(1.0 - 1.27 \frac{C_v}{\sqrt{n_p}} \right) \frac{q_{min}}{q_a} \tag{5.44}$$

Values of C_v are statistically determined from the measured flowrates from a large (>50) sample set of emitters all subjected to the same reference pressure head and is the ratio of the standard deviation of the measured flowrates to the mean flowrate. For point-source emitters, values of C_v less than 0.05 are considered excellent, and those between 0.05 and 0.07 as average, whereas values greater than 0.07 would range from marginal to poor (ASAE EP405.1, 2000). Similarly, C_v values for line-source emitters that are less than 0.10 are classed as good while those between 0.10 and 0.20 would be average. It is generally desirable to have resulting design emission uniformities within a subunit that range from 85% to 95% for most microirrigation system types and crops on uniform topography, mildly sloped (<2%) fields. Higher *EU* values are desired with higher cash value crops, systems that are also used for chemigation purposes, and when other economic or environmental constraints favor the additional cost associated with higher design *EU* values. However, these criteria may be difficult to achieve with fields that have steep or undulating topography and/or field slopes that exceed 2% and *EU* values of 80% may be acceptable (ASAE EP405.1, 2000).

Example 5.14.

A line-source microirrigation emitter has an exponent (x) of 0.446 and is to be used on laterals within a subunit with an emitter spacing of 0.50 m in a row crop system that has an average plant spacing of 0.25 m. The design average operating pressure (p_a) for the subunit is to be 70 kPa (7.14 m) with an average emitter discharge (q_a) of 1.44 L/h (4.00 10^{-4} L/s), and a design emission uniformity (EU) of 90%. The manufacturer's coefficient of variation (C_v) for the emitter is 0.05.

What is the minimum operating pressure within the subunit for these conditions?

Equation 5.44 is rearranged as:

$$\frac{q_{\min}}{q_a} = \frac{EU}{100 \bullet \left(1.0 - 1.27 \bullet \frac{C_v}{\sqrt{n_p}}\right)} = \frac{(90)}{100 \bullet \left(1.0 - 1.27 \bullet \frac{0.05}{\sqrt{1}}\right)} = 0.961$$

Using the relationship in Eq 5.31, the ratio of the minimum and average emitter operating pressures and the minimum and average discharge rates can be expressed as:

$$\frac{q_{min}}{q_a} = \frac{p_{min}{}^x}{p_a{}^x}$$

or

$$\frac{p_{min}}{p_a} = \left(\frac{q_{min}}{q_a}\right)^{\frac{1}{x}} = (0.961)^{\frac{1}{0.446}} = 0.915$$

and

$$p_{min} = 0.915 \bullet 70\,kPa = 64\,kPa$$

Therefore, based upon the average subunit operating pressure of 70 kPa, the minimum operating pressure within the subunit should be greater than 64 kPa (6.52 m of pressure head).

5.3.3.1. Lateral line design procedures

Calculations require information on the average slope for the lateral, the emitter discharge characteristics, the emitter spacing, and the lateral average desired operating or inlet pressure head. A computer or spreadsheet analysis can simplify the procedure. The calculation steps are as follows (modeled after procedures by Wu et al., 1986):

1. Obtain emitter characteristics (k_e, x, emitter spacing (s_e), and C_v) and select an allowable emitter flow variation (q_{var}) due to hydraulics for the subunit.
2. Calculate an acceptable pressure head ratio (h_{min}/h_{max}, Eq. 5.43) and pressure head variation (h_{var}, Eq. 5.42) based on an allowable emitter flow variation, q_{var}, from Step 1.
3. Partition the allowable subunit pressure head variation from Step 2 between the lateral and the manifold. Use a 50/50 partitioning as an initial starting point. This ratio can be adjusted as laterals are designed to allow more or less variation to occur within the manifold to accommodate specific or desired length, slope, and orientation characteristics of laterals and the manifold.
4. Select (or assume) a lateral length (L) and inside diameter (D) for the lateral.
5. Determine the number of emitters (n_e) on the lateral by dividing the lateral length (L) by the emitter spacing (s_e).
6. Specify a desired average operating pressure or head (h_a) and then calculate an estimate of the average emitter flowrate (Eq. 5.28) and lateral flowrate. If the inlet pressure head (h_o) is fixed or already specified, use that value as an initial estimate of the average pressure head, h_a.
7. Estimate the total lateral friction head loss using Eq. 5.18 with h_a and the lateral flowrate from Step 6.
8. Calculate the lateral inlet pressure head (h_o) using Eq. 5.37. If the value of h_o is fixed or specified, rearrange Eq. 5.37 to calculate h_a and compare with the estimated value of h_a from Step 6. If those values are very different, repeat Steps 6 and 7. (Note: differences between calculated and estimated values of 1 to 2 % or 0.1 to 0.2 m are generally acceptable.)
9. If the lateral is on a downward slope, go to Step 12.
10. If the lateral is on an upward slope compare elevation head losses ($S \bullet L$) with the allowable pressure head loss (h_{max} - h_{min}). If the elevation head loss exceeds the allowable pressure head loss, then the lateral length must be decreased or another lateral orientation must be selected that reduces elevation head losses.
11. If the lateral is on a level or acceptable uphill slope, calculate the distal end pressure head using Eq. 5.36 ($h_i = h_L$ and $R_i = 1$ at $L_i = L$) and then determine the pressure head ratio and resultant emitter flow variation (q_{var}) using Eq. 5.41 with the inlet and distal end pressure heads and compare with Step 1. Go to Step 13.
12. Compute a pressure head loss profile using Eq. 5.36 with the value of h_o from Step 8 for about 10 equally spaced segments along the total lateral length and identify the maximum and minimum pressure head values. As an alternative or supplement to computing a pressure head loss profile, Eqs. 5.38 and 5.39 can also be used to

estimate the location and the value of the minimum pressure head. Then determine the pressure head ratio and resultant emitter flow variation (q_{var}, Eq. 5.41) and compare with the criteria established in Step 1.

13. If the computed value of q_{var} is less than or equal to the initial design criteria, accept the design.
14. If the computed value of q_{var} is substantially less than the initial design criteria, consider increasing the lateral length or decreasing the diameter and repeat the design procedure.
15. If the computed value of q_{var} is substantially greater than the initial design criteria, adjust the design criteria as appropriate or reject the design and repeat the design procedure using a shorter lateral length, a larger lateral diameter, and/or by adjusting the operating pressure head.
16. When the lateral design is accepted, review and establish the allowable pressure head variation along the manifold based on the subunit flow and pressure head variation criteria established in Steps 1, 2, and 3. When the new manifold pressure head variation criteria appear acceptable, proceed with the manifold design.

Example 5.15.

A microirrigation lateral is to be designed using the drip emitters from Example 5.12 where $k_e = 0.216$ *for pressure in units of kPa,(for pressure head units of m,* $k_e = 0.598$*) and* $x = 0.446$ *(*q_e *is in units of L/h). Laterals come fabricated with emitters on a 0.50-m spacing and lateral inside diameters of 15.8 or 20.9 mm are available. Emitter connections are smooth and do not need to be considered in the lateral friction loss analysis. It is desired to operate the lateral line with an average pressure of 70 kPa (7.1 m of head) to provide an average emitter discharge of 1.44 L/h (*$4.00 \bullet 10^{-4}$ *L/s). The field has a 1.0% slope and is 200 m long. It is desired to have a maximum emitter flow variation of 10% within the subunit. From Example 5.13, a 21% pressure head variation will provide a 10% emitter flow variation for these emitters. This analysis will attempt to design for 50% of this subunit head loss to occur within the lateral. Therefore, the lateral design criteria will be such that* $h_{var} \cong 10\%$ *(the corresponding value of* q_{var} *is 5% from Eq. 5.41).*

The objective of this design analysis will be to specify the choice of lateral inside diameter and length. The previously discussed emitter and lateral flow design relationships were programmed into a computer spreadsheet. The spreadsheet analysis revealed that pressure head losses along the 1.0% slope were too large for the 15.8 mm ID lateral. Subsequently, the lateral was analyzed using the 20.9 mm ID lateral and provided acceptable results. The analysis results for the downward slope lateral are shown below and in Fig. 5.13. The 20.9 mm lateral ID with a calculated inlet pressure head of 6.86 m will provide a pressure head variation of 14% and an emitter flow variation of 6%. While these values exceed the above lateral criteria of $h_{var} \cong 10\%$ *and* $q_{var} = 5\%$*, the pressure head variation along the manifold can be analyzed to assess whether a reduced value of (21% - 14% =) 7% will provide an acceptable design.*

The location of the minimum pressure head is at a value of L_i/L =0.20 (Fig. 5.13 and Tab. 5.8). That location can also be estimated using Eq. 5.38 with Δz=2.0 m and h_f = (1.01÷ 0.36)=2.81 m (the multiple outlet value of h_f from Tab. 5.7 corrected back to a single outlet pipe) as:

$$\frac{L_m}{L} = 1 - \left(\frac{2.0}{2.81}\right)^{0.54} = 0.17 \quad and \quad L_m = (0.17)(200\,m) = 34\,m$$

Using the above data, the minimum pressure head is then estimated using Eq. 5.39 as:

$$h_{min} = 6.86\,m - (-0.01)(34\,m) - \left(\frac{2.81\,m}{2.852}\right)\left(1-(1-0.17)^{2.852}\right) = 6.79\,m$$

These results are consistent with those in the output table. For these stated conditions a downward sloped lateral with an ID of 21 mm and a length of 200 m can be used and should provide an average emitter discharge rate of 1.44 L/h with an inlet operating head of 6.86 m. An emission uniformity (EU) analysis of the subunit should be performed after all laterals and the manifold have been designed. This will be discussed in the next section.

Table 5.7. Lateral head loss data and calculation table for the downward sloped lateral analysis of Example 5.15.

Lateral head loss calculations			
Emitter constant (k_e) (head based)	k_e =	*0.598*	*specify*
Emitter discharge exponent (x)	x =	*0.446*	*specify*
Emitter spacing (m)	s_e =	*0.5*	*specify*
Lateral length (m)	L =	*200*	*specify*
Lateral average pressure head (m)	h_a =	*7.1*	*specify*
Lateral inside diameter (mm)	ID =	*20.9*	*specify*
Lateral slope (up "+"; down "-")	S =	*-0.01*	*specify*
Number of emitters per lateral	n_e =	*400*	*calculate*
Emitter discharge rate @ spec. h_a (L/h)	q_e =	*1.43*	*calculate*
Lateral flowrate (L/h)	Q_l =	*573*	*calculate*
Lateral flowrate (L/s)	Q_l =	*0.159*	*calculate*
Lateral friction head loss (m)	h_f =	*1.01*	*calculate*
Lateral inlet pressure head (m)	h_o =	*6.86*	*calculate*

Table 5.8. Lateral pressure head profile calculation table for the downward sloped lateral analysis of Example 5.15.

L_i/L	L_i (m)	$S*L_i$	R_i	R_i*h_f	h_i (m)	h_i/h_o	q_e (L/h)
0.00	0	0.00	0	0.00	6.86	1.00	1.41
0.10	20	-0.20	0.260	0.26	6.79	0.99	1.41
0.20	40	-0.40	0.471	0.48	6.78	0.99	1.40
0.30	60	-0.60	0.638	0.64	6.81	0.99	1.41
0.40	80	-0.80	0.767	0.77	6.88	1.00	1.41
0.50	100	-1.00	0.861	0.87	6.99	1.02	1.42
0.60	120	-1.20	0.927	0.94	7.12	1.04	1.44
0.70	140	-1.40	0.968	0.98	7.28	1.06	1.45
0.80	160	-1.60	0.990	1.00	7.46	1.09	1.47
0.90	180	-1.80	0.999	1.01	7.65	1.12	1.48
1.00	200	-2.00	1.000	1.01	7.85	1.14	1.50
h_{var} = 14%		q_{var} = 6%		h_a = 7.13		q_a = 1.44	

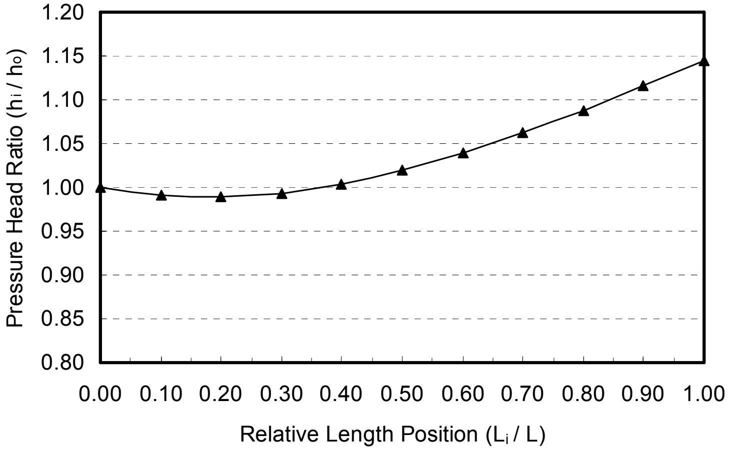


Figure 5.13. Lateral head loss spreadsheet analysis results for the downward slope portion of Example 5.15 using a lateral ID of 20.9 (21) mm (ID).

5.3.4. Manifolds

The manifold pipe supplies water from the mainline to the lateral pipelines (see Figs. 5.1 and 5.3). Because manifold pipelines have multiple outlets, design principles are similar to those used for the lateral pipelines and the previously discussed procedures and equations can be applied. The manifolds should be designed with sufficient capacity (size) to convey water within safe flow velocity guidelines and to maintain an acceptable pressure head variation across the inlets to all lateral lines. Sometimes a small header pipe (a secondary manifold) may be used to supply water from a primary manifold to two to four lateral lines as shown in Fig. 5.3. Substantial pressure variations along the manifold result in non-uniform pressure distributions to the lateral inlets and can result in substantial hydraulic discharge variations throughout the field or sub-unit.

Because manifold lines are typically placed up/down the slope, elevation head differences are often greater than in the laterals. Pressure head losses on steep upward slope orientations can require high inlet pressures to the manifold to compensate for the distal end elevation head losses. In addition, larger pipe sizes may be needed to minimize friction head losses. These conditions can result in non-uniform or higher than desired pressure head levels along the manifold and may require pressure regulators for several or all of the lateral lines. Pressure head gains on steep downward slope orientations may require pressure-reducing valves within the manifold to protect the pipeline and components as well as individual lateral line pressure regulators to ensure an acceptable level of pressure head variation along the manifold. Sometimes smaller pipe sizes are used to balance elevation head gains with friction head losses, but safe flow velocity guidelines must still be followed.

The pressure head variation (Δh_m) from the inlet end (1) to the distal end (2) of a manifold can be estimated using the general energy equation (Eq. 5.6). If velocity head differences are minimal Eq. 5.6 becomes:

$$\Delta h_m = h_1 - h_2 = z_2 - z_1 + H_F \qquad (5.45)$$

Furthermore, if the total friction head (H_F) is primarily associated with the internal pipe friction (h_f), Eq. 5.45 becomes:

$$\Delta h_m = z_2 - z_1 + h_f \qquad (5.46)$$

Friction head losses from pipe fittings can be included by using the equivalent length concepts as previously discussed. By analyzing h_f using Eq. 5.18, the pressure head ratio ($\Delta h/h_{ma}$) is

$$\frac{\Delta h_m}{h_{ma}} = \frac{1}{h_{ma}} \bullet \left[\left(z_2 - z_1\right) + (F)(L)\left(1.212 \bullet 10^{10}\right)\left(\frac{Q}{C}\right)^{1.852} D^{-4.87} \right] \qquad (5.47)$$

where h_{ma} is the average operating pressure head for the laterals along the manifold (and is equivalent to the average inlet pressure head for the laterals, h_o) and other terms are as previously defined. Expressing the slope (S) as the ratio of the elevation difference (z_2-z_1) to the manifold length (L) [such that S is positive for upward slopes], and substituting the friction head gradient (J) for single outlet pipes into Eq. 5.47 results in:

$$\frac{\Delta h_m}{h_{ma}} = \frac{L}{h_{ma}} \left[\frac{(F)(J)}{100} + S \right] \qquad (5.48)$$

Values of J can be obtained from tables and charts such as Tables 5.1a through 5.3. Using a multiple outlet factor (F) of 0.37 (as an average value for 10 or more outlets when the first outlet is one-half space from the manifold inlet), and a plastic pipe material factor (C) of 150, Eq. 5.45 can also be expressed as:

$$\frac{\Delta h_m}{h_{ma}} = \frac{L}{h_{ma}}\left[\left(4.2 \bullet 10^5\right)\left(\frac{Q^{1.852}}{D^{4.87}}\right) + S\right] \tag{5.49}$$

Equations 5.46 through 5.49 can be safely used when head loss due to friction is less than head gains due to downward manifold slope, and are therefore, applicable for all zero slope ($S = 0$) and upward slope (positive S) analyses. When elevation head losses from upward sloped manifolds exceed an acceptable pressure head loss based upon the desired pressure head ratio and operating pressure, the operating pressure must be increased to compensate for the elevation head losses as previously discussed or a different manifold orientation may need to be investigated.

When using Eqs. 5.46 through 5.49 for downward slope cases and $\Delta h_m/h_{ma}$ becomes negative, this indicates that total elevation head gains exceed total friction head losses. If the absolute value of $\Delta h_m/h_{ma}$ is less than the desired pressure head ratio, the selected pipe size may be acceptable. However, the previously outlined lateral line design procedures (Section 5.3.3.1) should be followed to assess the true locations of the maximum and minimum pressure heads and resulting pressure head ratio (see Example 5.15, and Figs. 5.12 and 5.13). If a smaller diameter pipe is selected to increase the friction head loss, pipeline flow velocities may exceed allowable limits. Therefore, larger ("safe") pipe sizes with special pressure regulation components may need to be incorporated into the design for some downward slope cases.

Example 5.16.

Manifold design.
A 75-m long microirrigation manifold is to be designed with a maximum pressure head variation of 7% (0.07) using SDR 41 PVC pipe for a system of laterals that are on a 1.5-m spacing. Each lateral is 200 m long with emitters on a 0.50-m spacing. It is desired to operate the lateral lines at 67.3 kPa of pressure (h_{ma} = 6.86 m of head) with an average lateral emitter discharge of 1.44 L/h (See Example 5.15). The manifold is on a 1.2% downward slope and supplies water at the upper end of the 200 m laterals (the laterals are on a 1.0 % downward slope, Example 5.15).

Based upon the preceding information, the 200-m long laterals have 400 emitters (see Example 5.15) and the average lateral flowrate (Q_l) is 573 L/h (0.159 L/s). Similarly, the 75-m manifold has 50 lateral connections and the estimated manifold flowrate is:

$$Q_m = (50\ laterals) \bullet \left(0.159 \frac{L/s}{lateral}\right) = 7.95\ L/s \approx 8.0\, L/s$$

Next, select a manifold diameter that has an acceptable flow velocity (<1.5 m/s) from Tab. 5.1a for SDR 41 PVC pipe (or use Eq. 5.3 as shown in Example 5.3). From Tab. 5.1a, a manifold ID of 84.6 mm provides a flow velocity of 1.42 m/s for a flowrate of 8.0 L/s. The corresponding head loss gradient (J) is 2.19 m/100 m. Therefore, the estimated friction head loss is (combining Eqs. 5.11 and 5.18 and using F=0.36 for a multiple outlet pipe with greater than 35 outlets) is:

$$h_f = (0.36)\frac{(2.19)(75\,m)}{100} = 0.59\ m$$

Head gains due to elevation changes will equal (0.012 m/m • 75 m =) 0.90 m. As a result, the manifold head gain due to elevation (0.90 m) exceeds the friction head loss (0.59 m). This will make the pressure head ratio negative as shown with Eq. 5.49:

$$\frac{\Delta h_m}{h_{ma}} = \frac{75}{6.86} \bullet \left[\left(4.2 \bullet 10^5\right) \bullet \left(\frac{8^{1.852}}{84.6^{4.87}} \right) - 0.012 \right] = -0.042$$

Equation 5.37 can be applied to estimate the inlet pressure for the manifold. If the average pressure head at the inlet to the laterals is to be 6.86 m, then the manifold inlet pressure head (h_{mo}) should be:

$$h_{mo} = 6.86\,m + (0.5)(-0.012)(75\,m) + (0.75)(0.59\,m) = 6.85\ m$$

The location of the minimum pressure head is estimated using Eq. 5.38 with Δz=0.9 m and h_f = (0.59)÷(0.36)=1.64 m (the multiple outlet value of h_f from the above head loss calculation corrected back to a single outlet pipe) as:

$$\frac{L_m}{L} = 1 - \left(\frac{0.9}{1.64}\right)^{0.54} = 0.28 \quad and \quad L_m = (0.28)(75\,m) = 21\,m$$

The minimum pressure head is then estimated using Eq. 5.39 as:

$$h_{min} = 6.85\,m - (-0.012)(21\,m) - \left(\frac{1.64\,m}{2.852}\right)\left(1-(1-0.28)^{2.852}\right) = 6.75\,m$$

The maximum pressure will occur at the distal end of the lateral and would be expected to be about 7.17 m ($h_{max} = h_{ma} + \Delta z - h_f$) The resulting pressure head variation would be:

$$h_{var} = \frac{h_{max} - h_{min}}{h_{max}} = \frac{7.17\,m - 6.75\,m}{7.17\,m} = 0.059 = 5.9\%$$

This value meets the criteria of a maximum pressure head variation of 7%.

An analysis of the lateral (not shown) at the minimum pressure location resulted in an estimated minimum emitter discharge rate (q_{min}) of 1.39 L/h. With an expected average emitter discharge rate of 1.44 L/h, using data from Example 5.15 (C_v = 0.05 and n_p = 1) the estimated emission uniformity (EU) is:

$$EU = 100\left(1.0 - 1.27\frac{0.05}{\sqrt{1}}\right)\frac{1.39}{1.44} = 90.4\% \approx 90\%$$

The subunit should have an acceptable emission uniformity with the selected lateral and manifold design conditions.

5.3.5. Mainline Pipe System Design

Mainline pipes convey water from the pump to the manifold and lateral network. The primary considerations for these pipes are (1) the water is being conveyed at a safe velocity; (2) the friction head loss is acceptable; and (3) the pipeline is economical. Consideration (1) has already been discussed and can be used as a starting point. The next two considerations are related. A larger pipeline will result in a lower friction head loss and the cost of larger pipes increases substantially with size. The designer must compare the amortized annual cost of the pipe material (and associated fittings) with the annual cost of pumping energy needed to overcome those friction head losses. In addition to these general considerations, pipeline pressure rating and elevation changes will influence the selection of the pipeline and whether special pressure reduction components or water hammer precautions need to be incorporated into the design.

The general hydraulic principles and relationships presented in Section 5.3.1 will be used to design the mainline. In contrast to manifolds and lateral lines, varying pressure heads along a mainline are not as critical and in many circumstances do not directly impact the uniformity of discharge throughout the system. In fact, many systems will include pressure control or regulation components at the inlet to the manifold from the mainline. This is particularly important on those systems with multiple length mainlines that provide water to several discrete field units.

The power required to pump water of a certain flowrate (Q) at a specified pump head (H_P) was discussed in section 5.3.1.2 and in Eqs. 5.8 and 5.9. The cost of pumping (C_P, \$) can be estimated using the required power for the pump (BP, kW), the time of operation of the irrigation system (T, h), a fuel use factor (K_F) that is specific for the type of power source (Tab. 5.9) and the cost of the fuel or energy (C_F, \$/unit) used as:

$$C_P = \frac{BP \bullet T \bullet C_F}{K_F} \tag{5.50}$$

Table 5.9. Fuel use factors for efficient power units. After Dorn et al.(1982).

Fuel/Energy source	K_F for efficient power units
Diesel	3.3 kWh / L
Gasoline (water cooled)	2.3 kWh / L
Propane	1.8 kWh / L
Natural gas	2.2 kWh / m^3
Electric	0.88 kWh / kWh @ meter

Example 5.17

A 10.0 kW electric motor provides power to a pump (70% efficient) that delivers 25.0 L/s of *water at a total dynamic head of 28.4 m (see Example 5.6). The pump operates for 1500 hours per irrigation season and electricity costs \$0.12/kWh at the meter.*

What is the expected irrigation season pumping cost for this system?

From the above information, BP = 10.0 kW; T = 1500 h; and C_F = \$0.12/kWh @ meter. From Tab. 5.9, K_F = 0.88 kWh/kWh @ meter.

Using Eq. 5.50

$$C_P = \frac{10.0\,kW \bullet 1500\,h \bullet \$0.12 / kWh@meter}{0.88\,kWh / kWh@meter} = \$2045$$

So the expected cost of pumping would be \$2045.

As previously discussed, the total dynamic head for the pump includes pressure head, elevation head, and friction head. When comparing mainline pipe sizes, the head required to overcome elevation changes and pressure differences is fixed for a given system and does not change with pipe size. However, the friction head associated with the specified flow does change with pipe size and is the only head component needed for energy related cost comparisons. The annual amortized cost is the other economic factor that changes with pipe size and is dependent on the initial cost of the pipe and associated components, the value of money (interest rate), and the expected life of the pipeline. With this latter information, a cost comparison can be performed between the annual pumping cost and the annual amortized (fixed) cost associated with different pipe sizes.

The capital recovery factor (*CRF*) can be used with the present worth (*PW*) of an item to determine the value of a uniform series of annual costs (*AC*) associated with the current value of money or interest rate (i) and the number of years (n) for the analysis as:

$$AC = (CRF) \bullet (PW) \tag{5.51}$$

where

$$CRF = \frac{i \bullet (1+i)^n}{(1+i)^n - 1} \tag{5.52}$$

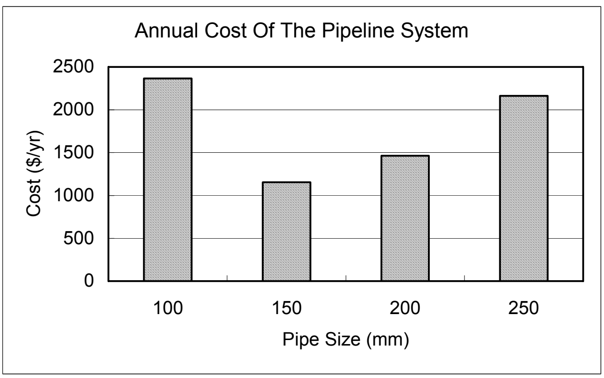
The economic mainline sizing process is outlined and demonstrated in Example 5.18.

Example 5.18

Consider a SDR 26 PVC mainline pipe (C=150) that needs to convey 25.0 L/s over a distance of 600 m. An efficient electric motor will be used with an electricity cost of \$0.12/kWh at the meter. In this example, the system needs to be operated for 1500 h annually and a pump efficiency of 70% will be assumed. The value of money is at 9% and the period of analysis (expected life of the pipeline) is 20 years.

Using this data and the initial cost data of the pipe for different sizes, a computer spreadsheet template can be designed giving results as shown below. Pipe sizes as shown represent the four pipe sizes available in Tab. 5.2b and the three largest are hydraulically acceptable for the stated flowrate. The smaller pipe size would have a flow velocity of 2.86 m/s (very high) and would require substantial precautions for water hammer. It is included in this example to demonstrate the higher energy related costs associated with the smaller pipe size.

Pipe size (mm)	*Pipe cost \$/100 m*	*Pipeline cost \$*	*Annual pipe cost \$/yr*	*Electricity cost \$/yr*	*Total cost \$/yr*	*Velocity check*
100	*600*	*3600*	*394*	*1971*	*2366*	*V>1.5 m/s!*
150	*1300*	*7800*	*854*	*300*	*1154*	
200	*2100*	*12600*	*1380*	*83*	*1463*	
250	*3250*	*19500*	*2136*	*28*	*2165*	



Pipe cost must be entered for each size and may include the cost of the associated fittings for each respective size. Based on the pipe length, the initial pipeline cost is calculated and the annual pipe cost is calculated using Eqs. 5.51 and 5.52. The annual electricity (energy) cost is determined for each respective pipe size using Eq. 5.50. The value for the brake power term (BP) in Eq. 5.50 is determined using Eqs. 5.8 and 5.9 with the substitution of h_f for H_P in Eq. 5.8 where h_f is calculated using the Hazen-Williams equation (Eq. 5.12) with the inputs of L, Q, and C as stated with the respective values of D for each pipe size.

These results show that the 150 mm pipe (actual ID = 155 mm) is the most economical with a total annual cost of $1154. Pipe cost increases substantially with size, whereas the energy cost (electricity) decreases (see table). The energy cost for the 100 mm pipe is over six times the energy cost for the 150 mm pipe. In addition to pipeline size, several other factors influence the energy cost and include the basic cost of electricity, annual time (h) of operation, and pump and motor efficiency. A substantial change in any of these factors will change the electricity cost and could result in a total cost advantage for the 200 mm pipe.

5.4. FILTRATION

Proper water treatment and filtration are essential to the continual successful operation of a microirrigation system. A clogged or partially clogged microirrigation system will result in non-uniform distribution of water (and injected chemicals) and will very likely result in crop quality degradation and yield loss. Water treatment and filtration systems and techniques are presented and discussed in Chapter 11, which includes some general information on screen filters, disc filters, media filters, settling basins, and cyclonic or centrifugal filters. The choice and arrangement of filters will largely depend on the quality of the source water (organic and inorganic suspended solids loads) and on the flowrate of the irrigation system.

In-line filtration systems may be a simple single filter or a parallel arrangement of filter units (See Fig. 11.3) designed to handle higher system flowrates. These systems will have an associated pressure or head drop (differential) across the individual unit or system of units that will vary with flowrate through the filter and may range from 14 to 34 kPa. However, manufacturer's product specifications and literature should be consulted for more specific data. As the filters collect and retain suspended solids from the irrigation water, the associated pressure drop increases. The maximum recommended pressure drop across the filter or filtration system prior to cleaning or flushing is approximately 70 kPa. This pressure loss and the associated local losses from the filtration system valves and fittings need to be incorporated into the overall irrigation design. In addition, automatic flushing filtration systems may also specify a minimum flushing pressure (e.g., 350 kPa) to ensure proper operation of the flushing components. This pressure requirement may become the primary irrigation system constraint and supersede other pressure requirements associated with the irrigation system.

Example 5.19.

Consider the water supply and control head arrangement in Fig. 5.2 with a system flowrate of 60 L/s and a required system operating pressure of 220 kPa at the entrance of the mainline that conveys the water to the irrigation zones (i.e. the last pressure gauge on the right). The mainline pipe is SDR 26 PVC 202 mm ID. The required pressure at the pump is to be determined.

The flow velocity in the pipe is 1.87 m/s (Tab. 5.2b) with an associated velocity head of:

$$\frac{v^2}{2g} = \frac{(1.87\,m/s)^2}{2 \bullet 9.81\,m/s^2} = 0.18\,m$$

The various control head components are summarized in the table below with their respective friction factor value or specified pressure drop. Friction heads are then determined and summed.

Component	*Friction factor, k_f*	*Pressure drop, (kPa)*	*Friction head, h_f (m)*	*No. of units*	*Subtotal of friction head (m)*
Tees for pressure gauges	*0.10*		*0.018*	*5*	*0.09*
Initial sand separator		*30*	*3.06*	*1*	*3.15*
Check valve	*2.00*		*0.36*	*1*	*3.51*
Gate valve	*0.08*		*0.014*	*1*	*3.52*
Main filter station		*50 (10)[a]*	*5.10*	*1*	*8.62*
Flowmeter		*5*	*0.51*	*1*	*9.13*
Control valve	*5.80*		*1.04*	*1*	*10.17*
Control head total					*10.17 m*

[a] *The initial pressure drop was specified at 10 kPa, but 50 kPa is to be used for flushing.*

Thus, the control head has an estimated pressure head drop of 10.15 m or 99.8 kPa and the required pressure head at the inlet to the control head is 319.8 kPa or about 320 kPa.

5.5 SUMMARY OF THE DESIGN PROCESS

Various aspects of the hydraulic design have been discussed and presented from general friction loss relationships to sizing laterals, manifolds, and mains. While the general steps of the design process were outlined in Section 5.1.3, this section will provide a review of the design process and general procedures.

The water supply system must be investigated for quantity and quality. Chapter 11 provides information to help with the assessment of the physical, chemical, and biological quality characteristics of the water. Suggested treatment and maintenance procedures such as water filtration and chemical amendment are also provided and discussed. The quantity and availability of the water source will help to determine the potential extent of the irrigated area and size of the zones or subunits.

The irrigated area and cropping system characteristics need to be assessed and laid out on a site plan. Field slopes, dimensions, and shapes must be configured along with cropping patterns (plant and row spacing, access alleys, etc.) to assist with the layout of the lateral network. Physical and hydraulic properties of the soil (Chapter 2) and crop water requirements (Chapter 3) also need to be characterized to help select the desired microirrigation emitter type and configuration (Chapters 12, 13, 14, and 15). Emitter hydraulic characteristics (k_e and x, Section

5.3.2) should be obtained and used with pipeline hydraulic principles and friction loss relationships (Section 5.3.1) for the lateral and manifold design processes (Sections 5.3.3 and 5.3.4).

The next part of the process involves design of the mainline system to provide water to the zones or subunits, and the control head. The mainline system (Section 5.3.5) should safely provide clean (filtered and, if needed, chemically amended) water to the subunits. The mainline system may be a single pipe that is laid out from the control head to a subunit or cluster of subunits, or it may be a network of pipes, providing water to distant and separated subunits. The mainline system design should assess both fixed and operating (energy) costs in determining the optimal size of the mainline pipes. The mainline system design process should provide an operating pressure that is required on the discharge side of the control head. Head loss through the control head (filtration units, chemical injection system(s), and control valves, Example 5.19) will then need to be determined to specify the required discharge head for the pump or entrance head for the control head so that the pump can be properly specified.

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LIST OF TERMS AND SYMBOLS

a	cross sectional area of flow in a pipe, mm^2
a_e	cross sectional area of flow in an emitter, mm^2
A	irrigated area, ha
A_z	irrigated area per zone, ha
AC	annual cost, $
BP	brake power associated with flowing water, kW
C	Hazen-Williams pipeline friction coefficient
C_e	emitter hydraulic coefficient
C_F	cost of fuel , $/unit
C_P	cost of pumping, $
C_v	manufacturer's coefficient of variation
CRF	capital recovery factor
D	inside diameter of a pipe, mm
D_b	diameter of a barb, mm

D_e	inside diameter of an emitter flow path, mm
D_l	inside diameter of a lateral pipe, mm
Dr	ratio of smaller to larger pipe diameter
E_a	irrigation system application efficiency, decimal
E_P	efficiency of the irrigation pump, decimal
ETc_{peak}	peak daily crop water requirement, mm
EU	design emission uniformity
F	multiple outlet friction loss factor
F_f	Darcy-Weisbach friction factor
g	acceleration due to gravity, 9.81 m/s^2
h	pressure head in the system, m
h_1 *or* h_2	pressure head at a location 1 or 2, m
h_A *or* h_B	pressure head of the pipe system at location A or B, m
h_a	average pressure head for a lateral, m
h_e	pressure head at the emitter, m
h_f	friction head associated with a specific pipe section, m
h_{fl}	friction head loss in an equivalent length of pipeline, m
h_i	pressure head (h) of a lateral at a location L_i, m
h_{ma}	average pressure head in the manifold, m
h_{max}	maximum pressure head, m
h_{min}	minimum pressure head, m
h_{mo}	inlet pressure head for a manifold, m
h_o	inlet pressure head for a lateral, m
h_{var}	variation in pressure head , % or decimal
Δh	general pressure head variation, m
Δh_l	pressure head variation along a lateral, m
Δh_m	pressure head variation along a manifold, m
$\Delta h_m/h_{ma}$	pressure head variation ratio in a manifold (ratio of the pressure head variation to the average manifold pressure head) [Note: Not to be confused with the pressure head loss ratio, R_i]
Δh_s	pressure head variation within a subunit, m
H	head, m
H_A or H_B	total head (energy) of the system at a location A or B, m

H_f	total friction head associated with water flowing through the pipes, m
H_F	total friction head (pipe and minor losses) through the system, m
$H_{F\ A\text{-}B}$	friction head loss in the system between locations A and B, m
H_m	total minor friction head losses associated with pipe fittings, valves, etc., m
H_P	total head (energy) associated with a pump, m
ΔH	general total head variation
i	annual interest rate or value of money, decimal
I_{gr}	gross irrigation depth per irrigation cycle, mm
I_{net}	peak daily net irrigation requirement, mm
J	pipeline friction loss gradient, m/100 m
k_e	emitter discharge coefficient
k_f	component friction loss factor
K_F	fuel use factor
l_e	length of emitter flow path, m
L	length of pipeline, m
LE	equivalent length of a pipeline, m
L_e	length of pipe between emitters, m
L_f	equivalent length of pipe associated with protruding barbs, m
$\mathrm{L_i}$	length along a lateral from the lateral inlet to a location "*i*," m
L_m	length from the inlet of a lateral to the location of the minimum pressure, m
N	number of outlets (lateral or emitter connections)
n	number of years in an analysis
n_p	number of emitters per plant
n_e	number of emitters on a lateral or 1, whichever is greater
p	system pressure, kPa
p_1 *or* p_2	pressure, kPa for an emitter at state point 1 (or state point 2) with a corresponding emitter discharge of q_1 (or q_2), L/h
p_e	emitter operating pressure, kPa
p_{min}	minimum pressure along a lateral or manifold, kPa
p_{max}	maximum pressure along a lateral or manifold, kPa
PW	present worth or value, $
q_1 or q_2	emitter discharge rate, L/h at state point 1 (or state point 2) for an operating pressure of p_1 (or p_2), kPa

q_e	emitter water discharge rate, L/h
q_a	average emitter water discharge rate, L/h
q_{max}	maximum emitter water discharge rate, L/h
q_{min}	minimum emitter water discharge rate, L/h
q_{var}	variation in emitter water discharge rate, % or decimal
Q	volumetric flowrate, L/s
Q_l	lateral flowrate, L/s
Q_m	manifold flowrate, L/s
Q_{max}	maximum volumetric flowrate capacity of the water supply system, L/s
Q_{peak}	irrigation volumetric flowrate during peak crop water demand periods, L/s
Q_{sys}	irrigation system volumetric flowrate, L/s
R_i	pressure head loss ratio; fraction of the total pressure drop in a lateral of length L that occurs at a position L_i ($0 \leq L_i \leq L$)
R_y	Reynolds number
S	slope (as a decimal, "+" = upward slope; "-" = downward slope)
s_e	spacing of emitters on a lateral, m
T	irrigation system operation time, h
T_c	irrigation system operating time per cycle, h
v	pipe flow velocity, m/s
v_e	velocity of water flow in an emitter flow path, m/s
v_A or v_B	velocity of water flow in a pipe at location A or B, m/s
$v^2/2g$	velocity head, m
WP	water power associated with flowing water, kW
x	emitter exponent
z_1 or z_2	elevation of the pipe system at location 1 or 2, m
z_A or z_B	elevation of the pipe system at location A or B, m
Δz	elevation difference between two locations, m

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6. ECONOMIC IMPLICATIONS OF MICROIRRIGATION

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"Technology defines the possibilities. Economics and policy provide the motivation."

6.1. INTRODUCTION

Microirrigation provides opportunities to improve both the farm-level net returns and the public net benefits generated with limited water resources. Potential farm-level benefits include reductions in water deliveries and labor costs, higher crop yields, and a broader set of production opportunities in regions where water supplies are particularly scarce or saline. Potential public benefits include higher farm-level net returns and the net values generated in agriculture and in other uses with water made available when farmers replace alternate irrigation methods with microirrigation. Public benefits also are enhanced when microirrigation reduces or eliminates negative impacts and opportunity costs, such as nutrient leaching, waterlogging, salinization, and the rapid depletion of nonrenewable groundwater resources.

6.1.1. The Farm-Level Perspective

Farmers can reduce water application with surface and subsurface microirrigation that can place water directly above or within the root zone or with microsprinklers that wet a smaller surface area than is possible with conventional sprinklers or surface irrigation methods. Microirrigation water requirements generally are reduced as less water is lost to surface evaporation, runoff, and deep percolation. The farm-level value of water saved is greatest in arid regions where water is scarce and in areas where farmers pay high prices for surface water or pump groundwater from significant depths.

Farmers can increase crop yields with microirrigation by improving the timing of water applications to match crop water requirements more closely than is possible with surface or sprinkler systems. Frequent, small irrigations with drip systems or microsprinklers enable farmers to minimize water stress on plants throughout the growing season. They also can apply nutrients and pesticides in a precise and timely manner with microirrigation systems and they can use microsprinklers to reduce economic losses due to frost and freeze damage of the fruits and trees. The farm-level costs of irrigation and other cultural practices are modified when farmers replace conventional systems with microirrigation. The initial cost of a microirrigation system is higher than most surface and sprinkler irrigation systems. Hence, the annual fixed costs of irrigation usually increase with adoption of microirrigation. Some of the variable costs of production will decrease with microirrigation, whereas others might increase. For example, the irrigation labor might be reduced, but maintenance, repairs, and replacement costs may increase substantially. Labor requirements for applying fertilizer and pesticides might be reduced if those materials are delivered with the microirrigation system. Reductions in labor can improve the farm-level economics of microirrigation by reducing salaries and the costs of hiring and retaining seasonal workers.

Management costs are higher with microirrigation than with surface and sprinkler systems, as greater knowledge and management efforts are required to ensure successful operation and maintenance. Irrigations must be scheduled correctly and the systems must be monitored regularly to ensure that emitters are working properly and delivering the desired volume of water. Clogged or broken emitters can negate potential yield improvements. In addition, the quality of water available for irrigation and the flexibility of service provided by a water delivery agency often must be improved or modified to support microirrigation.

The costs and benefits of microirrigation will vary among farms, crops, and geographic regions with differences in natural resources, cropping opportunities, weather conditions, prices of inputs and outputs, and availability and cost of capital. In regions where water supply is limited, relative to the supply of arable land, microirrigation may be able to support a larger irrigated area. Microirrigation also may broaden cropping choices in arid regions and allow expansion of crop production where reliable or affordable irrigation labor is scarce relative to the supply of land and water.

Microirrigation is technically feasible with most agricultural crops, but the range of crops and production settings for which it is financially and economically feasible is limited. Relatively few crops generate sufficient returns to microirrigation to justify farm-level investment at prevailing prices for water, labor, and other key inputs. In many cases, microirrigation improves water use efficiency, based on the volume or mass of crop yield per unit of water input, but farm-level net revenue is reduced. Efforts to encourage adoption of microirrigation in those situations will require financial incentives that supplement the farm-level value of water saved or the increase in crop yield.

Microirrigation is economically viable on many high-valued fruit and vegetable crops, where moderate responses to improved water management generate large increases in revenue. Positive returns have been shown also for cotton, sugarcane, and corn in some situations. By combining microirrigation with specific cultural practices, such as using plastic mulch on vegetables, or applying pesticides or fertilizer, profitability can be increased.

Farmers will readily adopt microirrigation if they can recover the costs of installing, maintaining, and operating a system through water and labor savings, improve crop yield or quality, expand crop activities, or reduce the cost of performing cultural practices. Adoption is also increased when a system can offer more than one benefit and when microirrigation enhances production opportunities. Examples include using microsprinklers to reduce frost damage or to provide evaporative cooling of trees, and using drip systems to apply saline water that would otherwise damage crops when applied with sprinklers. Subsurface drip irrigation systems may enable farmers to apply treated municipal effluent in regions with limited fresh water supplies or to dispose of wastewater generated in livestock operations. Wastewater use through microirrigation may generate both private and public benefits.

6.1.2. The Public Perspective

The public benefits of microirrigation include the net gains in value generated with limited water supplies in agriculture and the values generated in other uses with water saved by improving irrigation management. Such uses include industry, recreation, and environmental enhancement. Public benefits also are improved when microirrigation reduces the occurrence or magnitude of negative impacts and opportunity costs that often are not considered by individual farmers. For example, widespread adoption of microirrigation may reduce nitrate leaching into groundwater or increase the effective water supply for a large number of farmers within an irrigated area. Slowing the rate of depletion of a nonrenewable groundwater resource generates public benefits by reducing the rate of increase in regional pumping costs and extending the useful life of the resource. Waterlogging and salinization may be reduced. Water supplies for farmers furthest from the water source may be increased when farmers along the supply source replace surface irrigation methods with microirrigation.

In most irrigated areas, farmers do not face water prices or allotments that reflect the impacts of their decisions on downstream farmers or on the useful life of a groundwater supply. Thus, they will not adopt microirrigation at the rate that would maximize public net benefits. This divergence between farm-level and public benefits provides the basis for publicly funded research in microirrigation and public efforts to encourage its adoption. Such efforts may require supportive regulations or financial incentives in cases where microirrigation enhances public net benefits, but reduces the farmer's net returns at prevailing input and output prices.

The public or social goals for studying and promoting microirrigation and other related technologies might be described as: (1) increasing agricultural productivity, (2) enhancing farm incomes, and (3) generating greater public net benefits with limited resources. All of those goals motivate public and private funding for research, extension, and financing activities that provide information to assist farmers with the system acquisition, operation and maintenance. Farmers will invest in microirrigation independently or seek assistance from public agencies when the returns are positive. Public programs and policies will be required to encourage microirrigation adoption in regions where it is not economically viable.

Policies to motivate adoption include subsidies for investing in microirrigation systems and higher farm-level prices for water. Public investments in research to develop less expensive microirrigation options and new crop production alternatives that enhance the profitability of microirrigation also increase its adoption. The potential public gains from such policies may be substantial in arid and semi-arid regions where groundwater overdraft threatens the sustainability of irrigated agriculture, and where waterlogging and salinization reduce crop yields and limit production opportunities. Policy analysis is improved by microirrigation experiences and information describing the potential costs and benefits.

6.2. FARM-LEVEL COSTS OF MICROIRRIGATION

6.2.1. Fixed and Variable Costs

Investment in an irrigation system generates a fixed cost that must be paid each year, regardless of the volume of water delivered with the system. The annualized fixed cost includes the repayment of a loan or the opportunity cost of capital used to purchase the system, maintenance that must be performed regardless of use, depreciation, and any tax or insurance payments. In general, the annual fixed costs of microirrigation are larger than surface systems due to the greater initial investment required to purchase and install microirrigation systems.

Variable costs of irrigation include water, labor, energy, management, and material expenses that vary with the amount of water applied. The annual cost of water per hectare generally is reduced with microirrigation, whereas the annual labor cost may increase if the increase in labor required for maintenance and repairs exceed the reduction in labor required for delivering water. Energy costs per hectare will be reduced with microirrigation in regions where farmers pump groundwater and the total cost of pumping increases with the volume withdrawn. Energy costs may increase when microirrigation replaces a gravity-flow or subirrigation system if pumping is required to pressurize a drip or microsprinkler system. The costs of management and materials generally will increase with microirrigation.

Farm-level production costs will rise when the sum of annual fixed and variable costs for microirrigation are higher than the sum for an alternative system. Farmers will invest in microirrigation only if any increase in costs is offset by an improvement in the size, quality, or timing of crop yields, or by some other enhancement in production opportunities. For example, microirrigation may enable farmers to produce high-valued crops, to increase the number of crops grown per year, or to extend the number of years over which they can produce crops in regions with limited or saline water supplies. Microirrigation also enables some farmers to irrigate small, irregularly shaped parcels at a lower cost than is possible with other irrigation methods.

6.2.2. Examples from the Literature

The fixed and variable costs of microirrigation are described in several studies prepared since the 1980s. The cost estimates reviewed here are shown in the same, current dollar values reported in original articles. They are not adjusted for inflation because both the technology of irrigation and the cost of materials have changed substantially over time. Hence, it would not be appropriate to make intertemporal cost comparisons, even if the estimates were adjusted for inflation. However, inferences drawn from cost comparisons within a given year are helpful in describing the economic implications of microirrigation to the farmer.

6.2.2.1. Irrigating vegetables in Florida

The economics of irrigation methods for fresh-market tomatoes and other vegetables have been examined extensively in southwest Florida, where seepage irrigation utilizing high water tables has been used for many years. Irrigation requirements are reduced with microirrigation, but crop yields are not increased, and the farm-level value of water saved is not sufficient to justify the higher annual cost of irrigation. Thus, farmers would require compensation for potential losses in net revenue when switching from seepage irrigation to drip systems. Cost comparisons provide estimates of the level of compensation that might be required.

The popularity of seepage irrigation is due, in part, to a relatively low initial investment cost and the lowest sum of annual fixed and variable costs among alternative irrigation systems. The estimated initial investment cost of a seepage system was $333/ha in 1981, whereas the cost for a drip system was $1,534/ha, and subsurface drain system was $2,438/ha (Tab. 6.1). The estimated annual variable costs were lowest for the drip system, as less water was applied, even though more labor was required for maintenance than with the other systems (Prevatt et al., 1981). The assumed irrigation depths were 1,524 mm, 762 mm, and 254 mm for the seepage, subsurface drain, and drip systems, respectively. Without an improvement in crop yields, farm-level net revenue would have declined by an estimated $281/ha with conversion from seepage to drip irrigation for tomato farms in southern Florida.

Drip systems remained more expensive than seepage systems in 1984 and 1991, although the estimated annual total cost of a drip system was less than that of a subsurface drain, traveling gun, or center pivot system in 1984 (Tab. 6.1). The estimated annual variable costs were lowest for the drip system in 1984, as less water was applied and the unit cost of pumping was lowest with the drip system (Prevatt et al., 1984). The estimated water deliveries were 1397, 1,016, 914, 914, and 762 mm, for the seepage, subsurface drain, traveling gun, center pivot, and drip systems, respectively, while the estimated tomato yield was about 28 Mg/ha for all systems. The estimated annual variable cost of drip irrigation in 1991 included the cost of drip tubing that must be replaced each year ($344/ha). The estimated variable cost of pumping remained lowest for the drip system in 1991, although the annual total cost was lowest for the seepage system (Pitts and Clark, 1991).

Many Florida vegetable growers with sandy soils and naturally high water tables irrigate with semi-closed subirrigation systems where buried PVC pipe conveys water from the pump to lateral ditches in the field (Clark and Stanley, 1992). Higher water use efficiencies can be obtained with fully closed systems where drip tubing is used for conveyance and with drip irrigation, but the initial investment costs and the annual fixed and variable costs are higher for those systems (Prevatt et al., 1992a). The estimated initial cost was 36% higher for a drip system than for a semi-closed system in 1992, whereas the estimated sum of annual fixed and variable costs was more than 76% higher for the drip system (Tab. 6.1). Estimated annual variable costs include the cost of disposable drip tubing for the fully enclosed and drip systems. The estimated water deliveries were 1,676, 1,168, and 610 mm for the semi-closed, fully closed, and drip systems, respectively.

Drip irrigation enabled farmers to reduce water applications on potato fields in Florida, but pumping costs are greater than those required with seepage irrigation due to an increase in operating pressure (Smajstrla et al., 2000). Higher pumping costs, in addition to an estimated system conversion cost of $990/ha, lead to a substantial economic disincentive for farmers to replace subirrigation with drip systems. The conversion cost includes the cost of subsurface laterals, installation, irrigation pump and power unit replacement, and filtration and water treatment.

When water is not expensive and yield is not improved, drip irrigation of vegetables in southwest Florida is not economically viable. In particular, drip irrigation increases annual production costs, reduces the expected value of net returns, and increases risk (Prevatt et al., 1992b). Subirrigation generates higher levels of expected returns with less risk, in both single-cropping and double-cropping scenarios. Thus, farmers will not adopt drip irrigation systems for vegetables Florida without an economic incentive that compensates them for a reduction in expected net revenue and an increase in risk.

Table 6.1. Estimated fixed and variable costs of selected irrigation systems for use in vegetable production in Florida, in current (nominal) dollars per hectare.

Literature citation and cost category	Seepage	Subsurface drain	Drip irrigation	Traveling gun	Center pivot
Prevatt et al., 1981					
Initial investment	333	2,438	1,534		
Annual fixed costs	175	541	600		
Annual variable costs	208	98	64		
Annual total costs	383	639	664		
Prevatt et al., 1984					
Initial investment	792	2,978	2,470	1,137	1,547
Annual fixed costs	209	809	816	311	437
Annual variable costs	252	193	127	876	598
Annual total costs	461	1,002	943	1,187	1,035
Pitts and Clark, 1991					
Initial investment	1,350		1,700		
Annual fixed costs	243		306		
Annual variable costs	131		401		
Annual total costs	374		707		
Prevatt et al., 1992a					
Cost category	Semi-closed subirrigation	Fully closed subirrigation	Drip irrigation		
Initial investment	1,527	1,626	2,084		
Annual fixed costs	278	299	393		
Annual variable costs	229	376	498		
Annual total costs	507	675	891		

6.2.2.2. Irrigating field crops with subsurface drip irrigation systems

Surface and center pivot sprinkler irrigation systems are the most prevalent irrigation methods for field crops in the central Great Plains of the United States. Center pivot sprinklers are more expensive to own and operate than surface methods, but farmers can achieve higher application efficiencies with the sprinkler systems. Center pivot sprinklers have gained popularity in recent years as pumping costs have increased with declining groundwater levels. Subsurface drip irrigation (SDI) systems may enable farmers to reduce annual pumping costs further, while helping also to extend the useful life of nonrenewable groundwater resources.

The initial cost of a SDI system is considerably higher than a center pivot sprinkler system for a typical 65-ha rectangular field due to the large number of drip laterals required. However, a SDI system provides water to all parts of the field, whereas a center pivot sprinkler system irrigates a 51-ha circle, leaving 14 ha of non-irrigated land. Thus, the higher total revenue offsets a portion of the higher cost of the SDI system. SDI systems may have a cost advantage over sprinkler systems on small and irregularly shaped fields because the initial investment in equipment and materials varies directly with the size of the system. Thus, the per-hectare fixed cost of a drip system is nearly the same for large and small fields, whereas the per-hectare fixed cost of a center-pivot sprinkler system is much higher on small fields than on large fields (Bosch et al., 1992; O'Brien et al., 1998).

The estimated initial investment costs of center pivot sprinkler and SDI systems for irrigating a 65-ha field of corn in western Kansas in 1994 were $48,490 and $90,995, respectively (Tab. 6.2). The annual fixed cost is much smaller for the center pivot system, whereas the annual cost of pumping groundwater is smaller for the SDI system (Dhuyvetter et al. 1994). The sum of annual costs is higher for the SDI system, and as a result net returns are $55 per ha greater for the center pivot sprinkler system.

The estimated total cost of a center pivot sprinkler system in 1998 declined from almost $41,000 to less than $25,000 when the field size was reduced from 65 ha to 13 ha (Tab. 6.3). The initial cost of a SDI declined more steeply, decreasing from about $86,000 for a 65-ha field to about $21,000 for a 13-ha field (O'Brien et al., 1998). As a result, the per-hectare investment cost for a SDI system increases very slowly with decreasing field size, whereas the per-hectare investment cost of a center pivot system increases from $806/ha for a 65-ha field to $2,417/ha for a 13-ha field.

Crop income is higher with SDI than with a center pivot sprinkler because a larger portion of any rectangular field is irrigated, and the net revenue generated per hectare of irrigated land is greater than net revenue earned on non-irrigated corners of center pivot fields (O'Brien et al., 1997, 1998). Thus, while the net returns to crop production are higher with center pivot systems for field sizes ranging from 26 ha to 65 ha, a SDI system generates higher net returns on 13-ha fields (Tab. 6.4).

The relative economic viability of center pivot and SDI systems depends upon crop yield, prices, dripline costs, and the expected life of system components. For example, higher corn yields and prices improve the profitability of SDI systems that deliver water to all portions of a field (O'Brien et al., 1997, 1998). Similarly, a reduction in the cost of drip laterals or an increase in the expected life of the SDI system increases the net revenues. Efforts to reduce the cost of a SDI system by increasing the spacing between laterals may not be cost effective as the decline in crop yields may offset the reduction in system costs (Lamm et al., 1997; Bosch et al., 1998). Crop yields might be maintained with wider lateral spacing by applying more water (Powell and Wright, 1993), but the cost of additional pumping may offset potential gains in revenue in regions with substantial depths to groundwater.

Table 6.2. Estimated costs of center pivot sprinkler and subsurface drip irrigation (SDI) systems for use on a 65-ha field in the central United States, in dollars per hectare, 1994. After Dhuyvetter et al. (1994).

Irrigated area and cost components	Center pivot system	SDI system
Irrigated area (ha)	51	65
Initial investment cost (total $)	48,490	90,995
Initial investment cost ($/ha)	951	1,400
Annual fixed cost of irrigation system ($/y)	93	219
Annual pumping costs ($/y)	115	96
Other annual production expenses ($/y)	422	554
Sum of annual costs ($/y)	630	869
Crop income ($/y)	810	994
Net returns ($/y)	180	125

Table 6.3. Investment costs for center pivot sprinkler and subsurface drip irrigation (SDI) systems for various field sizes in the central Great Plains of the United States, 1998. After O'Brien et al. (1998).

	Center pivot sprinkler			SDI system		
Field size (ha)	Irrigated area (ha)	Total cost ($/field)	Cost per unit area ($/ha)	Irrigated area (ha)	Total cost ($/field)	Cost per unit area ($/ha)
65	50.6	40,782	806	64.8	86,210	1,331
52	40.5	37,948	938	51.4	72,258	1,406
39	30.4	34,527	1,138	38.5	54,388	1,415
26	20.2	29,909	1,478	25.9	34,836	1,345
13	10.1	24,459	2,417	13.0	21,251	1,641

Center pivot systems also are used on row crops in Virginia where yields on irrigated fields are significantly higher than on non-irrigated fields. The estimated investment costs for a SDI system and a towable center pivot sprinkler system for a 61-ha field were $1,381/ha and $1,242/ha in 1992, respectively (Bosch et al., 1992). Simulated crop yields for the two irrigation systems were similar, but less water was applied with the subsurface drip system. Simulated net revenue was higher with the SDI system on a 30-ha field, whereas the towable center pivot generated greater net revenue on 61-ha and 122-ha fields.

Table 6.4. Estimated income, costs, and net returns for center pivot sprinklers and subsurface drip (SDI) systems for various field sizes in the central Great Plains of the United States, 1998. After O'Brien et al. (1998).

	Center pivot sprinkler			SDI System		
Field size (ha)	Crop income (ha)	Crop costs ($/field)	Net returns ($/ha)	Crop income (ha)	Crop costs ($/field)	Net returns ($/ha)
65	1,023	785	238	1,256	1,072	184
52	1,023	795	228	1,246	1,074	172
39	1,023	811	212	1,244	1,074	170
26	1,022	837	185	1,256	1,074	182
13	1,022	912	110	1,261	1,123	138

Most farmers irrigating with groundwater pay only the costs of pumping water to the surface and distributing it on farm. Few farmers pay a severance tax or usage fee imposed by a public agency to slow the rate of groundwater depletion. Economic theory suggests that such a fee should reflect the scarcity value of groundwater, both within a current season and over time. Imposing a severance tax would increase the farm-level cost of water and enhance the net returns to investing in microirrigation. Severance taxes and other incentive policies would encourage farmers to adopt microirrigation in regions with severe groundwater overdraft.

6.2.2.3. Other examples

Drip irrigation is less expensive than other pressurized irrigation methods used on almond orchards in California. Both the initial investment costs and the annualized costs of operation, maintenance, and ownership are lower for drip systems than for solid-set sprinklers, microsprinklers or minisprinklers (Tabs. 6.5 and 6.6). The initial cost of a sprinkler system is increased when it is designed to provide some degree of frost protection, and such systems are included in the analysis that generated the cost estimates appearing in Tabs. 6.5 and 6.6 (Schwankl et al., 1999b). Thus, a portion of the cost differential between drip systems and sprinkler systems may be attributed to the frost protection provided by sprinkler systems. Installation is the largest component of the initial investment cost for drip systems, solid-set sprinklers, and microsprinklers, whereas the cost of sprinklers is the largest component for minisprinkler systems. Pumping and maintenance costs are similar for the solid-set sprinklers and the microirrigation systems. The widespread adoption of microsprinklers on almonds in California suggests that such practice is profitable.

The initial cost of a microirrigation system varies with system design, as the costs of laterals and emitters often are the largest cost components. Tiwari and Reddy (1997) examined the impact of drip system lateral and plant spacing on crop yields and costs and returns in banana production on 1-ha plots in Kharagpur, India. The estimated capital costs ranged from \$251/ha for a 2 m by 8 m spacing (laterals by plants) with four plants at each site, to \$1,006/ha for a 2 m by 2 m spacing with one plant at each site. The highest average yield and net return (31.25 t/ha and $2,438/ha) were obtained on the 2 m by 2 m spacing with one plant at each site. The net returns to microirrigation of bananas appear to be positive, but financial assistance may be required to support farm-level investments, particularly in developing countries.

Table 6.5. Estimated initial costs of irrigation system components for an almond orchard in California, in dollars per hectare, 1999. After Schwankl et al. (1999b).

Cost component	Solid-set sprinklers	Drip irrigation	Microsprinklers	Minisprinklers
Sprinklers or tubing and emission devices	855	626	423	797
Pipelines	1,011	184	263	373
Misc. equipment	363	279	347	419
Filters	257	467	566	243
Installation	1,630	642	659	612
Pump	516	225	350	426
Total	4,632	2,423	2,608	2,870

Table 6.6. Estimated annualized costs of alternative irrigation systems for an almond orchard in California, in dollars per hectare, 1999. After Schwankl et al. (1999b).

Cost component	Solid-set sprinklers	Drip irrigation	Microsprinklers	Minisprinklers
Irrigation system hardware	362	219	232	252
Electrical energy for pumping	466	406	464	441
Maintenance	107	108	97	97
Taxes and insurance	93	48	52	56
Total	1,028	781	845	846

Rubber pipe laterals and drippers account for more than one-half the estimated cost of $6,049/ha for a surface drip system for use on vegetables in Pakistan (Chandio et al., 1995). The 16,615 m of rubber pipe laterals are expected to last 10 years, but the drippers may need to be replaced annually at a cost of $887/ha, due to damage from high summer temperatures (40 to 45°C). Thus, both an improvement in materials and a reduction in cost may be needed before drip irrigation is adopted.

Microirrigation systems have been used for many years throughout the Middle East, where water is especially scarce. Improvements in technology and reductions in the per-unit costs of components have enhanced the economic viability of microirrigation compared with surface and sprinkler systems. For example, the estimated initial cost of a surface drip system for irrigating orange trees in Jordan was $687/ha in 1996, whereas the initial cost for a comparable sprinkler system was $1,188/ha (Ahmed and Mrayan, 1996). The main pipeline accounted for about one-half of the sprinkler system cost, whereas submain lines and laterals accounted for one-half of the drip system cost. The estimated annual maintenance costs for the drip and sprinkler systems were $1,459/ha and $2,517/ha, respectively. The high cost of irrigation water in the Middle East has motivated many farmers to adopt microirrigation in an effort to maximize the value generated with limited water resources.

6.3. FARM-LEVEL BENEFITS OF MICROIRRIGATION

Many studies of the agronomic implications of microirrigation have been published since the 1970s. Some authors have compared irrigation requirements, water management practices, and crop yields on experimental plots irrigated with microirrigation systems, sprinklers, and surface systems, whereas others have compared the farm-level costs and returns. Research studies cannot precisely replicate the agronomic and economic environments in which farmers operate, but they are useful in describing many of the potential impacts of microirrigation on variables that influence farm-level costs and returns.

6.3.1. Crop Yield Effects

6.3.1.1. Deciduous fruits and nuts

Microirrigation is appropriate in orchards and vineyards because only a small portion of the surface area is wetted so that farmers can spray, prune, cultivate, and harvest the crop without concern for the irrigation schedule. Soil compaction between rows of trees and vines caused by traffic on recently irrigated inter-row spaces also may be reduced (Dasberg and Or, 1999). Farmers in some regions gain additional benefits by using their systems to provide evaporative cooling and frost protection of trees and fruits. Other potential benefits include smaller water deliveries when trees are young and root systems are not fully developed, larger fruit size, earlier ripening, and better control of nematodes.

Overtree (overhead) sprinklers have promoted earlier harvest and improved the size, shape, and color of Red Delicious apples in North Carolina, which is a relatively warm apple-producing region (Unrath, 1972). Apple yields and quality also have been improved in Shandong Province, China by irrigating with overtree microsprinklers for one hour daily at dusk, beginning 40 days prior to harvest (Zhang et al., 1995). Daily misting may enhance the microclimate, accelerate assimilation, reduce respiration, and stimulate the formation of anthocyanin, which promotes red color development (Iglesias et al., 2000). Larger fruit size and reduced incidence of fruit drop have been achieved on semi-dwarf apple trees irrigated with overtree microsprinklers in Ohio (Funt et al., 1995), where boron and calcium were delivered daily through the irrigation system. Cumulative water deliveries during the first four years after planting of Redspur Delicious trees were reduced by 80% with drip irrigation compared with sprinkler irrigation plots in Washington state (Middleton et al., 1979).

Irrigation treatments ranging from 50% to 175% of estimated crop evapotranspiration (ET) were examined during a five-year experiment with drip-irrigated almond trees on a Panoche clay loam on the west side of California's San Joaquin Valley (Hutmacher et al., 1994). Almond yields increased with applied water from 50% of ET through 125% of ET. No consistent, significant increases in tree growth or nut yields were obtained at water applications in excess of 150% of ET. Vegetative growth and crop yield increased with the volume of water applied per tree during a five-year experiment with young, drip-irrigated almond trees in Spain (Torrecillas et al., 1989). An alternate bearing pattern that was evident during the first four years of the experiment on three of the irrigation treatments was not evident on the wettest treatment.

Almond tree growth and yields obtained with surface and subsurface drip systems and microsprinklers were compared during a five-year study on a gravelly, loamy sand in California's Sacramento Valley (Schwankl et al., 1999a). Both tree growth and crop yields generally were highest on plots irrigated with microsprinklers, due perhaps to the larger wetted area, which is described as particularly important at the site where the soil is coarse with limited lateral movement of water in the soil profile.

6.3.1.2. Citrus

Microirrigation has become the standard method of irrigation in Florida for citrus. Most new plantings are irrigated either with drip systems or microsprinklers as older overhead sprinkler systems have been converted (Boman and Parsons, 1999). Microirrigation was adopted rapidly in Florida, increasing from 2,400 to 210,000 ha during the period 1974 to 1995 (Smajstrla, 1993; Smajstrla et al., 1995). Microsprinklers are more popular than drip systems because they require only one emitter per tree, they can provide protection from freezes, and yields are increased by irrigating a larger portion of the root zone (Smajstrla, 1993).

Investment costs for microirrigation systems can be as high as $2,000 to $2,500/ha (Boman and Parsons, 1999) and annual maintenance costs also can be substantial. The estimated average annual cost of maintaining microirrigation emitters in Florida was $62/ha in 1994, as reported in a survey of 61 citrus production managers representing 53,000 ha of citrus groves (Boman and Ontermaa, 1994). Maintenance costs ranged from a few dollars to $198/ha, although most of the costs reported were between $25 and $98/ha (Boman and Parsons, 1999). The estimated average annual costs of maintaining drip systems and microsprinklers were $42/ha and $74/ha, respectively.

Microirrigation enables citrus farmers to minimize water application while maintaining or increasing crop yields. In addition, microsprinklers can reduce damage to citrus trees during frost and freeze events. Based on these dual sources of economic benefits, microsprinklers have replaced most of the heaters and wind machines that have been used in Florida to protect for frost and freeze protection of citrus groves (Boman and Parsons, 1999).

6.3.1.3. Small fruits

Microirrigation has been used in small fruit production for many years in both arid and humid environments. Drip systems have been particularly popular because nutrients can be applied with irrigation water at regular intervals throughout the growing season. The benefits of using microirrigation to deliver fertilizer vary among crops according to the amount and timing of nutrient requirements. For some crops, the continuous application of nitrogen and other elements improves crop yields, whereas for others a single application of fertilizer at a key time in the growing season may be more effective.

Drip irrigation promoted improved early fruit maturity, total yield, and fruit size of strawberry compared with overhead sprinkler irrigation in Florida (Locascio et al., 1977). The amount and timing of fertilizer application also had significant impact on crop yields. Highest yields were achieved when one-half of the seasonal nitrogen and potassium application was delivered with the drip system, and one-half was applied before planting.

In some areas of Florida, water is less expensive than other production costs and farmers have little incentive to minimize water deliveries (Clark et al., 1996a). Thus, although strawberry yields on plots maintained at soil water tensions of 5, 10, and 15 kPa with drip systems were not significantly different, the value of water saved may not have been sufficient to motivate farm-level investment in drip irrigation.

6.3.1.4. Tomato

Drip irrigation may increase yield of fresh-market tomato in arid and semi-arid areas, whereas yields in humid and sub-humid regions may be similar between a drip system and a carefully managed furrow system. Higher yields have been reported by using drip systems in combination with black plastic mulch that reduces direct contact between fruit and irrigation water. This method also may stimulate earlier ripening. Farmers can get higher prices with larger fruit and earlier marketability that can justify investment in drip irrigation.

Crop evapotranspiration (ET) of processing tomato was similar between drip-irrigated and furrow-irrigated lysimeters during two seasons in northern California. Tomato yield on a nearby drip-irrigated field were 13% to 19% higher than on a furrow-irrigated field, but differences were not statistically significant (Pruitt et al., 1984). The yield and size of fresh-market tomato obtained on subsurface drip and subirrigation plots in Florida also were similar (Clark et al., 1991). Microirrigation treatments were fertilized daily through the drip system and seasonal water applications were smaller on the drip-irrigated plots.

Higher yields of fresh-market tomato were obtained with smaller water deliveries using subsurface drip systems in Texas. Average tomato yields were 22% higher, whereas applied water volume was 75% less with subsurface drip than with furrow irrigation for three crop seasons (Bogle et al., 1989). Marketable tomato yields were 40% to 50% higher, and fruit size was about 5% larger with drip irrigation than with furrow irrigation in Ethiopia. In this case, groundwater with a conductivity of 3 dS/m was applied (Yohannes and Tadesse, 1998).

Drip irrigation, with or without plastic or sugarcane trash mulch, produced higher tomato yields than surface irrigation with no mulch on fine-textured heavy soils in Gujarat, India (Shrivastava et al., 1994). The estimated annual costs of the drip system and plastic mulch were \$665 and \$485/ha, respectively. Estimated net returns ranged from \$1,092/ha for drip irrigation at 60% of pan evaporation with plastic mulch and \$1,096/ha for surface irrigation with no mulch, to \$2,037/ha for drip irrigation at 40% of pan evaporation with sugarcane trash mulch. In general, drip treatments with no mulch and with sugarcane trash mulch had the greatest net returns. However, even though the estimated net returns were substantial, farmers may not be able or be willing to obtain financing for the initial investment required for a microirrigation system.

Tomato yields were increased by 22% to 36% and water applications were reduced by about 25% with microirrigation compared with surface irrigation in the Nainital Tarai region of India (Rao et al., 1995). Seasonal water depths, including rainfall, were about 23 cm with microirrigation and 32 cm with surface irrigation.

High water tables provide a large portion of the crop water requirements of fresh-market tomatoes in South Carolina, where the farm-level profitability of microirrigation is determined by improvements in the timing and size of marketable yield. Camp et al. (1989) obtained total yield improvements ranging from 21% to 47% with microirrigation, whereas the yield of extra-large fruit was increased by 33% to 57%. Farm-level profitability is evident because 75% of the commercial crop in 1989 was produced using subsurface drip irrigation.

In sub-humid regions, sprinklers may producer larger tomato yields than drip systems in very hot, dry years, whereas drip irrigation may have higher yields in other years. Higher marketable yields of tomato have been obtained with drip irrigation during the dry season in Taiwan (Lin et al., 1983). Marketable yields were 20% to 40% higher on drip-irrigated plots with irrigation intervals ranging from 1-2 days to 7-9 days, than on furrows irrigated to field capacity once per month. Less water was applied in two of the drip treatments than in the furrow treatment, and fruit quality was not affected. The higher yields obtained with the drip system may be attributable to a lower salinity environment in the root zone. The yield and quality of tomatoes irrigated with drip systems and sprinklers on sandy loams in Ontario, Canada varied with differences in rainfall and ambient temperatures (Tan, 1995).

Most of the 20,000 ha of processing tomatoes in Brazil are irrigated with center pivot sprinklers. Poor water management and widespread occurrence of *Sclerotinia sclerotiorum* have suggested the potential for using drip systems and microsprinklers. Silva and Marouelli (1995) increased commercial yield with a drip system operated at 6-day intervals to 70 t/ha compared with 50 t/ha with center pivot sprinklers in central Brazil.

6.3.1.5. Melons

Results with microirrigation of melons have been mixed. Some have obtained higher melon yields with less applied water using microirrigation, whereas others had no significant yield increase compared with furrow irrigation. Bogle and Hartz (1986) had the same yield of muskmelons with furrow and subsurface drip systems in Texas, although water use was reduced by more than 50% with drip irrigation. Elmstrom et al. (1981) obtained higher yields with drip fertigation of watermelon at one site in Florida while observing no significant difference at another site. The yield of early melons obtained with drip irrigation at the first site was 2.4 times greater than early yield obtained with microsprinklers. Water application with drip irrigation was 36% and 44% less than microsprinklers at the two locations.

Higher yields and better quality muskmelons were obtained with a combination of SDI with plastic mulch on silt loams and fine sandy loams in Indiana (Bhella, 1985). The early and total marketable yields were up to 54% and 74% greater with drip irrigation than with no irrigation. Harvested fruits were greater with drip irrigation and the proportion of culled fruit was smaller. No significant yield or quality effects of irrigation scheduling were observed on drip-irrigated muskmelons on a clay loam in Davis, California, although marketable yields on all treatments were almost double the industry average yield (Hartz, 1997).

Drip irrigation can improve net revenue and reduce nitrogen losses in watermelon production. The maximum predicted yield of drip-irrigated watermelon on a sandy loam in southern Arizona occurred when the average soil tension was 7.2 kPa, with a nitrogen application rate of 335 kg/ha (Pier and Doerge, 1995a). The maximum predicted net revenue ($10,819/ha) was obtained at an average soil tension of 10.6 kPa and a nitrogen rate of 243 kg/ha. The estimated annual returns to subsurface drip irrigation of watermelon on a fine sandy loam in Florida ranged from $2,300/ha to more than $16,000/ha, with average spring market prices of $120 to $250 per tonne (Clark et al., 1996b). The estimated cost of installing the subsurface drip system was $3,400/ha. Hence, it is possible to recover the initial investment within a few years, although watermelon prices and net revenue can change very quickly in response to changes in supply and demand conditions.

6.3.1.6. Other fruits and vegetables

Reports have indicated yield increases with microirrigation on other fruits and vegetables, particularly when used in combination with plastic mulch and or fertigation. For example, VanDerwerken and Wilcox-Lee (1988) compared the growth and yield of sprinkler and drip-irrigated bell peppers with and without black plastic mulch, on a sandy loam in New York. Maximum yields were produced by the combination of either irrigation system with the plastic mulch, whereas plots that were neither irrigated nor mulched produced 40% less fruit. Profitability was maximized using either drip irrigation or mulching, as the incremental yield obtained by combining both practices was too small to justify the additional cost. Higher yields of zucchini squash were obtained using either drip irrigation or black plastic mulch on a loamy sand in Indiana (Bhella and Kwolek, 1984). Drip irrigation increased yields up to 53%, whereas plastic mulch increased yields from 35% to 49%. Combining drip irrigation with plastic mulch did not produce an additional yield improvement.

Subsurface drip irrigation improved asparagus yields by enhancing transplant establishment over sprinkler systems or with no irrigation on a sandy loam in Virginia (Sterrett et al., 1990

Microirrigation is used for vegetable production in California where data suggest that economic returns are positive in some cases, but not in others. For example, some farmers have reported savings in fertilizer and tillage costs ranging from $247/ha to $494/ha with subsurface drip irrigation (Hanson, 1995). However, field experiments with lettuce showed little difference in yield due to irrigation system, and water savings were insufficient to justify the investment in a surface or subsurface drip system (Hanson, 1995; Hanson et al., 1997).

Drip irrigation improved crop yields and net revenue in western Gujarat, India, where farmers rely on groundwater to augment limited and erratic rainfall. Summer groundnut, sugarcane, garlic, eggplant, and castor bean crop yields and net revenues with drip irrigation generally were higher than with surface or sprinkler irrigation (Malavia et al., 1995). The highest yields and water use efficiencies were obtained when drip laterals were placed in alternate rows.

Water savings ranging from 37% to 61% and yield increases ranging from 16% to 19% were obtained with drip irrigation of cabbage in Pantnagar, India (Srivastava and Chauhan, 1995). Seasonal irrigation amounts, including 0.80 cm of rainfall, were about 10 cm with drip irrigation and 21 cm with surface irrigation. Cabbage yield on a plot irrigated with microtubes was 3.7% less than with surface irrigation. In a similar comparison of microirrigation and surface irrigation methods on eggplant in Pantnagar, estimated water savings with drip irrigation systems ranged from 33% to 48%, whereas eggplant yields were increased from 8% to 17% (Singh et al., 1995a). Seasonal water depths in that study, including effective rainfall, were about 50 cm with drip irrigation and 86 cm with surface irrigation.

Drip irrigation enhanced the productivity of nitrogen fertilizer, while increasing irrigation efficiency, over check-basin irrigation of chili pepper on a loamy sand in Jodhpur, India (Singh et al., 1999). Surface drip irrigation with 90 kg/ha of nitrogen improved crop yields and water use efficiencies similar to those obtained with check-basin irrigation and 180 kg/ha of nitrogen. Average irrigation efficiencies of 95% and 65% were achieved with drip irrigation and check-basins, respectively. The highest yields and water use efficiencies were obtained with drip irrigation and nitrogen applied at 180 kg/ha.

Nutrient uptake, plant growth, and yield were improved with drip irrigation of banana over basin irrigation during a complete production cycle in Bangalore, India (Hegde and Srinivas, 1991). Banana yields of both the planted and ratoon crops were significantly higher with drip irrigation than with basin irrigation. In particular, the average yields reported for the drip system were 84 t/ha for the plant crop and 73 t/ha for the ratoon crop, whereas average yields with basin irrigation were 74 t/ha and 66 t/ha, respectively. Water use efficiency was higher with drip irrigation primarily due to the higher yields.

Higher yields of gourd and watermelon have been obtained with drip irrigation systems than with sprinkler and furrow irrigation systems in Jodhpur, India (Singh and Singh, 1978). Yield increases were about 45% for long gourds with a range of 21% to 38% for round gourds and 10% to 32% for watermelon. Applied water was 18% less with drip irrigation than with sprinkler irrigation and furrow irrigation for gourd and 6% less on watermelon.

Estimated water savings with microirrigation compared to conventional irrigation methods ranged from 39% on tomatoes to 68% on papaya, and estimated yield increases ranged from 14% on eggplant and 23% on grapes to 98% on pomegranate (Sivanappan, 1994; 1995). The estimated microirrigation installation costs in Maharashtra during 1993 ranged from \$500/ha for coconut and mango and \$1,000/ha for pomegranate and tomato and up to \$1,600/ha for banana, cotton, and sugarcane.

Farmers using microirrigation on banana and grape in Maharashtra obtained higher yields with less water applied and at a lower cultivation cost. Crop yields with drip irrigation were 29% and 19% higher than yields using flood irrigation for banana and grape, respectively (Narayanamoorthy, 1997). Cultivation costs were 2.5% lower for banana and 9.1% lower for grape, while estimated reductions in applied water were 29% and 37%, respectively. The initial investment in drip irrigation for banana and grape can be recovered within one year, based on these estimated gains in crop yields and reductions in production costs.

Drip irrigation improved plant growth and crop yields of Assam lemons in India, where mean values of plant height, canopy diameter, and crop yield were highest with drip irrigation and black plastic mulch (Barua et al., 2000). Average crop yields generally were greater than 100 fruits per plant with drip irrigation, whereas average yields on rainfed plots ranged from 33 to 40 fruits per plant. Water use efficiency and the yield of papaya were increased by 9% with subsurface drip irrigation, when compared with surface drip irrigation in Bangalore, India (Srinivas, 1996). Both fruit number and the fruit weight per plant were higher with SDI.

Subsurface drip systems may enhance lettuce yields and net returns by reducing disease incidence and improving uniformity in the size of harvested plants. Sutton and Merit (1993) compared lettuce yields and water use efficiencies using sprinklers and subsurface drip systems in New South Wales, Australia. Average plant sizes were similar with sprinkler and drip irrigation, but there was less variability in plant size with drip irrigation. The largest commercial yield was obtained in the drip treatment designed to maintain soil moisture at field capacity. That yield was 7% greater than the yield obtained with sprinkler irrigation. The estimated irrigation requirement was 13.2 L per harvested plant on the best-yielding drip treatment and 33.2 L per harvested plant with sprinkler irrigation. Estimated gross margins were $1,950/ha and $1,524/ha with drip and sprinkler irrigation, respectively.

The incidence of lettuce leaf drop was significantly lower and the progress of the disease during the season was slower with drip irrigation than furrow irrigation in California's San Joaquin Valley (Subbarao et al., 1997). Corky root incidence was significantly lower with drip irrigation, but there were no significant differences in the incidence or severity of downy mildew. Lettuce yields, the proportion of marketable heads, and the volume and weight per head were significantly higher with subsurface drip irrigation than furrow irrigation.

6.3.1.7. Cotton

The farm-level returns from drip irrigation of cotton vary with soil type, cotton prices, the price and availability of irrigation water, and the level of management. Microirrigation is more profitable than furrow irrigation on sandy soils in the southwestern United States (Wilson et al., 1984; Hanson, 1995), in water-short portions of Texas (Henggeler, 1995), and in Israel, where irrigation water is scarce and expensive (Feinerman and Yaron, 1990). Microirrigation on sandy soils may enable farmers to reduce applied water and expenditures for fertilizer, weed control, and insecticides (Fishelson and Rymon, 1989). Microirrigation systems also enable farmers to minimize periods of water stress and to avoid canopy damage when irrigating with saline water (Meiri et al., 1992). In regions where deficit irrigation is practiced, microirrigation may be more appropriate than furrow irrigation. The degree of water stress, although continuous with microirrigation, is less severe, resulting in less shedding of squares and bolls (Mateos et al., 1991).

Crop budgets describing the potential impact of microirrigation on farm-level net returns in cotton production have been constructed using information obtained from farmers and extension specialists, and experiments conducted in Arizona, California, and New Mexico (Wilson et al., 1984). Cotton yields were increased in three of the eight experiments, with yield increases ranging from 7% to 29%. Water savings of up to 64% were achieved with microirrigation compared to furrow irrigation. Water savings and yield improvements were not observed on level, clay-loam fields, which were considered ideal for furrow irrigation. The largest water savings and yield improvements were observed on sandy loams and sands. The estimated returns to land, management, and risk were \$327, \$233, and -\$146/ha for subsurface drip, surface drip, and furrow irrigation, respectively. Key assumptions in the analyses included applied water depths of 1,041 mm, 914 mm, and 1524 mm, respectively, and a lint yield increase of 538 kg/ha with the subsurface drip system.

Switching to microirrigation of cotton can reduce water deliveries by one-half and improve crop yields in Arizona, where typical water applications with furrows range from 2,032 to 2,286 mm (Hanson, 1995). Average water deliveries with furrows in California are much smaller, and the impacts of switching to microirrigation systems are less clear. Hanson (1995) described the results of field-scale comparisons of drip and furrow irrigation of cotton in the San Joaquin Valley. Higher yields were achieved at three locations, and water deliveries were smaller at four locations. However, yield improvements generally were not sufficient to pay for conversion to microirrigation.

Yield differences with furrow and microirrigation of narrow-row cotton on a clay loam on the west side of the San Joaquin Valley were not statistically significant (Howell et al., 1987). Yields on treatments described as "well irrigated" ranged from 1,928 to 2,145 kg/ha, whereas a normal yield in the Valley was about 1,500 kg/ha.

Subsurface drip irrigation (SDI) of cotton may be economically viable in regions where shallow water tables can provide a substantial portion of crop water requirements and where environmental regulations limit the off-farm discharge of subsurface drainage water. Cotton yields increased from 1.4 to more than 2.0 t/ha with SDI during a three-year study in a drainage-constrained region in the San Joaquin Valley (Ayars et al., 2001). Furrow-irrigated yields were higher initially, but those yields remained constant, whereas drip-irrigated yields increased during the course of the study. The reductions in deep percolation achieved with SDI may reduce farm-level costs of compliance with regional drainage water reduction goals.

Historical lint yield of furrow-irrigated cotton in Texas has been about 786 kg/ha when grown under inadequate water supply, but SDI has increased average lint yield to 973 kg/ha (Henggeler, 1995). The estimated cost of installing SDI in Texas was about \$1600/ha. Cotton farmers using SDI reported that labor and cultivation costs each were reduced by about \$185/ha and herbicide costs were reduced by about \$12/ha (Henggeler, 1995). Water use and energy costs were not reduced. In addition, furrow-irrigated yields were generally increased when SDI was adopted because water no longer needed to pre-irrigate the SDI fields could be shifted to pre-irrigate the furrow-irrigated fields.

Microirrigation of cotton in Israel began in the 1970s and increased rapidly through the 1980s. By 1986, the proportion of cotton microirrigated ranged from 30% in the Yizre'el Valley to 70% in the Negev Desert (Fishelson and Rymon, 1989). Higher yields and greater profitability motivated rapid adoption of microirrigation on collective farms (kibbutz) which produce more than 90% of Israel's cotton (Feinerman and Yaron, 1990). The average microirrigated cotton yield from a survey of 38 collective farms in Israel for 1976 through 1983 was 10% higher than the average sprinkler-irrigated yield. Although the average annual investment costs reported were four times higher for microirrigation than for sprinklers, the increase in yield and reduction in water costs were sufficient to increase profits. Water prices reported in the survey, ranging from \$0.0541/m^3 in 1978 to \$0.0889/m^3 in 1980, are much higher than in most irrigated regions.

Water use efficiencies are similar for microirrigation and furrow irrigation in Australia, where most cotton is grown on clay soils with limited permeability and on fields with limited slope (Hodgson et al., 1990). Microirrigation produced higher yields than furrow irrigation in two of four years in a study of water use efficiencies and waterlogging (Constable and Hodgson, 1990). In one year, the yields were similar, and in another year the furrow-irrigated yield was slightly higher than with drip irrigation. Therefore, the potential for higher yields with drip irrigation may not be realized on slowly permeable soils, particularly in cool or wet seasons.

6.3.1.8. Sugarcane and sugarbeets

Microirrigation of sugarcane in Hawaii began in the 1970s to reduce pumping costs, improve distribution uniformity, and increase crop yields by reducing foliar damage caused by sprinkling with saline groundwater (Moore and Fitschen, 1990). Irrigation efficiency increased to 80% on sugarcane fields managed by the Hawaiian Commercial & Sugar Company. Water savings enabled the Company to plant an additional 1,820 ha of sugarcane, and helped to justify the cost of switching from furrow and sprinkler irrigation to microirrigation. The Company's furrow-irrigated area declined from 11,693 ha in 1977 to 254 ha in 1989, whereas the drip-irrigated area increased from 2,224 ha to 16,176 ha. Average yields on drip-irrigated fields were 27% higher than average yields on furrow-irrigated fields during 1977 through 1989 and average water application was 30% smaller.

Adopting microirrigation as a replacement for subirrigation may be profitable for sugarcane cultivation in Florida. Drip-irrigated sugarcane yields were 7% higher in plant cane, 16% higher in first ratoon, and 38% higher in second ratoon, than yields obtained on subirrigated plots (Shih, 1988). Higher yields may be attributable, in part, to deeper and denser root development with drip irrigation. Water use efficiencies for plant cane, first ratoon, and second ratoon were higher with drip irrigation. On average, 95 kg of water (ET) produced 1 kg of cane yield (millable cane harvested from the field) on the drip-irrigated plots, whereas 109 kg of water (ET) were required on the subirrigation plots.

Sugarcane farmers in Maharashtra, India have installed drip irrigation systems to reverse a decade-long decline in productivity caused by persistent leaching of nutrients on furrow-irrigated fields (Magar, 1995a). Uncertainty regarding water supply also was a motivating factor. Water savings of 64.3% and yield increases of 21.6% have been achieved on drip-irrigated fields at the Mahatma Phule Agricultural University. Drip irrigation of sugarcane in the shallow groundwater zones of eastern India may be viable economically if yields can be increased by at least 20% or if the farm-level total cost of electricity increases with the volume of groundwater withdrawn (Srivastava and Upadhayaya, 1998).

Drip irrigation of sugarbeet may improve crop yields, reduce nitrate leaching, and provide greater residual nitrogen for a subsequent crop. Higher yields and greater sugar content were achieved with surface drip irrigation than with flood irrigation of sugarbeet in Wyoming (Sharmasarkar et al., 2001). Estimated water and fertilizer use efficiencies, and residual soil nitrate concentrations were higher on drip-irrigated fields. The estimated investment costs and the time required to recover those costs ranged from \$2,500/ha and 7 years for a 40-ha system to \$3,250/ha and 11 years for a 10-ha installation (Sharmasarkar et al., 2000). Both crop yields and profitability of the drip system increased as the average irrigation interval was reduced from 11 to 5 days.

6.3.2. Frost and Freeze Protection with Microsprinklers

Farmers using microsprinklers can help protect fruits and vegetables and thus gain substantial economic benefits in regions subject to damaging frosts and freezes (Additional details are provided in Chapter 15).

Microsprinklers have protected young citrus trees during radiation frosts that occur on cold, calm nights in Florida by increasing the air temperature and the temperature of citrus leaves and tree trunks (Parsons et al., 1981). Trunks and leaves that were covered with ice showed little damage, whereas the canopy above the iced zone showed noticeably greater damage.

Microsprinklers also have protected citrus trees during advective freezes in Florida. Microsprinklers located 40 cm above the ground were operated during two nights of a severe advective freeze in December 1983, protecting the lower 70 cm of trees, including the bud union and lower scaffold branches (Parsons et al., 1985). One year later, protected trees were taller than 2 m, whereas unprotected trees were only 1 m tall. The extent of protection provided varied with the location of microsprinklers and the volume of water applied.

One-year-old citrus trees were protected during a severe advective freeze in Louisiana by irrigating scaffold branches with microsprinklers in the tree canopy at a height of about 75 cm above the soil surface (Bourgeois and Adams, 1987). Although more than 70% of the canopy was killed on protected trees, over 74% of those trees survived the freeze, whereas complete kill was observed in unprotected blocks. Similar results were achieved by irrigating scaffold branches on five-year-old citrus trees during a severe freeze in December 1989 (Bourgeois et al., 1990). All unprotected trees were killed, whereas 95% of protected trees were alive nine months later. The proportion of regrowth of the original canopy size ranged from 71% to 117%. Microsprinkler irrigation combined with plastic enclosures placed around individual citrus trees provided significant protection during the same December 1989 freeze in Louisiana (Edling et al., 1992). Ambient temperatures that reached as low as -11.1°C killed all unenclosed trees including those receiving irrigation. All six trees that were enclosed and irrigated survived the freezing conditions and showed excellent growth the following year.

Many unprotected trees in Florida's Central Ridge citrus area were killed when minimum temperatures reached -8.3°C and temperatures remained below freezing for more than 43 hours during a major advective freeze in Florida in December 1989 (Parsons et al., 1991). However, many of the trees irrigated with microsprinklers during the freeze were saved. Microsprinklers elevated within the canopy provided better protection than microsprinklers placed close to the ground even though the upper parts of the tree canopy were killed. Trees protected with elevated microsprinklers regained their original size within six months after the freeze due to rapid regrowth from the undamaged portion of the canopy.

The extent of frost protection provided by overhead microsprinklers on Golden Delicious apple and Conference pear trees in Lleida, Spain was demonstrated in an indoor simulation of frost events (Solanelles and Planas, 1993). Blossom damage was reduced by about 80% on the pear trees with a water application rate of 2.9 mm/h. A protection rate of about 50% was achieved with an application rate of 1.9 mm/h. Similar results were achieved with apple trees.

Overhead sprinklers are used by most strawberry producers in Florida to prevent freeze damage that occurs during December through February. Drip irrigation does not provide additional protection beyond that provided by the plastic mulch used in strawberry production (Hochmuth et al., 1993). The volume of water required to provide frost protection with conventional sprinklers operated continuously may be reduced with microsprinklers controlled by an automated decision system that turns them on and off repeatedly during the night. Both types of sprinklers reduced blossom kill on strawberrry plants significantly below the non-irrigated plants during two frost events in Ohio (Stombaugh et al., 1992). Model simulations suggest that the volume of water required may be reduced by as much as 89% with an automated microsprinkler system.

6.3.3. Fertigation

Application of plant nutrients through microirrigation (fertigation) can improve fertilizer timing and reduce non-beneficial losses in deep percolation and surface runoff. Fertigation enables farmers to increase crop yields, while reducing both the variable costs and potential environmental impacts of nutrient application (Feigin et al., 1982; Levinson and Adato, 1991; Guimera et al., 1995; Ro and Park, 2000; Shock et al., 2000).

Gains in net income due to fertigation can help justify the initial investment and the variable costs of operating and maintaining microirrigation systems. Those gains are more likely to be achieved on high-valued crops, such as fruits as vegetables. Camp (1998) summarized several fertigation studies in his review of literature of subsurface drip irrigation.

Careful management is required to achieve the potential benefits of fertigation (Mmolawa and Or, 2000), and benefits will vary with crop, location, and management level (Bar-Yosef, 1999). For example, yield increases ranging from 29% to 227% with fertigation have been reported for selected fruit and vegetable crops in Cyprus (Papadopoulos, 1996). Nitrogen application in a surface drip irrigation system did not enhance raspberry yields on the southern coast of British Columbia (Kowalenko et al., 2000).

Tomato yields have been increased with careful water management and precise fertigation in small-plot and field experiments at the USDA Water Management Research Laboratory in California. Nearly twice as many tomatoes were grown with the same amount of water with SDI and precise fertigation were practiced than with conventional irrigation practices or with inadequately fertilized microirrigation systems (Ayars et al., 1999).

Tomato yield as high as 110 t/ha was obtained when nitrogen and phosphorus were applied through a drip irrigation system on coastal sand dunes in southern Israel (Bar-Yosef, 1977). The nitrogen concentration in the soil solution was maintained at about 140 mg/L. The daily nitrogen uptake was 100 mg/plant and daily water consumption ranged from 0.4 to 1.0 L/plant. Phosphorus-use efficiency on tomatoes was higher when the nutrient was applied with a subsurface drip system on soils testing low in phosphorus, than when it was incorporated in the soil before planting (Carrijo and Hochmuth, 2000). Maximum yields were obtained when one-half the phosphorus recommended for broadcast pre-plant application was delivered through the drip system.

When using fertigation, reducing the dripline spacing may increase tomato yields. Average yields on plots with 2.4 m spacing between surface drip laterals ranged from 38 to 45 t/ha, whereas average yields on plots with 1.2 m spacing ranged from 59 to 73 t/ha on a coarse loam in Jodhpur, India (Singh et al., 1989). The average increase in yield of about 20 t/ha may have been sufficient to justify the closer spacing of drip system laterals, although cost data were not reported in the study.

Watermelon yields may be increased substantially by maximizing the interactive effects of water and nitrogen applied with SDI. Marketable melon yields increased with higher levels of water and nitrogen in the first year of an experiment on a sandy loam in southern Arizona, whereas lower yields were observed on drier plots receiving excessive nitrogen in the second year (Pier and Doerge, 1995b). Maximum yields in excess of 110 Mg/ha were achieved with applications of 220 to 300 kg of actual N/ha. The average commercial yield of watermelon, which are largely furrow irrigated in Arizona, was 36.4 Mg/ha during the early 1990s.

Many advances have been achieved in fertigation methods, but some of the potential advantages may be offset by costly investments in fertilizer injectors, safety devices, and the storage and shipping large volumes of dilute liquid fertilizers (Bar-Yosef, 1999). For example, the estimated costs of producing drip-fertigated tomatoes and sprinker-irrigated, broadcast-fertilized tomatoes in a recent study were \$14,000 and \$8,500/ha, respectively (Steffen et al., 1995). Gross income was higher with drip irrigation, but the differential was not sufficient to justify the higher cost of fertigation. However, the comparison reported by Steffen et al. (1995) was conducted during a season with sporadic heavy rains that may have had a greater adverse effect on yields in the drip-fertigated treatments (Bar-Yosef, 1999).

6.3.4. Chemical Application of Non-Fertilizer Materials

Pesticides also can be applied using microirrigation systems, although results obtained to date suggest more research is needed regarding environmental and economic implications. The potential advantages of applying pesticides with a drip system include reduced pesticide drift, less exposure to humans and non-target organisms, and reduced application costs (Royer et al., 1989). Drip application is less costly than foliar application of insecticides, but only phloem-feeding insects are controlled with drip application, and control is achieved more slowly than with foliar application. Only insecticides that act systemically within plants can be applied successfully using drip irrigation systems.

Information regarding the types of pesticides that can be applied effectively in drip systems and the levels of control that can be achieved consistently is not yet complete. In addition, the potential movement and impacts on soil and water resources of active ingredients applied with microirrigation systems are not yet fully established.

Total residue levels in samples of asparagus spears treated with disulfoton applied with a subsurface drip irrigation system in Washington exceeded tolerance levels established by the U.S. Environmental Protection Agency (Wildman and Cone, 1986). Although aphids were controlled effectively with the disulfoton, rapid root development in the wetted area around the drip emitter may have increased the uptake of the active ingredient, resulting in relatively high residue levels.

Effective control of root-knot nematodes was achieved when methyl bromide was applied alone or mixed with chloropicrin through surface or subsurface driplines on okra and tomato on sandy soils in Florida (Overman, 1976). Okra yields were increased with the methyl bromide-chloropicrin mixture, whereas tomato yields were increased with methyl bromide.

Drip irrigation and post-plant nematicides have reduced nematode populations in peach orchards in Maryland (Funt et al., 1982). Drip irrigation, alone, reduced the number of stunt and dagger nematodes significantly from pretreatment counts within three months. Pin and lesion nematode population was reduced on drip treatments within 1.5 months and the populations remained at a reduced level for 17 months. The combination of drip irrigation with granular carbofuran applied at 11.1 kg/ha reduced dagger and lesion nematodes for 17 months. No trees were killed on those plots at the end of the first season. Daily water applications may have increased the distribution and activity of the granular nematicide. In addition, regeneration of new roots in optimal moisture conditions may have enabled plants to withstand nematode damage.

Fenamiphos has been used to control nematodes on pineapples in Hawaii since the 1970s (Caswell and Apt, 1989). Preplant fumigation and postplant application of fenamiphos in a drip irrigation system have produced larger yields, larger fruit size, and greater root biomass in the second crop (the ratoon crop), but had no significant impact on the first crop (Schneider et al., 1992, 1995).

Leib et al. (2000) examined the effectiveness and movement in a silty clay loam soil of imidacloprid applied to control striped cucumber beetles on muskmelon in Pennsylvania. Treatments included single and split applications through a subsurface drip system under plastic mulch, and surface banding of the insecticide on non-mulched rows. In general, better control was achieved on drip-treated plots under plastic mulch than on non-mulched, surface-banded plots. Harvestable yields on drip-treated plots receiving single and split applications of imidacloprid ranged from 19,000 to 22,000 kg/ha, whereas the average yield on mulched plots receiving no insecticide was 8,800 kg/ha. The yield on surface- banded plots was 5,750 kg/ha and 2,350 kg/ha on non-mulched plots receiving no insecticide.

Significant leaching of imidacloprid below the emitter depth can occur if daily irrigations with a drip system exceed evapotranspiration (Felsot et al., 1998). Farmers can reduce potential leaching and the risk of exceeding plant tolerance limits by applying chemicals in drip systems only when target pest populations exceed economic thresholds (Wright and Cone, 1999). Good water management and lower rates of chemical application will minimize leaching problems, but rainfall events following application can cause leaching despite those efforts (Schneider et al., 1990).

6.3.5. Irrigation with Saline Water and Effluent

Drip irrigation is considered the best method for applying saline water because it avoids leaf injury and provides optimal soil water conditions (Shalhevet, 1994). Canopy damage is avoided by placing saline water on or below the soil surface to form a wetted zone where salinity is relatively low and where plant roots tend to accumulate (Mmolawa and Or, 2000). Salts also will accumulate at the perimeter of the wetted zone and farmers using drip irrigation with saline water must implement an appropriate management strategy (Oster, 1994). For example, supplemental leaching with sprinklers may be required in regions where rainfall is insufficient to move salts below the root zone.

Yields of some vegetable crops can be reduced substantially when irrigating with saline water. The severity of yield reduction may vary with the type of irrigation system and the volume and frequency of water applications. For example, bell pepper yields in southern California were reduced by 14%, 54%, and 94%, with drip, furrow, and sprinkler irrigation, respectively, using water with a TDS of 2,450 mg/L (Bernstein and Francois, 1973). Increasing the frequency of irrigation of the furrow and sprinkler irrigation systems achieved smaller proportional reductions in crop yield of 18% and 59%, respectively. Maximum yields were obtained using about one-third less water with drip irrigation than with furrow irrigation.

The total and marketable yields of drip-irrigated tomato on a clay loam in southeastern Spain were higher when irrigated at a daily rate that replaced about 100% of crop ET, using groundwater with an average conductivity of 5.2 dS/m (Franco et al., 1999). The incidence of blossom-end rot was higher on treatments irrigated at about 50% of crop ET. The total and marketable yields were 5.18 and 5.09 kg/plant for the full irrigation, and 2.89 and 2.65 kg/plant for partial irrigation. The proportions of total fruit with blossom-end rot were 8.3% with partial irrigation and 1.8% with full irrigation.

Irrigation with saline water may enhance tomato fruit quality, when evaluated by taste, color, and the concentration of soluble solids (Mizrahi and Pasternak, 1985). Drip irrigation of tomato using 3 dS/m water on coarse sand improved fruit taste with no significant reductions in crop yield (Mizrahi et al., 1988). In another study with saline water, higher total and marketable fruit yield, and higher average fruit weight of tomato and snap bean were achieved with drip irrigation than with subirrigation (Scholberg and Locascio, 1999). Both marketable and total fruit yield increased with the volume of water applied with the drip systems.

Farmers in the Arava Valley of Israel irrigate vegetables and alfalfa successfully with groundwater ranging from 2 to 4 dS/m by using sprinklers during germination and establishment, and surface drip irrigation after that (Oster, 1994). Oron et al. (1999) irrigated pear trees with saline water (1.2 and 4.4 dS/m) using surface and subsurface drip systems in the Negev Desert of Israel. With good quality water, pear yields were 11% to 19% higher with emitters at a depth of 30 cm than with a surface drip system.

Drip irrigation may improve cotton yields when using saline water on moderately saline soils. Ayars et al. (1986) compared cotton yields obtained using drip irrigation and saline water (8 dS/m) with yields from using furrow irrigation and nonsaline water (0.2 dS/m) on a saline soil in the San Joaquin Valley. Less water was applied on two of three drip irrigation treatments, than with furrow irrigation, whereas seed cotton and lint yields were similar for all irrigation treatments. Seed cotton yields ranging from 5.7 to 6.4 t/ha were obtained with drip irrigation using water conductivities ranging from 1.0 to 7.3 dS/m on a sandy loam loessial soil in the Negev (Mantell et al., 1985). Highest yields were obtained with 3.2 dS/m water, while yields obtained on 1.0, 5.4, and 7.3 dS/m treatments were not significantly different. Soil salinity ranged from 1.8 to 3.2 dS/m at the various soil depths ranging from zero to 150 cm.

Drip irrigation also may enhance bermudagrass turf yields when irrigating with saline water. Turf yields on clay and sandy loams in southern Nevada were 6% to 11% higher with SDI than with sprinklers when irrigating with 2.2 dS/m water (Devitt and Miller, 1988). However, the cost of installing and maintaining the SDI system may have exceeded the benefits gained. Suarez-Rey et al. (2000) obtained similar results for subsurface drip and sprinkler irrigation of bermudagrass turf on coarse-loamy and sandy soils using tertiary reclaimed municipal wastewater from Tucson, Arizona. The water was classified as medium to high in salinity, with a low sodium hazard, and an adjusted sodium adsorption ratio of 4.7 meq/L. Total irrigation depths and estimates of productivity were similar with SDI and sprinkler irrigation.

Microirrigation also may enable farmers to utilize municipal effluent in areas where the water supply is limited. The yields of cotton, corn, peas, and wheat irrigated with effluent from a domestic sewage treatment plant in Beer Sheva, Israel were similar when irrigated with either a surface or subsurface drip system (Oron et al., 1991). Wheat yields generally were higher on plots with two drip laterals than one.

Farmers in various parts of the world may be able to use subsurface drip systems to irrigate field crops using wastewater from large livestock operations. Key challenges include developing a strategy that prevents the clogging of emitters, while achieving optimal nutrient and salt management, and maintaining economic viability (Trooien et al., 2000). A successful strategy for using livestock wastewater could generate substantial private and public benefits, as farmers would gain a source of irrigation water and society would gain a cost-effective method of reducing potential pollution problems from livestock effluent.

6.4. FARM-LEVEL OBSERVATIONS

Most of the papers reviewed in this chapter describe research where the potential benefits of microirrigation are examined in a carefully managed experimental setting. The research-grade microirrigation systems are designed and maintained carefully, and the discharge rates of emitters are monitored to ensure that desired volumes of water are delivered according to specific timing and uniformity criteria. Many of the efforts undertaken at experiment stations will not be duplicated in the field if the farm-level cost of careful design and maintenance exceeds the perceived farm-level benefits of achieving optimal performance. Thus, while microirrigation systems provide farmers with an opportunity to reduce water deliveries, improve distribution uniformity, and enhance crop yields, proper design, operation and management practices must be followed to maximize income.

Farmers adopting microirrigation gain control of the flowrate, duration, and frequency of irrigations, but pressure variations due to improper system design and component selection can reduce potential benefits (Pereira, 1999). Such problems arise because farmers are "induced to adopt microirrigation systems to save water, without appropriate technical support." The amount of support available to farmers varies among regions and may be a function of input and output prices, and extent of water scarcity.

Farm-level water savings and yield improvements have been smaller than expected by farmers adopting microirrigation in Maharashtra, India. Inadequate system maintenance, cleaning, and filtration have resulted in the persistent clogging and emitter breakage causing considerable variation in emission uniformities (Dalvi et al., 1995). Approximately 17% of the farmers reported water savings of at least 45% water by converting to drip irrigation. Ten percent of the farmers reported less than a 15% water savings, due largely to leakage in drip systems and broken emitters. Some farmers (33%) reported no change in crop yield after converting to drip irrigation, whereas other farmers (29%) reported no change in monetary returns. Overall 62% of the farmers did not observe a change in yield or financial improvement after converting to drip irrigation. Farmers who were not familiar with the proper operation and maintenance procedures for drip systems did not improve crop yield. When farmers were asked to describe restrictions they faced regarding adoption, operation, and maintenance of drip systems, most described financial constraints that included the high initial cost of drip systems and high cost of replacement parts (Dalvi et al., 1995). They also suggested that most farmers would not be able to afford a drip system without a subsidy to offset the high initial cost. Lack of proper knowledge on operating and maintaining drip systems was an additional problem. Some farmers (52%) had difficulty in scheduling irrigations with drip systems and 48% were not aware that chemicals could be used to prevent emitter clogging. Many farmers (38%) had not analyzed their soil or water resources. In addition, 40% were not familiar with methods for measuring system pressure or the discharge from emitters.

Similar difficulties have been described in the farm-level operation and maintenance in Tamil Nadu, India where about 5,400 ha were irrigated with drip systems in 1994 (Somasundaram et al., 1995). The high initial cost has limited the adoption of microirrigation in Tamil Nadu and 90% of farmers who have installed a system were unable to maintain it correctly after just one season. Many farmers applied more water than necessary. System operating pressures were incorrect on 60% of the farms. Improved educational services provided to farmers that include information on irrigation scheduling and fertilizer and chemical application may enhance adoption and performance of microirrigation in Tamil Nadu.

Irrigation system evaluations involving 189 microsprinkler, 56 drip, and 13 sprinkler systems were conducted to measure the distribution uniformity of irrigation events on 258 fields (4,000 ha) in five resource conservation districts in southern California (Little et al., 1993). The average distribution uniformity was a “poor” 74% and the average, area-weighted distribution uniformities for drip systems and microsprinklers were 75% and 72%, respectively. The primary cause of low distribution uniformity was pressure variation within manifolds and laterals. The poor uniformity results cannot be attributed to the use of low-cost water or production of low-valued crops. Water prices and price ranges in the five districts were \$0.012/m^3, \$0.053 to \$0.162/m^3, \$0.074 to \$0.284/m^3, \$0.284 to \$0.405/m^3, and \$0.319 to \$0.500/m^3. The systems were used to irrigate avocados, citrus, and deciduous fruit and nut trees.

The mean distribution uniformity for 174 microirrigation systems in the central coast area of California was 70%. The distribution uniformity on three-fourths of the systems was less than 85%, suggesting that potential water savings were not being achieved on many farms (Pitts et al., 1996). The cost of water varied by location, ranging from \$0.016/m^3 for pumping groundwater in coastal valleys to \$1.04/m^3 for water from municipal sources. The average water cost was \$0.11/m^3 and the average irrigation depth was 700 mm. About 60% of the evaluations were performed on orchard and vine crops, 17% on row crops, 14% on pasture and alfalfa, and 10% on turfgrass. Improvements in farm-level maintenance, such as better filtration and emitter clogging control, and using emitters with good initial uniformity would improve distribution uniformity.

6.5. PUBLIC BENEFITS AND POLICY IMPLICATIONS

Farmers will adopt microirrigation when farm-level gains exceed costs and financing is available to support the initial investment. Microirrigation has become the method of choice on citrus groves in Florida, fruit and nut tree orchards in California, and sugarcane plantations in Hawaii. Many farmers in Israel and other arid countries have adopted microirrigation to maximize the farm-level value of their limited water supply. Adoption will continue to increase in the future with improvement in technology and because of the increasing shortage of irrigation water.

Public efforts to enhance the rate of adoption may be justified in regions where negative off-farm effects of irrigation and drainage reduce public net benefits and where the opportunity cost of irrigation water is greater than incremental values generated in current agricultural uses. Examples include waterlogging, salinization, regions where groundwater overdraft threatens sustainability, and where municipal and industrial demands for water strongly compete with agriculture for limited water supplies. Public subsidies and other incentive policies may be appropriate to motivate greater adoption of microirrigation in those areas.

Public support also may be appropriate for technological developments that will reduce the costs of installing, operating, and maintaining microirrigation systems in developing countries. The initial costs of drip systems can be reduced by replacing expensive, precision-fabricated emitters with simpler emitter devices that can be made on or made available to small farms (Hillel, 1997). Costly and sophisticated filter systems can be replaced with filters made with nylon cloth and containers available in local areas (Polak et al., 1997). Bubbler systems that operate with much larger emitters and require much less filtration may be particularly appropriate for tree fruits and other widely spaced crops in developing countries (Hillel, 1997). Portable drip systems where laterals are moved manually from one row to another may be appropriate (Polak et al., 1997). Public subsidies for the development of less expensive systems may stimulate market development and promote adoption by reducing the risks involved in implementing unfamiliar irrigation methods.

Dhawan (2000) describes “productive” and “protective” benefits of drip irrigation that are similar to the notions of farm-level and public benefits. Productive benefits include farm-level water savings and improvements in crop yield, while protective benefits include the public values generated by reducing pressure on limited water resources and improving environmental quality. Public support for microirrigation may be justified by protective benefits that are not considered by farmers when they choose irrigation methods. However, subsidies for investment, alone, may not be sufficient to guarantee successful operation and maintenance (Dalvi et al., 1995; Somasundaram et al., 1995).

A delay in obtaining the returns from an investment in microirrigation is another source of divergence between farm-level and public benefits, particularly with perennial crops that require several years to reach fruit-bearing age. Farmers irrigating young fruit and nut trees may not be able to absorb the cost of a microirrigation system during the years before harvests begin. However, public benefits may be generated during those years if water use is reduced on fields with microirrigation systems.

Two states in India have established subsidy programs to promote farm-level investments in microirrigation. Farmers in Maharashtra adopted microirrigation rapidly in response to subsidies implemented in the 1980s (Magar, 1995b). By 1993, drip irrigation had been implemented by 36,000 farmers on 31,000 ha in the state. More than one-fourth of that area was planted in grape and one-half was planted in sugarcane, citrus, pomegranate, and banana. By 1997-98, the drip-irrigated area had increased to about 122,000 ha in Maharashtra or about 50% of the estimated 246,000 ha served by drip irrigation throughout India (Deshpande and Narayanamoorthy, 2001). Farmers in Rajasthan, India's second largest state also may obtain government subsidies to support installation of drip irrigation systems (Singh et al., 1995b).

Microirrigation may increase public costs when irrigation labor is displaced by conversion from conventional methods to drip irrigation (Dhawan, 2000; Ramanathan, 1994). This concern may be valid in some areas and for some period of time following microirrigation investment. However, the water savings, the increase in crop yields, and the expansion of crop production alternatives may be sufficient to create new and better employment opportunities, over time. Public support of programs that enhance the transition to new production activities may be appropriate to minimize any public costs of microirrigation, while maximizing public net benefits.

6.6. SUMMARY

The farm-level economic implications of microirrigation will vary among farms and regions, and among crops and resource endowments. Farmers producing high-valued crops in arid and semi-arid regions have a greater likelihood of gaining financially by adopting microirrigation than farmers producing low-valued crops in humid and sub-humid climates. The farm-level value of water saved by reducing irrigation requirements will vary with the cost and availability of irrigation water, and with the cost of energy and the labor required to obtain and deliver the water. Farm-level gains due to increased yields will vary with the crops produced and prices received.

Many of the studies reviewed in this chapter describe opportunities for improving profitability by adopting microirrigation, whereas other studies suggest that traditional irrigation methods will produce greater net returns. In some cases, net returns can be improved by combining microirrigation with other cultural practices, such as using plastic mulch on vegetables and small fruits. The return on an investment in microirrigation may be increased also by using the system to apply nutrients or pesticides, or to provide frost and freeze protection. Farmers in regions where fresh water is particularly scarce may benefit by using microirrigation systems to apply saline water or municipal effluent.

Empirical studies of irrigation performance in India and the United States suggest that many farmers using microirrigation are not achieving maximum water use efficiency. Even in regions with relatively high water costs, many farmers do not replace emitters when they become worn, resulting in uneven distribution of irrigation water. Thus, the results obtained under research conditions must be properly evaluated to reflect the actual practices in which those systems will be operated and maintained on commercial farms. Further research on farm-level operation and maintenance would enhance understanding of the true potential for improving agricultural production with microirrigation, and for developing public policies that promote efficient use of limited water resources.

The public benefits of microirrigation also will vary among regions with differences in the amount and quality of water resources. Water savings will be particularly valuable in regions where the sum of competing demands exceeds the available supply, and where improvements in water management will reduce any negative, off-farm effects of irrigation and drainage. Public benefits also are derived when microirrigation enables farmers to produce high-valued crops or to extend the time during which crops can be produced in regions with limited or saline water supplies. Economic incentives and other policies may be needed to encourage adoption of microirrigation in areas where public net benefits exceed farm-level net returns. The returns to public investments in research and extension services to develop and promote affordable microirrigation methods may be substantial in regions where rapid population growth increases pressure on limited surface and groundwater resources.

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7. AUTOMATION

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"Water spilt on the ground.....cannot be gathered again..... Samuel II, 14:14."

7.1. INTRODUCTION

Irrigation is the process of applying water essential for crop growth (Israelson and Hansen, 1967). A well controlled irrigation system should optimize the spatial and temporal distribution of water not necessarily to obtain the highest yield or to use the least amount of water, but to maximize the benefit to cost ratio (Hillel, 1980). Traditionally, irrigation applications are managed so that they consist of relatively brief periods of infiltration followed by extended periods of water redistribution and plant water extraction. This type of irrigation management is based on decisions dealing with "when" and "how much" water to apply. Typically, enough irrigation water is applied to refill the root zone to "field capacity" after most of the "available water" has been depleted (See Chapter 3 for a detailed discussion of irrigation scheduling).

Plant water uptake to satisfy evapotranspiration processes follows a diurnal cycle with the water moving from a periodically replenished root zone through the plant to the atmosphere. Under traditional irrigation management at the end of an irrigation cycle, soil water storage becomes depleted, the hydraulic conductivity decreases drastically and the root system cannot supply water fast enough to meet the evapotranspiration demand of the plant, thereby creating a plant water stress condition.

Irrigation methods capable of operating frequently, such as center pivot and lateral move sprinklers, and microirrigation, offer the means to maintain soil water at nearly constant levels and, thus minimize or control plant stress levels as determined by the irrigator (Phene et al., 1982).

However, as irrigation frequency increases, control of the soil-water-root environment is critically dependent upon the irrigator, regardless of whether the manager is a person or computer. Any disruption or disturbance to the irrigation schedule may quickly create detrimental water or oxygen stress on the crop. Therefore, control of high frequency microirrigation must be automatic, redundant, and capable of responding to small and rapid changes in soil water, plant water, or evapotranspiration.

Automating irrigation systems is not simply a process of selecting physical components to operate valves, motors, pumps, and switches, but rather one of collecting and interpreting data on soil water status, plant water use and stress, and weather, and then using this information to schedule irrigation based on previously established management goals. These might be maximum yield, maximum water use efficiency, or a quality objective (e.g., sugar content in wine grapes or solids in processing tomatoes). The objectives of this chapter are to discuss; (1) basic control theory, (2) automatic control system methods and applications, and (3) microirrigation system instrumentation and hardware.

7.2. CONTROL THEORY

Control theory or systems analysis consists of mathematical techniques used to model how one component controls or influences the activity of another component in an interlinked system (Riggs, 1970). Usually, control systems are divided into two categories: (1) open loop systems; (2) closed loop systems.

In an open loop control system, the operation is preset and independent of any sensor input with an operator making the required decisions. For irrigation systems, two decisions are made (1) when to irrigate and (2) how much to irrigate. Examples of open loop irrigation control systems are presented in Fig. 7.1.

In a closed loop control system, the controller is directly dependent on an output from a sensor or control algorithm through a feedback mechanism to the input. Precise control can be achieved by closing the loop via the feedback device and comparing the output with some reference input signal (either constant or variable). For example, in the closed loop feedback control system shown in Fig. 7.2, crop evapotranspiration (Et_c) is either measured or calculated and this information is used to adjust either the irrigation volume or time so that the depth of irrigation water applied to the field (d_i) is proportional to Et_c such that

$$di = Etc \,/\, Ie \tag{7.1}$$

where I_e is the irrigation application efficiency of the irrigation system.

7.2.1. Control Methods

Three major control modes are available within both open and closed loop categories: (1) on-off control, (2) stepwise control, and (3) continuous control. Linear systems, discussed later, are used only for closed loop systems since they require feedback elements to adjust water application.

7.2.1.1. On-off control

The on-off control system turns the system on or off, and the control condition is independent of the system and is illustrated as a block diagram of this control system (Fig. 7.1a) where the irrigation valve is either on or off. Most irrigation systems are controlled by this model. In some cases, the operator is replaced by a timer switch or more sophisticated devices, but the control condition remains independent of the system.

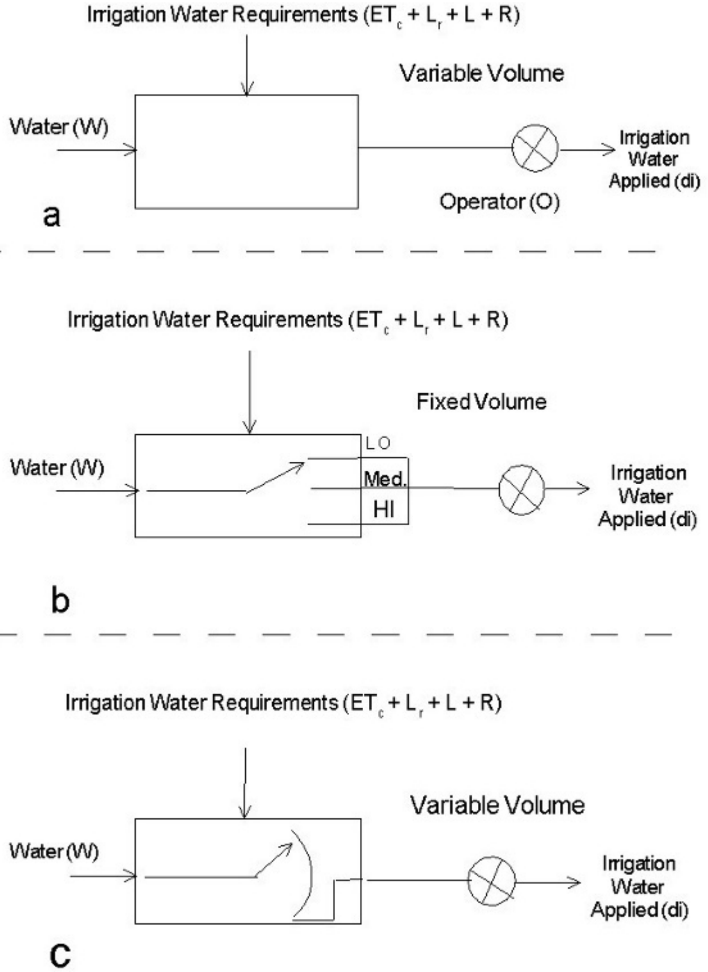

Figure 7.1. (a) Open loop, on-off irrigation control system. The operator calculates the water requirement of the field and opens a valve for a given amount of time *(t)* to apply the required amount of water *(d_i)*. Time as set by the operator is the only variable available. (b) Open loop, stepwise irrigation control system. The operator calculates the water requirement of the field and can select either Hi, Med, or Lo volume of irrigation before the valve is opened to deliver the required amount of water *(d_i)*. Three preset irrigation volumes are variables available to the operator to achieve the irrigation objective. (c) Open loop continuous irrigation control system. The operator calculates the water requirement of the field and can select any irrigation volume before he opens the valve to deliver the required amount of water *(d_i)*. An infinite number of irrigation volumes are available to the operator to achieve the irrigation objective.

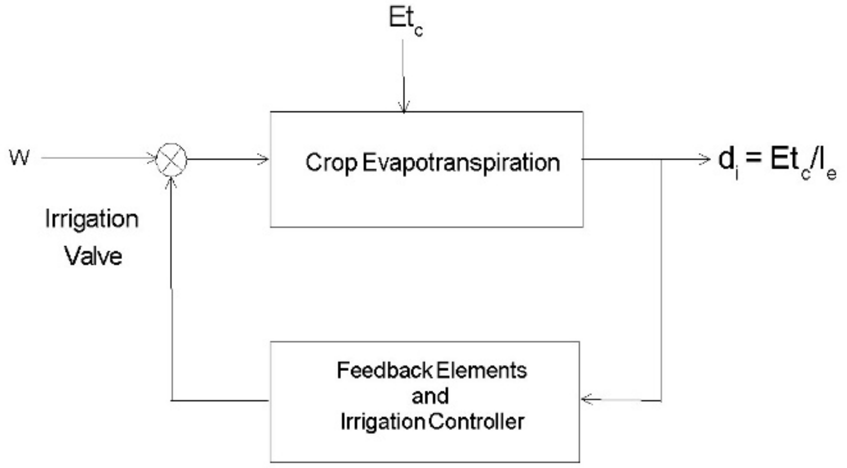

Figure 7.2. Closed loop, feedback irrigation control system. No operator is involved. Evapotranspiration *(Et_c)* of the crop is calculated and the irrigation valve is turned on until the required amount of water *(d_i)* is applied accounting for the irrigation efficiency *(I_e)*. The feedback system has the capability to modify the application by either stopping the irrigation if it is raining or increasing the irrigation set if a change in weather conditions requires it.

7.2.1.2. Stepwise control

For stepwise control (Fig. 7.1 b), d_i may be varied by selecting different positions on a valve, a flowmeter, or a timer to give different irrigation volumes and more precisely to meet Et_c, for instance, early in the season when Et_c is low, position LO could be used. As Et_c increases, positions MED, then HI, could be selected to increase d_i and to apply progressively more water with each irrigation. The volume of water applied to meet Et_c is not a direct function of Et_c, but an estimate based on other measurements. The application of stepwise control in irrigation is sometimes implemented by a time clock with fixed intervals of time control, but operated exactly like the on-off control. The irrigation time T_i can be calculated from the relation

$$T_i = 100\frac{Et_c I_f}{I_e I_a} \tag{7.2}$$

where T_i is the irrigation time in h, Et_c is the crop evapotranspiration in mm/day, I_f is the irrigation frequency in days per irrigation, I_e is the irrigation efficiency in (%,) and I_a is the application rate of the irrigation system in mm/h. Et_c can be multiplied by a linear factor to adjust for leaching and percolation losses. Rainfall can be accounted for in the computation by delaying irrigation the number of days equal to the depth of rainfall divided by the daily Et_c.

7.2.1.3. Continuous control

For continuous control (Fig. 7.1c), the depth of irrigation water can be selected from minimum to maximum values by adjusting time or volume of water in a continuous manner. Any value of time or volume between maximum and minimum can be achieved by varying the time or the volume setting on the flowmeter. The final volume of water applied may meet the water requirement more precisely than possible with on-off or stepwise control, but it is not a direct function of Et_c.

7.2.2. Linear Systems

A system is classified as linear if the output is directly proportional to the input (i.e., the ratio of the output to the input is constant). For irrigation in arid regions where insufficient rainfall occurs during the growing season, the input variables are Et_c, leaching requirement *(L_r)* for salinity control (See Chapter 4 for a detailed discussion), irrigation system losses *(L)*, and runoff *(R)*. The output variable is d_i and the objective is to irrigate so that

$$d_i = \frac{Et_c + L_r + L + R}{I_e} \tag{7.3}$$

For example, if the leaching requirement *(L_r)* to keep the soil free of salts is 15 percent of Et_c, I_e = 0.90 and both L and R are zero, the correct amount of water to apply d_i is

$$d_i = \frac{Et_c(1 + 0.15)}{0.90} = 1.28 Et_c \tag{7.4}$$

In irrigation practice, the principles governing closed loop feedback control systems are provided by linear systems theory, where the input represents the command or cause and the output represents the results of the system process. In the preceding example (Eq. 7.4), d_i is the result of an operational adjustment to apply just enough water to meet Et_c of the crop being irrigated, L_r to maintain a satisfactory salt balance in the root zone with an irrigation system I_e of 0.90.

7.3. AUTOMATIC CONTROL SYSTEMS

Irrigation scheduling is the method to manage soil water in order to meet crop water requirements within the limitations of the irrigation system and crop production goals. Unlike traditional irrigation, microirrigation is more sophisticated whereby varying amounts of water can be supplied frequently to a crop, provided an adequate supply of water is available. Technology is now available to modify an irrigation schedule using real time analysis of factors such as weather, crop growth stage, desired plant water stress, soil aeration, soil water potential, and soil water salinity. However, scheduling of many irrigation systems (microirrigation systems included) has been limited to an on-off control system using time or water volume as the control variable. The computer is programmed merely to sequence solenoid valves and to check flowrates and pressures, wind, temperature, and other variables used to determine evapotranspiration. Improved electronics and computer controls coupled with expert systems have made it possible to improve the operation of an irrigation system to meet a wide range of objectives ranging from frost protection to maintaining minimum variation of soil water potential.

To achieve a minimal cost-to-benefit ratio and the most efficient use of the water supply, high water use efficiency (WUE) must be achieved simultaneously with high crop yield. The factors contributing to excess irrigation application in Eq. 7.3 must be either eliminated or reduced so that water application only meets the crop requirement. Microrrigation should be managed so that L and R are near zero, I_e is high (90 percent or greater), and L_r is achieved either by applying an adequate preplant irrigation or by applying a percentage of water, based on the water quality, in excess of the plant water requirement with each irrigation. The dominant factor of Eq. 7.3 is Et_c and it is also the most difficult factor to estimate (See Chapter 3 for a detailed discussion). It is a function of weather, soil, plant, and sometimes irrigation systems and is variable on a daily and seasonal basis. Factors affecting irrigation scheduling are listed in Tab. 7.1. Most of these factors are interdependent and variable, both spatially and temporally.

Table 7.1. Factors affecting irrigation scheduling.

<u>Water factors</u>	<u>Soil factors</u>
availability (amount and time)	aeration
quality (salinity, specific ion conc.)	depth
	drainage rate
<u>Climatic/weather factors</u>	fertility
ambient temperature (day/night)	hydraulic conductivity
day length	infiltration rate
humidity	mechanical impedance (layers)
length of growing season	micro and macroorganisms
rainfall	salinity
solar radiation	structure
wind speed, direction	temperature
	texture
<u>Plant factors</u>	water retention characteristics
crop variety	water table
drought tolerance	
growth stage	<u>Management factors</u>
harvestable component	critical growth stages
length of growing season	crop protection
nutrient requirement	cultivation
rooting characteristics	date of planting/harvesting
salt tolerance	fertilization
yield and quality	irrigation system
	plant population

Many crops are good integrators of the factors affecting Et_c. Accurate scheduling of irrigation can minimize the adverse effects of some of these factors and may maximize attainable crop productivity for a set of constraints. Basic closed loop feedback systems for automated irrigation scheduling can be constructed using data from; (1) soil water, (2) plant water, (3) plant physical characteristics, (4) evapotranspiration, (5) combinations of 1, 2, 3, and 4 assuming that water, fertilizer, and management factors are not limiting. Each of these approaches has advantages and disadvantages that are not discussed in detail; instead, examples using each of the data sets are discussed in terms of how they may be implemented and managed.

7.3.1. Soil Water Methods

Soil is composed of three phases; (1) solid, (2) liquid, and (3) gas. Depending on the soil type, conditions, and use, the relative amount of these three phases can vary greatly. Water is the main component of the liquid phase and air, the gaseous phase. The composition of the soil air is greatly affected by the water content through the irrigation application, and in turn affects root activity. For the purpose of irrigation, one should be concerned with the energy, mass, and volume relationships between liquids and gases because the solid phase of the soil will remain nearly constant (See Chapter 2 for a detailed discussion). The balance between the liquid and gas phases is most critical because it regulates root activity and plant growth processes, which are of interest in irrigation and evapotranspiration.

Aeration (gas exchange) in soil is primarily a diffusion process that is controlled by diffusion coefficients. These diffusion coefficients are inversely proportional to the thickness of water films in soil pores. Thus, aeration depends upon the porosity of the soil and the concentration gradient of O_2 and CO_2. Adequate aeration of the root zone is necessary to maintain plant growth. Proper irrigation management is required to maintain a suitable balance between air and water, which depends on applying only the volume required to replenish soil water in the root zone.

The water holding capacity of soils differs greatly with soil type. In sandy soil, plants may be subjected to rapidly changing soil water values ranging from saturated to wilting conditions within a day. In clay soils, water values change more slowly. Therefore, the frequency of irrigation for optimum crop productivity may vary between several irrigations per day to irrigation every few weeks depending on soil characteristics. As irrigation frequency increases, the total water holding capacity of the soil becomes less important because applied water matches Et_c and less water is stored during each irrigation. Furthermore, because the frequency of the irrigation application can conceivably be very high, the apparent application rate can be adjusted to fit the infiltration rate of the soil. This allows water to move through soil under unsaturated conditions, maintaining continually favorable conditions for gaseous diffusion and adequate aeration of the root zone.

7.3.1.1. Soil water potential

The potential energy of soil water in the root zone of the crop results mostly from the various force fields to which it is subjected. Water will flow or diffuse along gradients from high to low energy status. For instance, in the transpiration process, water moves along the potential gradient as the stomata of crop leaves open at dawn and the transpiration process begins (Fig.7.3). Hence, plant responses are directly dependent on soil water potential values rather than soil water content. This dependence can be used effectively to maintain a desired plant water stress level. Scheduling frequent irrigations can be accomplished with automatic feedback control based on soil water potential. In this type of irrigation scheduling, there is a smaller margin for error so that timeliness is important because the water storage capacity of soil is de-emphasized and water is applied to match evapotranspiration.

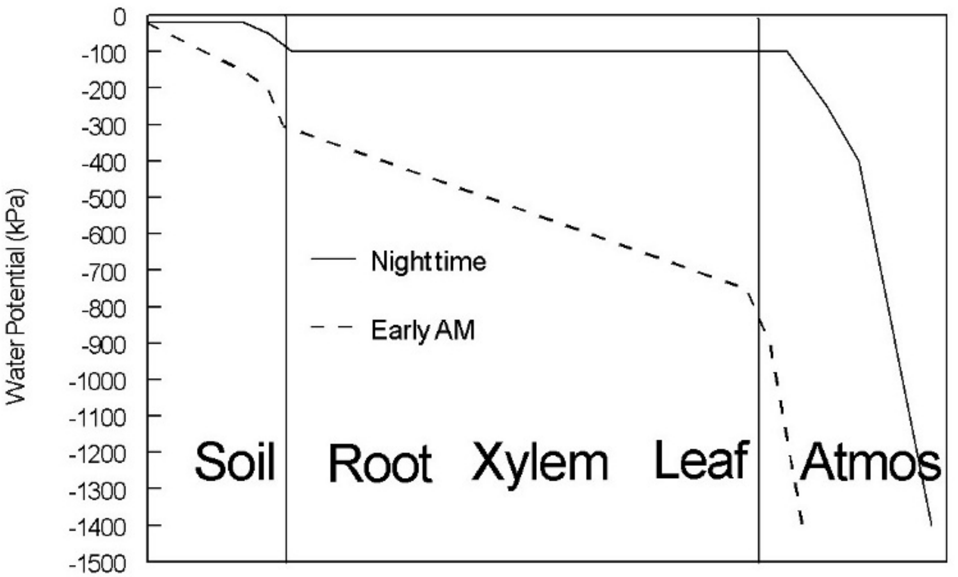

Figure 7.3. Soil-plant-atmosphere water potential continuum as affected by the opening of the plant stomata.

Irrigation based on soil water potential is one of the oldest irrigation scheduling techniques. Tensiometers (Richards and Gardner, 1936), thermal methods (Shaw and Baver, 1939), gypsum blocks (Bouyoucos and Mick, 1947), and thermocouple psychrometers (Richards and Ogata, 1958), have been applied successfully. Microprocessors connected to sensors can be used to simplify irrigation applications (Cary and Fisher, 1983). Sensors can provide real-time information to assist in making decisions on irrigation water application. Microprocessor-based circuits can be coupled to micrologger/computers to give an estimate of the time of the next irrigation, from field data and an operator supplied parameter. The program in the micrologger/computer can assess the output from the soil matric potential sensor and use it to extrapolate the soil drying rate to estimate the date of the next irrigation. The time of operation may vary from hours to days depending on the soil type, crop, climate, and whether the goal is to maintain nearly constant soil water potential or to allow some variation in the potential.

A thermal method, which measures soil matric potential independent of soil texture, temperature or salinity, is based on frequent measurements of the heat dissipation from a small source by a porous ceramic sensor (Phene et al., 1973; Phene and Clark, 1990). With proper calibration, the sensor can be used in any soil to monitor soil matric potential and control irrigation automatically.

In addition to water potential, soil physical properties such as oxygen diffusion (aeration) and soil mechanical strength (compaction) are used to define the range of soil matric potentials *(P_m)* optimal for root growth and activity. An example of the optimal P_m for a Hanford fine sandy loam is shown in Fig. 7.4. Within this range, a soil matric potential value is selected at which irrigation is to be started (threshold). Data in Fig. 7.4 have a range from about -10 to -60 kPa and indicate that the optimal P_m should be about -25 kPa. The optimal P_m may be in a large range when the soil texture is finer, but is extremely small in compacted coarse-textured soils. Therefore, the optimal P_m of sandy soil must be measured, but may be estimated for fine textured soils.

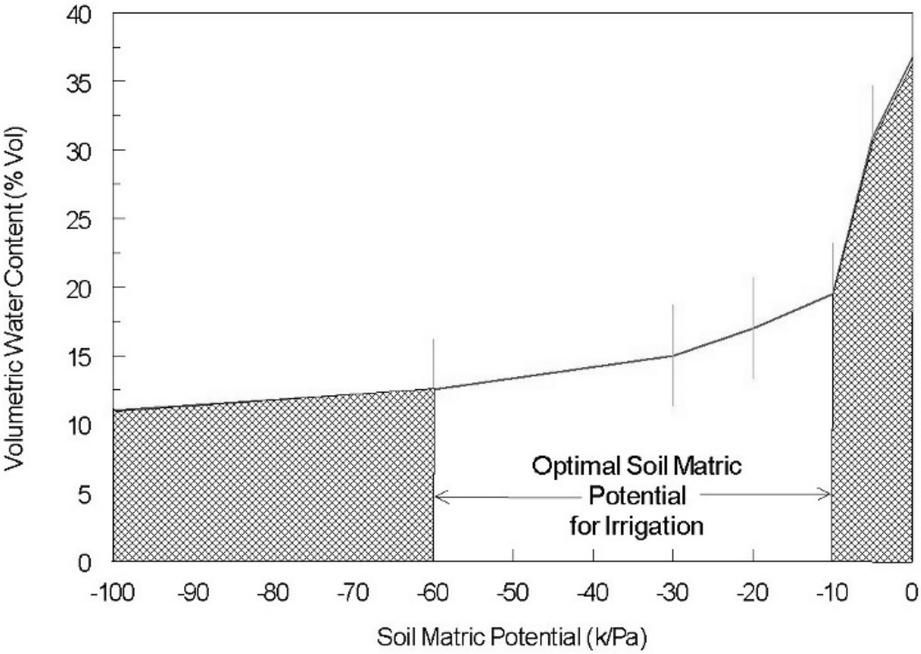

Figure 7.4. Water desorption curve and optimal m for irrigation of a Hanford fine sandy loam soil (Typic Xerorthents).

Monitoring soil matric potential and controlling an irrigation system requires equipment; (1) to automatically sample several sensors sequentially, (2) to compare each sensor output to the soil matric potential at which irrigation is to start (threshold), and (3) to have computer outputs capable of controlling the irrigation system. Both desktop computers and microprocessors have been successfully used (Phene and Clark, 1990). Commercial equipment is available to measure soil matric potential and control the irrigation system automatically (Charlesworth, 2000).

The soil sensor should be placed in the middle of the mature crop root zone for closed loop-feedback automated irrigation. In this location, the majority of the root zone is never allowed to dry beyond the soil matric potential threshold before the sensor detects the drying trend and triggers irrigation. Early in the season, when the roots are shallow and the soil near the surface dries out rapidly, the threshold P_m can be increased so that water will be available in the active root zone (Phene and Clark, 1990).

Tensiometers have traditionally been used in a manual mode that required daily reading or at least several times a week depending on the soil type. Interpretation of these data along with crop water use was required and a schedule was manually entered into the controller. The sensors were often installed at two depths to characterize the water use in the upper part of the profile and to determine if the water advanced to the bottom of the root zone. Advances in electronics have made it possible to automate tensiometer measurement of soil water potential, and thus, control an irrigation system. Zazueta et al. (1994) reported on the successful application of a switching transducer tensiometer in turf and a microirrigated citrus field. In these applications, irrigation was initiated when the P_m decreased below the threshold and was continued until the soil water returned to acceptable levels when P_m was above the threshold. Irrigation occurred up to five times a day. Because tensiometers have requirements for frequent maintenance, operational requirements will require decision criterion to check for tensiometer failure. This is the general principle of operation described for the soil matric potential sensors. The critical questions to be answered are the placement of the sensors and the selection of the thresholds for operation.

Methods that schedule irrigation based on soil water potential have the advantage of being transferable across a range of soil types. Plant water use is dominated by potential gradients with the soil matric potential being the dominant resistance to crop water uptake in soil. The osmotic potential component is usually negligible in the total soil water potential and it can be disregarded in the calculations.

7.3.1.2. Soil water content

When soil water content is used, the soil type and the water holding capacity are the basis for the irrigation decisions. Previously, soil water content was used in automation algorithms as the storage component in a water balance calculation. Soil water content was measured manually using either gravimetric methods or neutron attenuation techniques. However, neither method is suited to real time control in a close loop system and can only be used in an open loop system. Developments in electronics and microloggers have enabled the real time measurement and continuous logging of changes in soil water content with depth. Both time domain reflectometry (TDR) and frequency domain reflectometry (FDR) can be adapted to closed loop systems to automate irrigation.

Time domain reflectometry has been used for many years by various cable industries to locate breaks or damages to the cable. The approach is based on sending an electromagnetic wave pulse along a cable and detecting a reflected echo or signal. Part or all of the pulse will be reflected by interference along the cable. By knowing the speed at which the pulse moves through the cable and the timing of the reflected pulse, the operator can calculate the location of the problem.

The key property that influences the speed of conductance of an electromagnetic wave through a medium is the dielectric constant of the material. With increasing dielectric constant, both the electric field and the velocity of propagation of electromagnetic signal are reduced. Therefore, the higher the dielectric constant, the slower the pulse moves through the medium. By using significant difference in dielectric constant between dry soil and water (3 to 5 versus 80), Topp et al. (1980) adapted the TDR technique to measure soil water. The research linked the travel time of an electromagnetic wave to the volumetric water content of soil. A third order polynomial was used to relate the apparent dielectric constant to the water content of the soil.

Soil water content is measured over the length of the wave guides or probes and indicates the average water content. When the probes are installed vertically into the soil, an average water content with depth can be obtained. Also, probes can be installed horizontally in the wall of a pit or buried horizontally at various depths. The measured water content would have to be integrated with depth to obtain average water content. Changes in the water content may be used to determine water use and to schedule irrigation. This equipment is currently used primarily in research applications. Hand-held units that may be used to determine soil water at a point in time and space are available, but are not suited for automation.

Frequency domain reflectometry is also identified as a capacitance technique and is being used in a new generation of equipment for monitoring soil water content and for making decisions regarding irrigation time and depth of application. The capacitance method for measuring soil water has been made possible with the advent of inexpensive electronics and the recognition that interfacial polarization in the capacitor, a problem in precision applications, could be overcome by use of frequencies greater that 50 MHz. In the current application, the soil to be measured becomes part of the capacitor in a feedback loop of an inductance-capacitance resonance circuit of a Colpritts or Clapp high frequency oscillator. The oscillator resonance angular frequency is related to the capacitance of the probe which is related to the dielectric constant of the soil.

These new probes use split cylindrical electrodes that are either buried in the soil or positioned at different depths in plastic access tubes buried in the soil. The oscillator circuit and other electronics are placed within the cylindrical electrode probe. With this configuration of probe placement, some of the electromagnetic field between the electrodes passes through the plastic access tube and the interior of the probe. The relative amount of the field penetrating the probe, the access tube, and the soil, depends on the radius of the cylindrical electrodes, the gap between the probes, and the relative dielectrics of the components. The dielectric material between the cylindrical electrodes must have a low dielectric constant to ensure an adequate and accurate response to low a soil dielectric constant, which is low soil-water content. The zone of influence is small around most of the current measuring devices and is centered on the gap between the electrodes. The probe is most sensitive in the region adjacent to the gap which means that the probe is very sensitive to any air gap between the probe, access tube, and soil. Special care must be exercised during the installation of the access tubes to ensure that no air gaps exist between the soil and access tube.

The vertical array of sensors used in the improved instrumentation enables the user to monitor in detail root development and crop water use within the soil profile. Software provided with the FDR system can be used to determine set points for refilling the root zone and thus controlling the irrigation system. Data in Fig. 7.5 show the variation in soil water content to a depth of 1m and the water extraction at progressively deep locations in the soil profile under a cotton crop.

The variation in total water content over the growing season for a cotton crop is shown in Fig. 7.6. Irrigation was initiated when the total water content reached 34% of the available water. Total application was set to be the difference between the top and bottom limits of the envelope defined by the 53% and 34% soil water content. Root zone development caused the envelope size to increase.

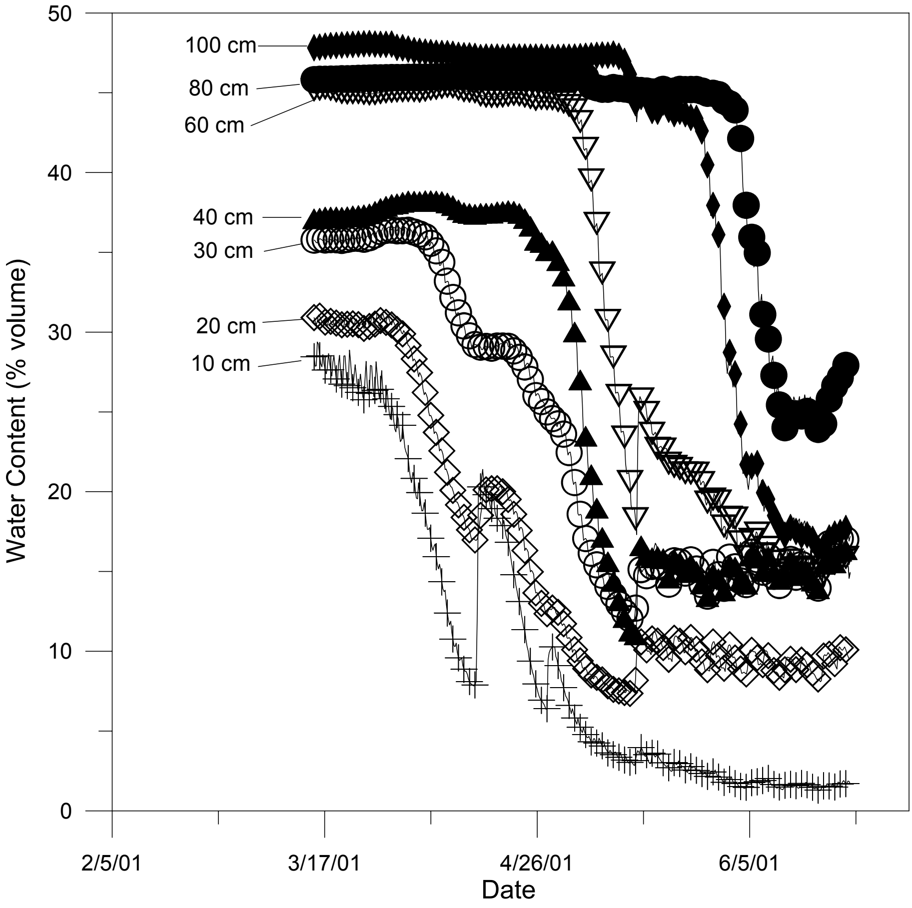

Figure 7.5. Soil water content measured using capacitance probes at 10 cm depth increments under a flood irrigated cotton crop.

7.3.1.3. Wetting front detection

The objective of irrigation is to wet the soil profile to "field capacity" to a desired depth. Sensors have been developed that indicate when the objective has been reached. Charlesworth (2000) labeled these devices wetting front detectors. The irrigation system is set to operate at a fixed interval based on knowledge of the soils, crop rooting depth, and maximum water use. Irrigation is initiated by the timing device and stopped when the wetting front is detected by the control device. Depth of application is based on the premise that the wetting front advances faster in wet soil than in a dry soil. In such cases, the depth of application would be reduced for the wet soil compared with the dry so the total water application is reduced. Examples of this type of control device include the FullStop™ (Hutchinson and Stirzaker, 2000), and the wetting depth probe (Zur et al., 1994).

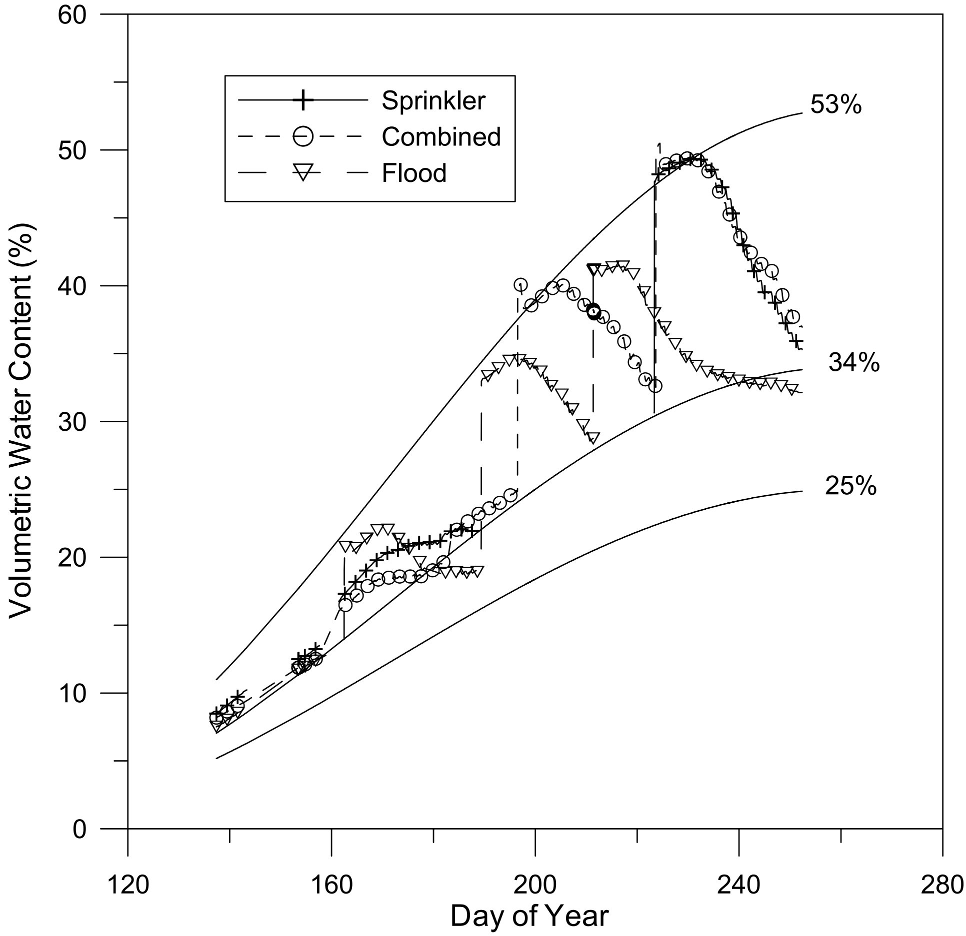

Figure 7.6. Variation in total soil water content to a depth of one meter measured using capacitance probes under sprinkler irrigated, flood irrigated, and combined (sprinkler then flood irrigated) cotton plots.

The FullStop™ (Hutchinson and Stirzaker, 2000) is a funnel shaped container filled with soil and buried at the control depth. When the wetting front passes the container, water is collected by the funnel and concentrated in a reservoir where it is detected by a float switch that stops the irrigation. The system is reset by the water in the reservoir being absorbed back into the soil mass. The system is prone to over irrigate early in the season because of the fixed irrigation period and fixed depth of the detector. The root zone is small early in the growing season and the transpiration demand is low so the potential is high for excessive deep percolation losses. This can be corrected by using a second detector closer to the surface or reducing the irrigation volume.

The wetting depth probe (Zur et al., 1994) consists of a column of ceramic sensors with stainless steel electrodes fitted on each end. When the wetting front arrives, the circuit is completed across the sensor and the time of arrival is recorded. Irrigation is stopped when the wetting front reaches a critical depth. Zur et al. (1994) developed an expression to calculate the critical depth based on the velocity of advance of the wetting front, which was shown to be inversely proportional to the initial soil water content. An iterative learning process based on the real time output from the probe during irrigation is proposed to account for the non-uniformity of the field situation. The acquired wetting front data are used to estimate a critical depth and a planned final depth for the wetting front during irrigation. These measurement and calculation processes are included in the depth probe and used to stop irrigation and control the quantity of water applied.

7.3.2. Plant Water Methods

Water is usually the most limiting factor in crop production. However, most of the water taken up by plants is lost to transpiration in response to the evaporative demand of the surrounding atmosphere. Less than one percent of the water absorbed is actually retained by the plant. Even this small fraction of water is sometimes used to make up the deficit between water uptake and transpiration; thus, any lack of water, causes a deficit in plant water. Total leaf water potential (the sum of turgor, matric, and osmotic potentials) is used to indicate the water status of a plant. Most of the plant growth processes are affected by plant water deficit. Cell enlargement (growth), photosynthesis, pollination, and fruit setting are affected at low plant water stress levels to the point where yields can be reduced.

The plant process most sensitive to water deficit is probably growth by cell enlargement (Hsiao, 1973). When subjected to water deficit, the cell water content decreases, and as the positive pressure potential (P_p) (also referred to as turgor pressure) approaches zero cell enlargement stops, even though all other necessary chemical and physical requirements are met. Photosynthesis is also reduced when the plant loses its turgor pressure because, as the guard cells deflate, the stomata close, reducing the diffusion pathway for CO_2 transport into the leaves. With reduced photosynthesis, the rate of dry matter production is decreased.

Pollination and fruit setting are also sensitive to water stress and fruit yield will be reduced even though the production of dry matter may not appear to be affected. Hence, a high (small negative value) total leaf water potential (P_L) should be maintained during pollination and fruit setting to obtain maximum fruit yield. Regulated deficit irrigation (RDI) demonstrates that there are periods when it is possible to stress plants without adverse effects on yields (Chalmers et al., 1981, 1986).

Several methods are available to estimate plant water status. These include determination of relative water content, leaf diffusive conductance, plant water potential, and plant temperature. Plant water potential obtained either from direct or indirect measurement is probably the best indicator of plant water stress. Automatic feedback control of microirrigation systems can be achieved by measuring total leaf water potential using the leaf psychrometer (Hoffman and Rawlins, 1972), plant canopy temperature using the infrared thermometer (Jackson, 1982; Howell et al., 1983; Wanjura et al., 1992), and leaf water potential indirectly based on stem diameter measurements (Parsons et al., 1979).

7.3.2.1. Leaf water potential method

Leaf water potential *(LWP)* measurements are routinely made by excising the first fully open leaf from the top of the plant and measuring the potential using a pressure chamber (Kite and Hanson, 1984; Meron et al., 1987). These data can be used to schedule the timing of irrigation, but provide no information on the required depth of water. The depth of application has to be determined by a measurement of the stored soil water through gravimetric sampling or other soil water content measurement methods. The need for manual measurements limits the frequency of irrigation. Major limitations of the procedure are the lack of data relating *LWP* levels to plant responses (yield, growth, etc.) for a wide variety of crops and the labor required to make the measurements. Consequently, this technique is suitable for only the open loop control systems.

7.3.2.2. Plant canopy temperature method

The surface temperature of a body is related to its black body radiation according to the Stefan-Boltzmann equation

$$T_s = \left(\frac{R}{\varepsilon\sigma} \right)^{1/4} \tag{7.5}$$

where T_s is the surface temperature in K ($^oC + 273$), R is the emitted black body radiation in W/m^2, ε is the emissivity of the body (ratio of emitted radiation to that of a perfect black body) and σ is a constant (5.674×10^{-8} $W/m^2/K^4$). Most crops are near perfect emitters in the 10 to 14 μm waveband. This principle has been applied to measure the surface temperature of a crop canopy by non-contact infrared thermometer *(IRT)*. The *IRT* accuracy in measuring plant canopy surface temperature is dependent on accurate calibration. Measurements are sensitive to ambient temperature changes due to cloud interference, and interactions with surrounding surfaces, especially from the soil surface when the crop canopy does not completely cover the soil.

Crop canopy temperature measurements have been used in the Crop Water Stress Index *(CWSI)* concept to estimate crop water stress (Jackson, 1982). For a given crop, the ratio of the difference between crop canopy and air temperatures to vapor pressure deficit *(VPD)* is bounded by two baselines (a well watered or lower baseline and a terminal stress or upper baseline), which are determined for the specific crop by either theoretical or empirical methods. The basic concept is outlined in Fig. 7.7 for a cotton crop. The *CWSI* is calculated by dividing the distance $(A - A_0)$ by $(A_1 - A_0)$ at the same *VPD*. The crop water stress index has a value of "zero" for no water stress and "one" for terminal stress or an essentially dead plant.

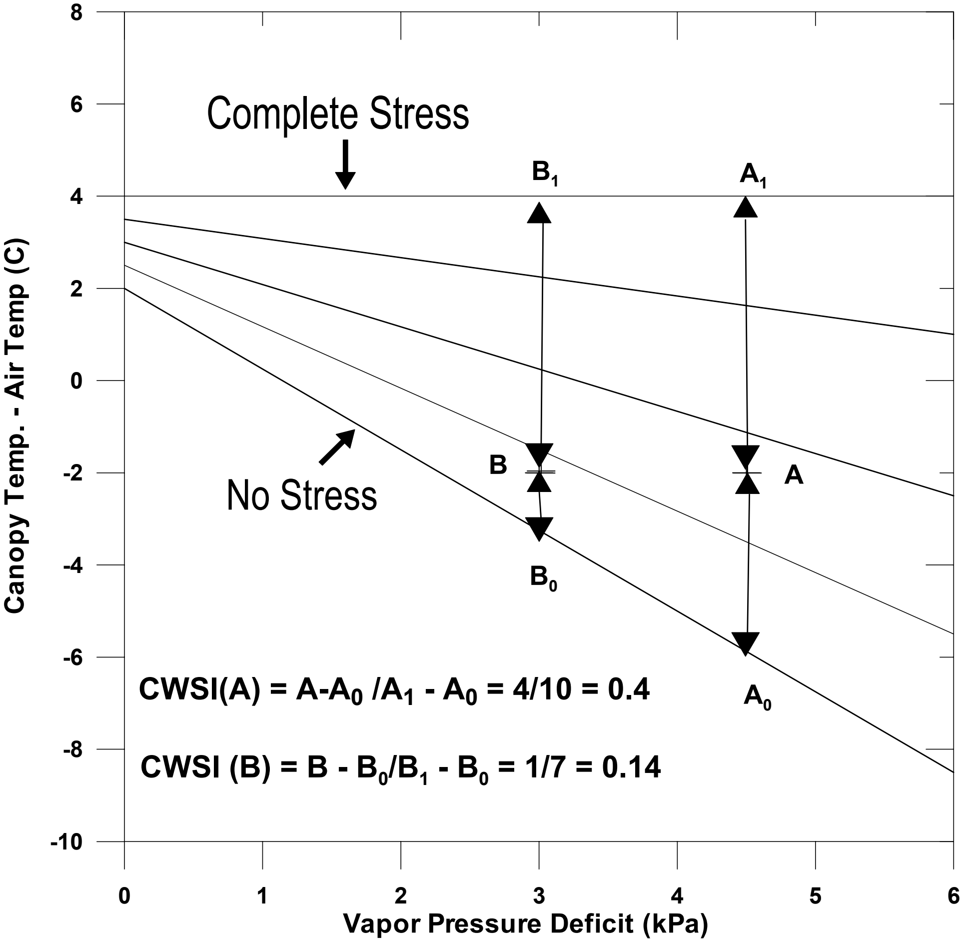

Figure 7.7. Crop water stress index (CWSI) relationships for a cotton crop. After Howell, et al., 1984).

Although the *CWSI* has not yet been used to automatically schedule irrigation, it can serve as the feedback to monitor, and if necessary adjust the irrigation schedule. Software can be developed to collect data, calculate *CWSI,* make comparisons with irrigation threshold values, and make decisions on irrigation. For example, if a *CWSI* of 0.25 is set as the irrigation threshold, the system would call for irrigation at point *A*, but not at point *B*. Although the temperature difference is the same in both cases, the lower *VPD* in case *A* would create a greater evapotranspiration rate and, thus, a larger *CWSI.*

Howell et al. (1984a) pointed out that "although the *CWSI* appears to be useful in assessing crop water stress in cotton, irrigation scheduling requires decisions for both timing and amount." Therefore, traditional irrigation scheduling models (Jensen et al., 1970, 1971) should be used to predict the irrigation application amount necessary to refill the crop root zone when an irrigation requirement is sensed by any plant indicator (either leaf water potential, *CWSI* or other plant measurement). In many cases, soil water depletion can be directly measured either by gravimetric or neutron methods. In irrigation systems that are frequency or rate controlled, such as center-pivot sprinkler, lateral-move sprinkler, and microirrigation systems, the *CWSI* can be used to indicate the need to either increase or decrease irrigation amounts or frequencies.

Another type of irrigation control uses an infrared thermometer developed for continuous outdoor operation. Wanjura et al. (1992) used an infra-red thermometer, thermometers within the crop canopy, and anemometers to schedule drip irrigation of cotton. Irrigation was initiated whenever a calculated temperature threshold was exceeded and water was applied incrementally in fixed increments until the threshold was no longer exceeded. Subsequent research (Wanjura et al., 1995) included a time and temperature threshold *(TTT)* to control irrigation. This method was successful, but is probably better suited to research than practical field applications.

The research by Wanjura et al. (1992, 1995) led to the development of a biologically-based irrigation scheduling protocol termed Biologically Identified Optimal Temperature Interactive Console, *BIOTIC*, (Mahan et al., 2000). This system uses species-specific optimal temperature values and continuous monitoring of plant canopy temperatures to determine the need for irrigation. The concept is based on the theory that plant metabolism is impaired above specific temperatures resulting from stress caused by a water deficit. Irrigation is initiated when the canopy temperature exceeds the plant-specific threshold value. However, the elevated temperatures must be evaluated to determine that the increase is caused by a water deficit. This system has been used successfully to schedule irrigation for 10 years on a variety of crops and different types of irrigation systems.

An inexpensive irrigation control system using an air-leaf temperature differential was reported by Abraham et al. (2000). The air-leaf temperature differential is correlated to soil water content and is used as an indicator for scheduling. Irrigation was applied in fixed increments until the temperature is less than the threshold value of the air-leaf temperature differential.

7.3.2.3. Plant turgor methods

Stem diameter and leaf water potential are closely related (Klepper et al., 1971). Thus, stem diameter measurements can be used to monitor continuously long-term stem growth and plant water status. Two methods are available that use stem diameter to predict the diurnal variation of xylem water potential (Huck and Klepper, 1977). The first and simplest procedure, the Shrinkage Modulus Method, determines an arbitrarily calibrated shrinkage modulus and relates a measured change in stem diameter to a corresponding measured difference in leaf water potential. The second procedure, the Dynamic Flux Method, simulates water flow between xylem and associated phloem parenchymal tissues that results from changes in plant water potential. Water potential differences between the xylem and surrounding tissues are assumed to induce a radial flux of water across the cambial boundary layer causing swelling and shrinking of the stem.

Stem diameter change *(S)* of continuously drying cotton plants was measured with a linear variable differential transformer (Parsons et al., 1979). The reference for computing stem diameter change was the stem diameter measured on a well watered plant before sunrise.

Stem diameter stress can be integrated numerically using the equation

$$ISS = \int_{t_0}^{t_1} \Delta S_{(t)} dt \tag{7.6}$$

where *ISS* is the Integrated Stem Stress, in mm /day, t_0 is the pre-sunrise time (h), t_1 is the post-sunrise time (h), and $\Delta S_{(t)}$ is the stem diameter change from the non-stressed stem diameter at time *t* (mm).

Leaf water potentials may be inferred from measurements of the hydraulic pressure necessary to cause water flow from the uncut edge of a leaf at sunrise and periodically each day to insure that the maximum and minimum values are obtained. The relationship between the observed stem diameter changes and the minimum observed P_L is presented in Fig. 7.8.

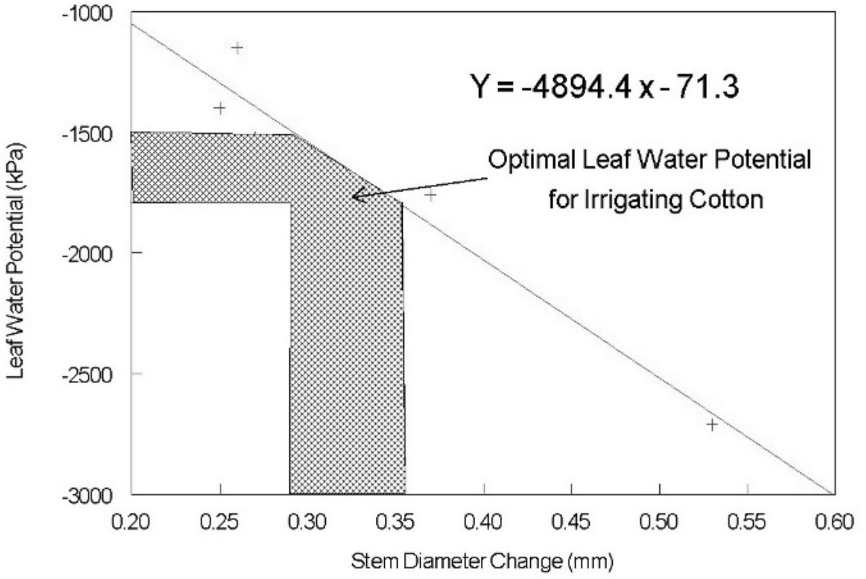

Figure 7.8. Linear regression of minimum observed leaf water potential versus maximum stem diameter change from the reference stem diameter. Broken line represents 90% confidence intervals. Adapted from Parson et al. (1979).

These measurement techniques could be used for feedback control of automatic microirrigation systems. To be useful periodic calibration of stem diameter changes versus P_L must be obtained at least for each plant phenological stage. In the case of cotton, the irrigation threshold P_L = -1.8 MPa is based on calibrated stem diameter measurements for feedback control. Using crop phenological stages and known water requirements of cotton, the P_L threshold values can be adjusted as required. As with the *IRT* method, simultaneous measurements of soil water and/or E_t should be used (initially at least) to establish confidence in the method.

Huguet et al. (1992) determined that both the maximum daily shrinkage *(MDS)* and daily evolution *(DE)* are required to understand water stress in peaches and apples. The *MDS* appears to be related to environmental factors affecting plant transpiration, whereas *DE* is linked to disturbances or stresses related to plant physiology. *MDS* reflects daily variation in stem diameter whereas *DE* considers the change over a 24 h period. More research is required to understand the use of these variables in development of an objective irrigation schedule. Micromophometry appears to be a reliable method of logging changes in plant water status as reflected by both stem shrinkage and fruit and stem growth (Huguet et al., 1992).

Goldhamer and Fereres (2001) used trunk diameter measurements *(TDM)* to develop irrigation protocols for both young developing peach trees and mature peach trees. Maximum daily shrinkage was used to determine irrigation for both low (≥ 3-day intervals) and high (≤2-day intervals) frequency. The daily evolution of the minimum daily trunk diameter *(MNTD)* was used for young peaches irrigated at ≤2-day intervals.

Moriana and Fereres (2002) monitored several water status indicators in irrigated young olive trees in Spain and determined that trunk diameter change was the most sensitive indicator for automated irrigation scheduling. Trunk diameter fluctuation was monitored continuously, while stem water potential, and leaf photosynthesis and conductance were monitored periodically on trees where irrigation was either interrupted or fully irrigated for two drought cycles. Trunk diameter changes were measured several days before the other indicators responded to the drought conditions. Maximum daily shrinkage was not a significant parameter in young olive trees.

Plant turgor has been shown to be an accurate and sensitive measure of plant water status as it affects plant metabolism. Sharon and Bravdo (1998) found a significant linear correlation between leaf thickness and leaf turgor potential and developed a system to trigger irrigation. A strain gauge based on a miniature printed circuit of a Wheatstone bridge fastened to the face of a spring steel blade was found to be sufficiently accurate to measure changes in leaf thickness with an accuracy of ±1 μm. The system was robust enough to withstand the weather and agrochemical practices without interfering with leaf function (Sharon and Bravdo, 1998). They tested the system on citrus, avocado, and cotton and compared it with conventional practices. The crop yield and quality in treatments where irrigation was controlled by the sensor were equal to or better than the control, and water use efficiency was significantly higher in the sensor treatments.

7.3.2.4. Evapotranspiration estimates

7.3.2.4.1. Evapotranspiration models

Irrigation scheduling models based on evapotranspiration have been widely used in the United States and worldwide (Jensen et al., 1970, 1971). Essential evapotranspiration *(Et_c)* information required for these models and the irrigation decision criteria include (1) a climatically estimated reference evapotranspiration *(Et_r)*, (2) an index for relating "expected" crop water use to Et_r (crop coefficient curve), (3) an index for estimating the additional soil water evaporation from a wet soil surface, (4) an index for estimating the effect of soil water depletion on the actual Et_c rates, (5) an estimation of extractable soil water volume by a specific crop from the specific soil, and (6) a relationship between "target" crop yield and crop water use. Many of the input variables needed to operate irrigation scheduling models are still not well defined and need to be estimated. Although the Jensen model (1970, 1971) can predict irrigation requirement accurately for low frequency application, it is not presently feasible for scheduling high frequency microirrigation because data are limited. For instance, one of the most important inputs, the crop coefficient (item 2) data are still limited. Accurate weighing lysimeters and a network of weather stations are needed (Howell et al., 1984b, 1985; Phene et al., 1989, 1991) to determine crop coefficients. Recently, California, Arizona, Washington, Texas, New Mexico, Nebraska, Oklahoma, Kansas, and Florida have developed networks of weather stations for use in irrigation scheduling.

Weighing lysimeters must provide sufficient resolution (0.1 mm/h) to permit measuring hourly crop water use rates. An ideal situation is to have one lysimeter planted to grass, to provide Et_o, and a second lysimeter planted to the crop being studied to measure Et_c. The ratio of *Et* from the two lysimeters, (Et_c/Et_o) is the crop coefficient with reference to grass. Irrigation scheduling models use the weather station output and a crop coefficient to compute the Et_r expected from a healthy reference crop under no water stress conditions such as grass to compute daily crop water use. Daily Et_r from integrated hourly values are calculated and used for irrigation scheduling (Doorenbos and Pruitt, 1977; Pruitt and Doorenbos, 1977).

7.3.2.4.2. Direct measurement of Et_c

Et_c can be measured and used to schedule irrigation automatically (Phene et al.,1989). A modified lysimeter planted to the same crop served as a feedback irrigation controller for a crop growing around it. A water tank was attached to the lysimeter so that the weight of the daily irrigation water was included in the weight of the lysimeter. The lysimeter was automatically irrigated in 1 mm increments by a deep subsurface drip irrigation system (45-cm deep) to maintain steady state soil water potential without disturbing the lysimeter weight. The lysimeter water tank was automatically refilled daily at midnight to a constant level. Therefore, the accumulated daily change of lysimeter weight represented the crop growth and total weight. The soil water potential was maintained nearly constant by this high-frequency irrigation. Grass Et_r was measured by the reference lysimeter and calculated by the hourly integrated Penman Equation (Penman, 1948, Pruitt and Doorenbos, 1977). Figure 7.9 illustrates a crop coefficient curve obtained for drip irrigated peach (Ayars et al., 2000) that provides the type of information needed for irrigation control, as indicated at the beginning of this section, except for the relationship between the expected crop yield and water use.

Automated evaporation pan systems have been successfully used to irrigate cotton and tree crops (Phene et al., 1992, 1996; Phene, 1996). In this system, the water level in a class A evaporation pan is measured hourly using an electronic water level sensor and a data acquisition and control system. The change in water level is multiplied by a pan factor (K_p) to correct the pan evaporation *(Epan)* to reference evapotranspiration and a crop coefficient (K_c) to get the crop Et_c. The equation is $Et_c = Epan * K_p * K_c$. A 3- to 5-h lag period exists between the time of maximum Et_c and *Epan,* but the total daily evapotranspiration is well correlated to the corrected daily pan evaporation values. Irrigation is initiated when a user-determined threshold of crop water use is reached. The control system can be instrumented with soil matric potential sensors to provide feed-back control. This system is well adapted to high frequency irrigation (Phene, 1996).

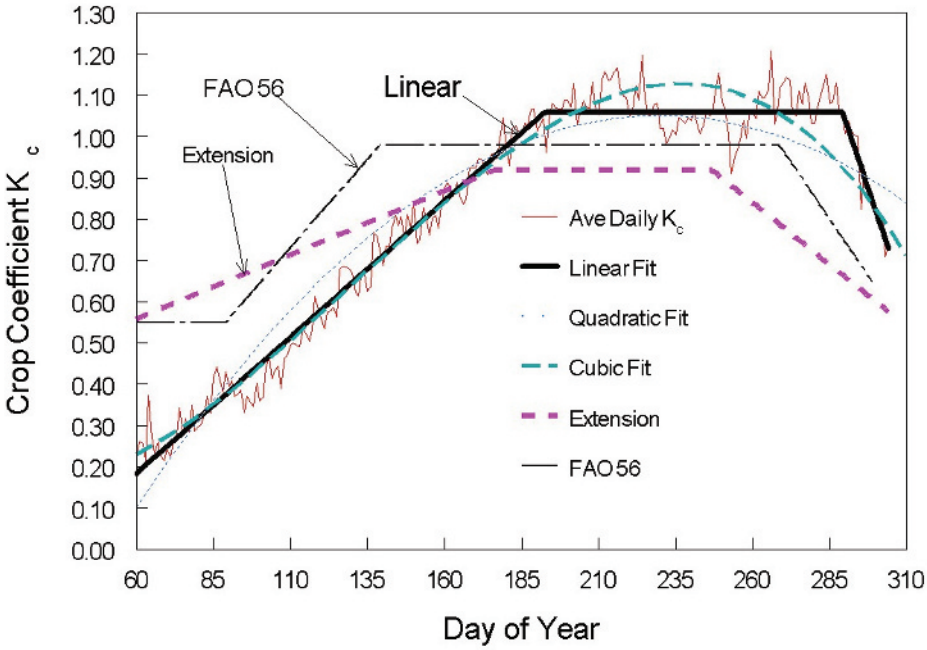

Figure 7.9. Crop coefficient for late season peach developed using lysimeter data. After Ayars et al. (2000).

7.4. INSTRUMENTATION AND HARDWARE

Automation of a pressurized microirrigation system can potentially provide optimum crop yield and use of agricultural water. An automated irrigation control system should use sensors to provide real-time feedback values for important variables such as water quantity, flowrate, water pressure, and environmental conditions including wind speed, air temperature, soil water content, solar radiation, rainfall, crop canopy temperature, etc. Continuous monitoring and control of system performance will enable irrigation operation at maximum efficiency (Clark and Phene, 1992). Data and control signals can be transmitted via electrical cables, hydraulic lines, radio frequency transmission, microwave, laser, and infrared devices.

The interest in microirrigation system automation has resulted in increased research and development in the field of instrumentation and hardware required to accomplish this task. A large variety of instrumentation and hardware with a wide range of characteristics is available commercially. This hardware can be subdivided into six major categories:

1) controllers
2) valves
3) flowmeters
4) filters

5) chemical injectors
6) environmental sensors.

The main function of the hardware will be described in this chapter in terms of their respective mode of control. Details on selection, installation, function, and maintenance are covered in other chapters of this book.

7.4.1. Controllers

Controllers receive feedback data on the volume of water applied, line pressure, flowrate, weather data, soil water content, plant water stress, etc. from sensors in the field. This information is compared with desired limits and the irrigation cycle is modified accordingly. A controller issues (automatically) or is set to issue (manually) commands for operation of water valves, boosters, fertilizer or water treatment injectors, filter cleaning, etc. according to the modified irrigation cycle (Clark and Phene, 1992).

7.4.2. Valves

Automated valves are activated electrically, hydraulically, or pneumatically and are used to switch water on or off; flush filters, mains, and laterals, sequence water from one field or segment to another; and regulate flow or pressure in mains, submains, or laterals. Different valve types regulate different functions. The controller issues commands for valve operation and receives feedback information to verify correct valve operation.

7.4.3. Flowmeters

Flow measuring feedback devices allow the computer to determine the rate and volume of water applied for determining whether the irrigation scheduling requirement has been accomplished. Propeller and turbine flowmeters are the two most commonly used for monitoring flow in irrigation pipes. Usually, the output from these flowmeters are digitized and calibrated in counts per unit volume of water applied (totalizing meter) or in counts per unit volume per unit time (flowrate meter).

7.4.4. Environmental Sensors

Various types of soil water instruments (tensiometer, gypsum blocks, heat dissipation sensors, soil psychrometer, TDR, FDR, wetting front advance meters), weather instrumentation (weather station, automated evaporation pan, etc.), plant water stress (leaf psychrometer, stomatal diffusion pyrometer, infrared thermometer, and stem diameter sensor) are available and can be used in a feedback mode for irrigation management. Soil water sensing devices are commonly used to override a system controller. If the soil at a particular station is “too wet,” the sensor disables part of the valve circuitry and the station is bypassed.

7.4.5. Filters

Clogging of emitters caused by physical, chemical, or biological contaminants is universal and is usually considered to be the primary maintenance problem with microirrigation systems. Filtration is accomplished with various types of media (sand) filters, disk filters, cartridge filters, and screens. Suspended materials trapped by the filter eventually decrease filtration efficiency and the filter must be cleaned. Either manual or automatic backwashing operations are available for media, screen or disk filters to improve filter function and efficiency. Excessive pressure loss across the filter is typically used to control automatic backflushing (See Chapter 11 for a detailed discussion on maintenance). In other filter types, the filter element must be removed and cleaned or replaced.

7.4.6. Chemical Injectors

Various types of injectors are used for injection of fertilizer, algicides, and other chemicals into irrigation systems. These include (1) pressure differential, (2) venturi (vacuum), and (3) positive displacement pumps. In the pressure differential system, a pressure difference is created by a valve or pressure regulator, installed between the tank inlet and outlet, causing flow of water through the tank. Precise control valves maintain a preset injection rate. In the case of venturi type injectors, a rapid change of water velocity caused by a reduction in the pipe diameter creates a pressure drop (vacuum) across an orifice which draws chemicals from a tank. The third method uses a rotary gear, piston, or diaphragm pump to inject the solution. In all cases, digital flowmeters can be used in a feedback mode to adjust the chemical injection proportionally to the water flowrate and maintain a constant concentration of chemical in the irrigation water. Injectors must be made inoperable whenever the main water flow is stopped (See Chapter 8 for a detailed discussion on chemigation).

7.5. SUMMARY

For full potential of microirrigation to be achieved, automation is necessary. Improved water use efficiency, improved fruit quality, and increased yield require both the accurate placement of the required volume of water and the accurate timing of the application. This is most easily achieved through automation. Automating the control of a microirrigation system may be staged as the operator gains confidence and experience with the system. Initial control may be with an open loop system with the operator setting the irrigation frequency and duration. Later, a closed loop system using a simple feedback control such as switching tensiometer to start the system for a fixed run time can be used. The final step may be the implementation of a closed loop system using soil water sensors such as TDR or FDR to both initiate and stop irrigation. Alternatively, a scheduling approach based on calculated crop water use from measured weather data or evaporation pans could be used.

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

8. APPLICATION OF CHEMICAL MATERIALS

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"When we are absolutely certain about something, we either know absolutely everything or nothing about it."

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"God sends the rain on the just and the unjust and when He decides not, He's provided irrigation engineers."

8.1. INTRODUCTION

8.1.1. Definitions

Chemigation is defined as the application of a chemical with irrigation water. Chemicals are injected into microirrigation systems to fertilize crops, to control clogging, and to control pests. A properly designed chemigation system includes a pumping plant, chemical injector, storage tanks for various chemicals, calibration devices, a backflow preventor, and adequate safety equipment.

Chemigation is required for sustainable operation of microirrigation systems. This practice includes the injection of chlorine or other biocides, acids, or chelating agents to reduce emitter clogging due to calcium carbonate precipitation, prevent bacterial growth in emitters, laterals, filters, and pipe lines, as well as preventing root intrusion into emitters on subsurface drip irrigation (SDI) systems.

Microirrigation systems are frequently used to apply water-soluble fertilizers. In addition, soil amendments (e.g., acids, various polymers, $CaSO_4$), plant growth regulators, insecticides (usually systemic), herbicides, nematicides, and other compounds can be efficiently and effectively applied through microirrigation systems. SDI systems are particularly amenable to the application of soil fumigants as well as other chemicals that tend to be fixed by the soil particles (e.g., some pesticides and specific fertilizer formulations).

Many different chemicals can be injected into microirrigation systems, and each must be handled according to its intended use, physical properties, and associated legal requirements. Microirrigation must be managed as both a water and chemical application system. Water management is critical and personal safety protection must be assured for any successful chemigation program.

8.1.2. Basic Information

The use of chemicals through microirrigation systems requires a thorough understanding of the biology, chemistry, and physics of the water and soil. These include knowledge about the potential interactions of the various chemicals that could cause clogged emitters, soil sealing, and nutrient availability problems. Changes in water quality with time (during season and/or between years) must be identified. Laboratory tests are necessary to determine the nature, proportions, and composition of organic and inorganic contaminants that may create significant problems in the long-term management of the system, as well as affecting the crop's utilization of water and nutrients. Specific water concerns include pH, Ca^{2+}, Mg^{2+}, Na^{+}, CO_3^{2-}, HCO_3^{-}, sodium adsorption ratio (SAR), salinity levels, iron, manganese, sulfur, colloidal clays, silt, oils, algae, aquatic weeds, insects, fish, frogs, or other biological agents. Thus, the chemical and physical control program must be directed toward managing any combination of these water-borne components.

8.1.3. Advantages of Chemigation

Microirrigation potentially offers numerous benefits for chemical application because of its flexible delivery arrangement. These include:

- Reduced chemical usage through better and more flexible timing for targeting the problem (apply any time).
- Improved uniform application of a chemical with well-designed, well-managed systems.
- Lower energy requirements for applying agrochemicals.
- Less supervision and labor are needed during injection.
- Minimal percolation of water transporting undesirable chemicals and minerals below the root zone.
- Improved productivity through better control of the root environment relative to water and nutrient availability throughout the growing season.
- Reduced soil compaction due to much lower vehicular traffic.
- Reduced foliar crop damage.
- Rapid correction of crop pest problems (e.g., systemic insecticides).
- Improved and timely application of micronutrients (e.g., chelated iron, manganese, zinc and other micronutrients) fertilizers and pesticides through microirrigation systems, which increase efficacy and reduce costs.
- Reduced wind drift of agrochemicals
- Improved incorporation of agrochemicals into the soil matrix.
- Reduced application cost.
- Reduced herbicide degradation. Many herbicides provide longer term protection in moist soils, and thus fewer herbicides are needed over the season.

- Decreased worker exposure to agrochemicals hazards (especially with SDI). Chemical concentrations are often less than traditional methods and air drift can be eliminated.

8.1.4. Disadvantages of Chemigation

There are also disadvantages to chemigation which include:

- High management requirements. Careful management and supervision is required for accurate and safe applications, calibration, handling, maintenance and use of safety equipment.
- Uniformity of chemigation will depend upon a well designed and operated system.
- High initial equipment costs. Injectors, safety equipment, emergency showers, and containment areas are needed, but are usually less costly than for ground application equipment. Restricted storage and containment facilities for large volumes of dilute liquids may be required. Portability of injection equipment is usually limited unless mounted on trailers.
- Restrictions placed on some agrochemicals. Application of pesticides through irrigation systems must be on the label. In addition, there are relatively few agrochemicals labeled for injection through microirrigation systems. Microirrigation systems are also limited in their ability to apply many herbicides and insecticides due to small coverage area.
- Complexity of chemical interactions. Various chemicals may have to be injected at separate points to limit reactions with fertilizers and/or biocides that are applied simultaneously.
- Chemical corrosion may reduce the life of microirrigation system components.
- Environmental risk of system mismanagement or improper design. The possibility of water source contamination is increased if appropriate equipment is not correctly installed, operated, and maintained.
- Irrigation/chemigation scheduling difficulties. Timing, amount, and label requirements for chemigation may influence irrigation scheduling and depth of water applications. Fertilizers might be required when irrigations are not necessary, further increasing the potential for leaching.
- Placement problems of agrochemicals. Limited wetted area could limit access to nutrients in the dry soil volumes resulting in temporal crop nutrient stresses. Excessive applications of some agrochemicals and nutrients may induce micronutrient deficiencies that are difficult to correct.
- Application of relatively high concentrations of some chemicals in a limited soil volume may negatively affect beneficial soil biota, (e.g., earthworms, bacteria, fungi, and insects) as well as the target organisms.
- Problems caused by changes in soil pH. The pH of the limited wetted soil volume may decline rapidly under chemigation due to the application of relatively concentrated agrochemicals. This may induce availability problems with some nutrients.

- Enhanced biological clogging hazards. Bacterial growth may be enhanced in the microirrigation system components by nutrient chemigation.
- Saturated soils. High soil water contents may cause problems with the sorption of some chemical formulations which may limit their use with microirrigation systems
- Disposal of backflush and rinse water. Backflush water from filter cleaning activities as well as rinse water from cleaning injection equipment may require special disposal measures due to the presence of various agrochemicals.

8.1.5. Types of Agrochemicals

Agrochemical characteristics will dictate chemigation methods and processes. Three broad classes of injected agrochemicals are fertilizers, pesticides, and chemicals to clean and disinfect the irrigation system. Agrochemicals can be water soluble, wettable powders, oil-soluble, and gaseous. Most agrochemicals injected into microirrigation systems are water soluble or gaseous, but can also include wettable powders and oil emulsions.

Another major difference among agrochemicals is their mode of action. Some agrochemicals are designed to be incorporated into the soil to be effective, some must be applied to the foliage, and others remain resident in the irrigation system (i.e., disinfectants and line cleaners). Other agrochemicals may be absorbed through plant tissues and dispersed throughout the plant (systemic), whereas others must stay on the plant leaf surfaces as a protectant.

8.1.5.1. Water soluble chemicals

Chemicals that readily dissolve in water are the easiest to handle and use. The solubility of a compound depends on its physical properties, water temperature, and the irrigation water quality. Thus, the irrigation water's ability to dissolve a chemical is limited by its pH and the presence and concentration of other dissolved chemicals such as sodium, calcium, magnesium, nitrates, and carbonates. Injection of a mixture of soluble chemicals can also produce chemical reactions that may form insoluble products and clogging problems.

8.1.5.2. Wettable powders

Wettable powders are insoluble, but they are designed to stay in suspension with agitation in the chemical supply tank in order to maintain a relatively uniform concentration when injected. There must be adequate turbulence in the irrigation distribution system to maintain the suspension, which is often a problem in microirrigation laterals. In addition, distribution and mixing of wettable powders may be affected by electrostatic charges in the suspension.

8.1.5.3. Emulsifiable (oil soluble) chemicals

Emulsifiable chemicals are materials that are dissolved in various oils, but are designed to be applied in a water solution. They must be carefully injected to ensure that the oil-chemical mixture is well dispersed. Agitation of the chemical in the supply tank is often required. These chemicals may also require special handling because of their flammability.

8.1.5.4. Gases

Gases can be successfully injected into microirrigation systems with appropriate measures. Some gases will dissolve or react with the water to form soluble solutions. Other gases are entrained and subject to volatilization and may be lost to the atmosphere when it is discharged from the irrigation system. Some agrochemicals, such as some fumigants, may form toxic gases in water that may preclude their use in surface microirrigation systems.

8.1.6. Safety

The first rule of chemigation is safety. Special chemigation safety devices check valves and air relief valves are required for all chemical injection systems under federal and state regulations. The publication ASAE Engineering Practice EP409.1, "Safety Devices for Chemigation" covers this subject (ASAE, 2002). The water source must be protected from reverse flows, system drainage, or back siphoning. Electric and/or hydraulic interlocks must be installed between the injectors and irrigation pumps to prevent chemical injection when the microirrigation system is not operating. The use of time delays and flow sensors is recommended to start injections only after the hydraulic system is fully pressurized and water is flowing into the laterals.

Chemical injection areas should always be securely fenced with appropriate containment facilities in the event of a spill. Special protective equipment, safety showers, and any required chemical neutralizing agents should be readily accessible and clearly marked. In many regions, personnel must be specifically trained and licensed for chemical applications. Injection of any pesticide into a microirrigation system must be specifically permitted by the pesticide label and may also be subjected to additional state regulations. Detailed records of all chemical applications must be maintained for safety, operational evaluations, legal, and regulatory requirements.

Care should always be taken when mixing or preparing agrochemical solutions and mixtures. Never mix acids with sodium hypochlorite or other chlorine compounds because highly toxic chlorine gas can be produced. Some combinations could be potentially explosive, and thus must be checked with the chemical supplier before attempting new mixtures. Always add the chemical to the water and never add water directly to any chemical.

8.1.6.1. Following the label and other regulations

The use of chemicals may pose certain health and safety risks to the user. Operators of chemigation systems should always read and follow the label directions on the product regarding system requirements and personal protective equipment. Labels for pesticides used in the United States for chemigation carry the following statements about the system:

- The system must contain a functional check valve, vacuum relief valve, and low pressure drain appropriately located on the irrigation pipeline to prevent contamination of the water supply from back flow.
- The pesticide injection pipeline must contain a functioning automatic, quick-closing check valve to prevent the flow of fluid back toward the injection pump.
- The pesticide injection pipeline must also contain a functioning normally closed, solenoid-operated valve located on the intake side of the injection pump and connected

to the system interlock to prevent fluid from being withdrawn from the supply tank when the irrigation system is either automatically or manually shut down.

- The system must contain functioning inter-locking controls to shut off automatically the pesticide injection pump when the water pump motor stops.
- The irrigation line or water pump must include a functioning pressure switch that will stop the water pump motor when the water pressure decreases to the point where pesticide distribution is adversely affected.
- Systems must use a metering pump such as a positive displacement injection pump (e.g., diaphragm pump) effectively designed and constructed of materials that are compatible with pesticides and capable of being fitted with a system interlock.

Managers and operators of chemigation systems must be trained regarding the requirements of the federal, state, and local worker protection standards that apply in their locale. Some general guidelines regarding personal protection when utilizing chemigation include:

- Read and follow the label, wear rubber protective equipment as required by the product label.
- Use separate injection systems if so required.
- Avoid eating or drinking, smoking or chewing tobacco when servicing or filling the chemical supply container.
- Wash hands and other exposed areas to avoid contaminating other parts of the body or clothing.
- Properly store, maintain, and launder personal protective equipment.
- Protective clothing saturated with a pesticide should be treated as a hazardous waste and disposed accordingly.

All systems employing any form of chemigation should incorporate backflow prevention and safety devices commensurate with the injection of the most hazardous class of labeled agrochemicals to be applied (e.g., biocides.) Because the equipment for injection of fertilizers is the same as for the injection of biocides, government agencies cannot assess the intent of the applicator from the equipment configuration alone and may require the more complete system. Backflow prevention will be discussed in more detail later in this chapter.

All sites being treated with a pesticide through the irrigation system must be posted with signs during the complete chemigation treatment. Signs must contain the signal word from the pesticide label, name of the pesticide, date of treatment, and reentry date as described by the pesticide label.

8.1.7. General Considerations

The distribution uniformity of chemical application by an irrigation system usually follows the distribution uniformity of water application. Because a well-designed microirrigation system should have a distribution uniformity in the range of 90%, it is reasonable to expect that the distribution uniformity of chemical application should also be 90% or greater.

Maximum concentration of chemicals in irrigation water is governed by two primary factors, namely the salinity of irrigation water and potential corrosion of irrigation equipment. Maximum salinity concentration in irrigation water depends on the salt sensitivity of crop and the leaching fraction of irrigation water (USSL Staff, 1954). For example, if the maximum allowable salinity in irrigation water is 1,000 mg/L, then the injection rates of agrochemicals should not exceed 0.1%, by mass, of the system water flowrate. Because injection of chemicals should not be performed at the same time as leaching, care must be taken to avoid a buildup of salts in the root zone. Adequate leaching must take place in the off-season either through rainfall or irrigation. Concentration limits for hazardous chemicals such as chlorine and pesticides are dependent on label requirements, toxicity to the crop, or on the maximum concentration that is noncorrosive to the irrigation system. Corrosion is discussed in more detail in Section 8.2.4.

As a general safe operating procedure when injecting pesticides and fertilizers, operators should always assume that the safety and anti-siphon systems may fail. Thus, mixing separate solutions or batches for each irrigation zone reduces the likelihood of error during the application process, ensures proper concentrations, and allows for proper flushing of lines.

Whenever possible, pesticide and fertilizer injections should be made in small, frequent doses that fit within regularly scheduled microirrigation events (designed to match plant water use) to help avoid unnecessary leaching. Similarly, excess water applications for leaching soil salts should never be done when chemicals (except chlorine) are being injected. Fertilizers and other agrochemicals (except chlorine) should never be left in the pipeline when the system is not operating.

It is important to be aware that the concentration of injected chemicals is not constant due to time delays in the movement of the water-chemical mixture through the piping system. Figure 8.1 illustrates a chemical concentration profile for a positive displacement injection system. Because of these time delay effects, injection programs often follow a common sense guide called the “one-fourth” rule. This general rule is that chemigation should start after one-fourth of the total irrigation set time, injection should occur during the middle two-fourths, and the lines flushed with clean water during the last one-fourth of an irrigation event. However, as with any rule, there are always exceptions and it a good idea to conduct a dye test (e.g., dark blue granular food color) or other test to determine the length of time required for the last of a chemical to exit the system.

The injection pump, storage tanks, and other equipment should be placed on platforms above ground level and the equipment kept clean. A fresh water supply valve with hoses upstream from the chemical injection point should be available to provide a source of fresh water for safety and cleanup. These valves should also be equipped with a small backflow prevention device such as an inline check valve.

All chemical injections should be filtered. Injection should occur after the pump and before the media or final screen filters to trap any undissolved or precipitated material before it enters the main system. Injection installations should always provide complete mixing and uniform concentrations before the chemicals reach the field.

Materials should be injected into the center of the water flow to ensure quick dilution to reduce deterioration of the filter tanks, piping, valves, or other components. Care must be taken to reduce potential corrosion that may result as a consequence of the injection of concentrated chemicals.

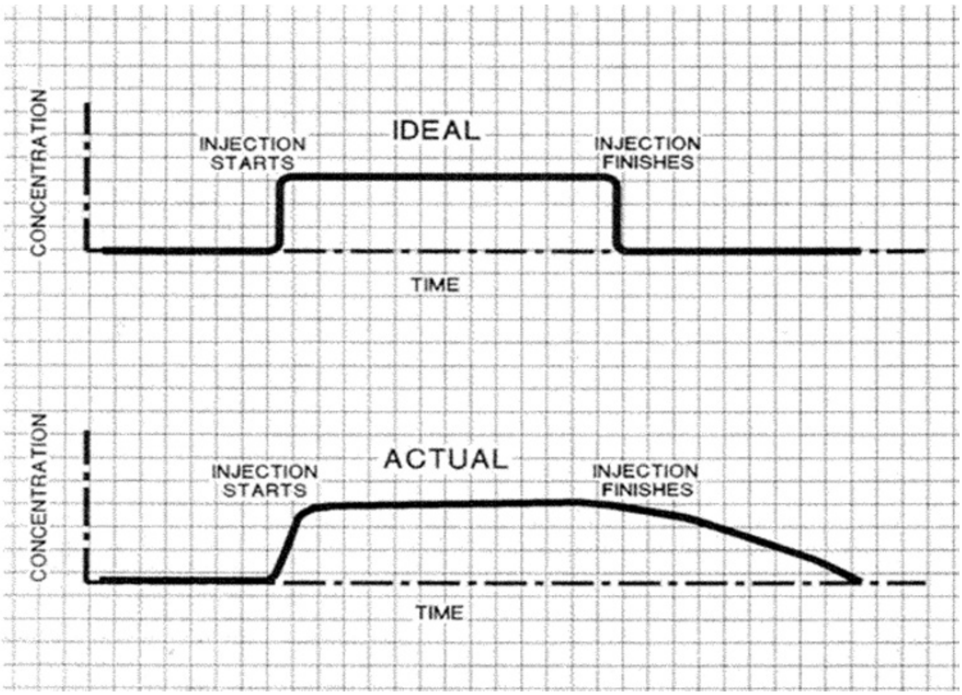


Figure 8.1. Comparisons between an ideal and actual concentration profile using a positive displacement injection pump. After Van der Gulik (1993).

A different injection pump and port should be used for each different chemical being injected at the same time. Each injection system must have its own check valves and other safety equipment. This arrangement keeps hoses, valves and fittings clean while minimizing irrigation system clogging problems. Injection ports should be separated by at least one meter of mainline piping and individual mixing chambers may be required after each port to ensure thorough mixing of a chemical before the next one is injected. Acids are usually the first material injected when multiple chemicals are injected simultaneously.

8.1.7.1. Problems with chemical mixes

Special considerations must be taken to avoid injection of chemicals in ways that might harm the microirrigation system. Injection of two or more chemicals at the same time may cause chemical reactions and the resulting precipitation of the reactants may clog microirrigation laterals or emitters. It is critical that all the chemicals being injected at one time are compatible with each other and that the water chemistry and concentration limits are not exceeded. The chemical properties of the water and various chemicals will determine the solubility limits of each material/compound in the solution. Precipitates will form if these solubility limits are exceeded. Some chemical combinations such as calcium nitrate and phosphoric acid will immediately form a precipitate creating a severe clogging situation. Emulsifiable pesticide concentrates and wettable powders may require special design and management considerations (e.g., mechanical supply tank agitation) to help ensure uniform applications and reduce potential for clogging. Modification of the water pH may sometimes be required prior to injection of a chemical. The chemical supplier should have information about the chemical compatibilities of their products. University or government agency sources may also have chemical compatibility charts.

A recommended method used to pre-test for chemical precipitation is to appropriately mix the chemical or mixture of chemicals in a transparent glass jar or other clear, inert container of irrigation water at slightly higher concentrations than field application. The jar is shaken and observed for 24 h or more to see whether precipitation has occurred. The presence of precipitates mandates that the mixture must be modified to avoid clogging problems. If cloudiness occurs, it is highly likely that the injected mixture will also cause some clogging and that remedial measures are needed. These “jar tests” should be conducted at the same pH, temperature, and other similar conditions that the chemicals will be applied. Safety glasses and protective clothing should always be worn when conducting jar tests.

Simultaneous injection of some chemical combinations may not cause precipitations, but produce compounds that decrease or eliminate their efficacy. For example, chlorine is usually not injected simultaneously with many other agrochemicals, except for acids, because the interactions and absorption may decrease the activity of both chemicals even if precipitates are not formed.

Injection of a chemical can also change the pH of the irrigation water. For example, injection of anhydrous and aqueous ammonia and phosphorous will raise the pH, which can cause mineral precipitates if the water pH is greater than 7.5 and calcium and/or magnesium bicarbonates are present. The result is a catastrophic clogging of the entire irrigation system. Additionally, these two fertilizers are subject to volatilization, which decreases efficacy with surface applications. As a rule, never inject any chemical into microirrigation systems that could raise the pH of the water without pre-acidification to counteract the effect. However, irrigation water pH generally should not be lower than 6.5 because of potential for system corrosion and excessive soil acidification.

Some chemical mixes may damage crops. Phytotoxic damage can range from slight to severe, and may have serious consequences on final crop yield. The chemical supplier should be able to provide information on tank mixes that produce these phytotoxic effects. Alternatively, it may be a good idea to check all chemicals and chemical-water mixtures before any injection occurs by applying the mixture to a small area of the field and observing the plants for a few days for possible damage.

In addition, increasing water temperature will lower the critical pH at which carbonate precipitation occurs. These temperature effects are discussed in Chapter 11. This may be a problem in surface microirrigation irrigation systems where the water becomes warmer during the daytime as it moves through the black plastic tubing. Acid injection rates may need to be slightly increased to compensate for heating.

8.2. CHEMICAL INJECTION METHODS

Chemical injection into irrigation systems (Fig. 8.2) requires three basic components: (1) chemical supply tank; (2) injection system; and, (3) safety and anti-pollution devices to prevent any potential contamination of the water source.

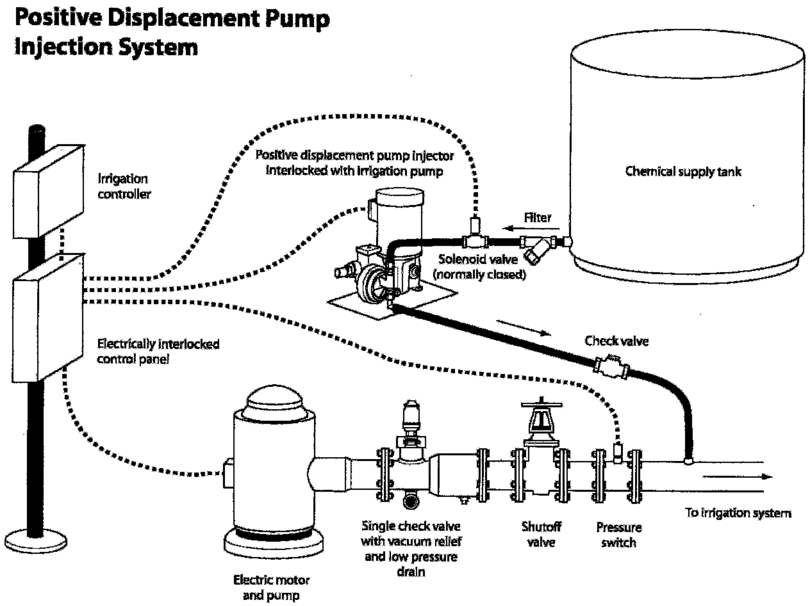


Figure 8.2. Typical layout for a positive displacement injection pump system. Courtesy of L.J. Schwankl, Univ. of California-Davis.

8.2.1. Injection Pumps and Systems

The three major types of injection systems used for chemigation are piston pumps, diaphragm pumps, and Venturi injectors. Piston pumps and diaphragm pumps are classified as positive displacement pumps, whereas Venturi injectors rely on the Venturi pressure drop principle to draw chemical from the tank into the irrigation pipeline.

Positive-displacement pumps are recommended where precise control of injection flowrate of chemicals is required. Flowrate of positive displacement pumps remain constant over a range of irrigation pipeline pressures and chemical viscosities, whereas Venturi injection flowrate is dependent upon chemical viscosity as well as irrigation pipeline pressure. Positive displacement pumps can typically control injection flowrates with a range of error of ±1% to 2%.

Both piston and diaphragm pumps consist of a pumping device and two check valves. As the diaphragm or piston is retracted, chemical is drawn into the chamber from the tank through the first check valve. As the diaphragm or piston is pushed out, the chemical is forced out the second check valve into the irrigation pipeline. Diaphragm pumps have a small flexible

Teflon or rubber diaphragm that is moved in and out of a small chamber. They have less contact with the chemical than piston pumps that draw chemical into a long metal cylinder. Thus, diaphragm pumps are less prone to corrosion than piston pumps. The advantage of both diaphragm pumps and piston pumps is that injection rate does not vary with downstream pressure as long as there is minimal pressure in the irrigation pipeline. For piston pumps, care must be taken to select a piston and cylinder that will not be corroded by the chemicals. Both piston pumps and diaphragm pumps are adjustable; however, some pumps cannot be adjusted while the system is running. Flow adjustment is easier with a pump that can be adjusted while it is operating.

In Venturi injector systems (Fig. 8.3), water is extracted from the main line and pressure is added with a centrifugal pump or by a pressure differential created in the mainline. The water velocity increases within the Venturi and the pressure decreases below atmospheric pressure in the throat of the Venturi causing the chemical to be sucked into the injector from the chemical reservoir. Because chemical is sucked into the irrigation system after the centrifugal pump, there is no contact between the chemical and the pump; thus, Venturi injection systems are less susceptible to corrosion than positive displacement pumps.

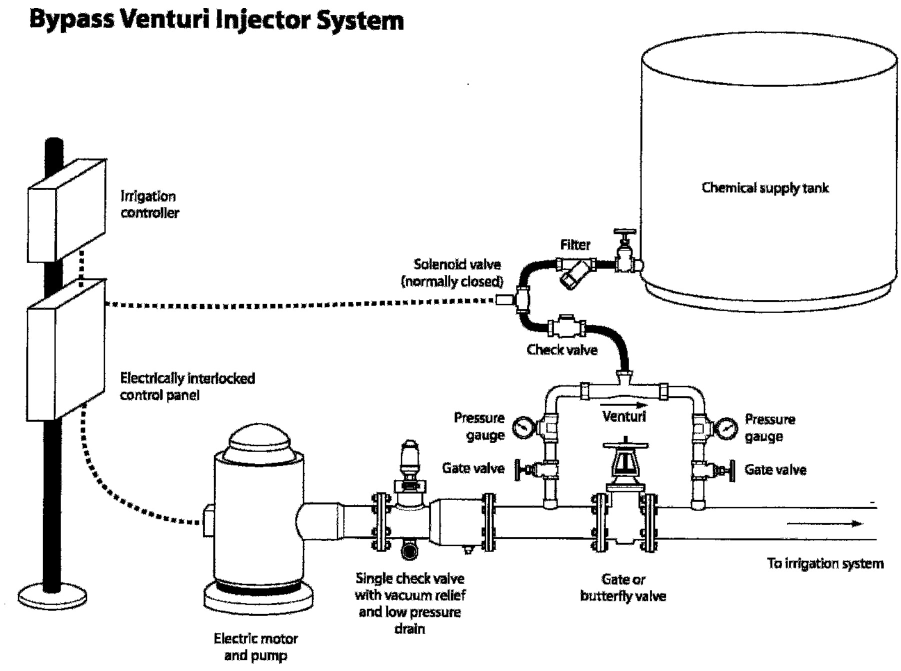


Figure 8.3. Typical layout for a Venturi injector system (Courtesy of L.J. Schwankl, Univ. of California-Davis).

Venturi injector flowrate can vary dramatically with change in irrigation pipeline pressure if the pressure differential is low across the upstream and downstream sides of the Venturi. However, as long as the pressure differential across the upstream and downstream sides of the Venturi is greater than approximately 200 kPa, then injection flowrate is relatively insensitive to irrigation pipeline pressure changes. The minimum pressure within the Venturi throat is slightly above the limit of zero absolute pressure, and a pressure differential of greater than 210 kPa cannot reduce the pressure lower than the minimum pressure. The pressure differential at which each Venturi injection system reaches a minimum can be observed on the manufacturer's curves of flowrate versus pressure differential. If a constant chemical injection flowrate is required, then a high pressure differential across the Venturi must be maintained, and, in these cases, it is often recommended to use a centrifugal pump to boost pressure in the Venturi bypass line. Thus, the piping system shown in Fig. 8.3 is not complete for such cases.

Venturi injection flowrate is also sensitive to chemical viscosity change with temperature. The change in Venturi injection flowrate can be in the range of 5% to 10% for a temperature change of 20°C for viscous fertilizers such as urea ammonium nitrate (UAN32) or calcium ammonium nitrate (CAN17). However, there is no change in flowrate with temperature for nonviscous chemicals (i.e., viscosity similar to water) because chemical viscosity change with temperature is minimal. The only method to keep viscous chemical flow constant with temperature change is with a flowmeter sensor, feedback, and control system.

When a known volume of chemical must be pumped during the irrigation cycle, and a constant chemical flowrate into the irrigation system is not required, then a sensor can be placed within the chemical tank or a flowmeter sensor can be placed on the irrigation injection line. The sensor shuts the injection system off after the required volume of chemical is injected.

Fertilizers are typically applied at a higher injection rate than other chemicals (e.g., acid, chlorine, or pesticides); thus, it is often necessary to use separate pumps for fertilizer and pesticide injection. Dual piston pumps can be purchased with two different sized cylinders on either side of the pump in order to provide a range of injection flowrates. Venturi injection systems with feedback and control are available in a unit with different sized Venturi injectors to provide a broad range of injection flowrates.

In addition to flowrate range, the primary selection criteria for chemigation systems are durability, accuracy, ease of operation and repair, service life, and susceptibility to corrosion. Systems that control Venturi flowrate with a feedback and control system are also available. The cost of Venturi injectors is much lower than the other alternatives; however, the cost of Venturi injectors with feedback and control systems is in the range of the cost of positive displacement pumps.

It is convenient to place a flowmeter in the injection line in order to adjust the injection system to the proper flowrate. If a chemical flowmeter is not available, then the injection flowrate can be adjusted by measuring the volume of chemical that is injected over a period of time such as 1 or 2 min. In order to do this, a small container with a known volume of chemical can be connected to the suction side of the injection pump, and the time required to inject the chemical is measured. It is always recommended that the injection pump be connected to the irrigation system during calibration because the injection rate will affected by the system operating pressure.

Injection installations should always provide for complete mixing and uniform concentrations before the chemicals reach the field. Chemical will mix naturally with water in an irrigation pipeline due to turbulent eddies. However, a minimum length of pipe is required for complete mixing. With Venturi injectors, mixing of chemical with irrigation water is facilitated in the Venturi system. However, with all injection pumps, it is recommended to have a mixing chamber or injection device that mixes chemical with irrigation water at the point of injection into the main irrigation pipeline.

Injection systems are available where the chemical injection flowrate can be adjusted based on irrigation pipeline flowrate. These systems can be advantageous where different irrigation zones have a range of flowrates.

8.2.2. Pollution Prevention

Adequate backflow prevention is required to protect groundwater and drinking water supplies from chemical contamination. If an injection pump remains operating while the irrigation water is turned off, then the potential for water contamination is great. In addition, back siphoning to the water source may occur if the water source is turned off. Many types of backflow prevention are available. These include double check valve, atmospheric vacuum breaker, reduced pressure backflow prevention device, swing check valve, and others. Check with the state and local codes or manufacturers instructions for the best selection for each installation. In addition, many governmental agencies specify that the location of the chemigation system must be a minimum distance, such as 30 m, from a water well, stream, drainage way, or other water source to reduce the pollution potential.

Chemigation has three main ways of potentially polluting irrigation water sources if safety devices are not functioning correctly (Wright et al., 1993):

1. *The chemical in the supply tank and in the irrigation pipeline could flow or be siphoned back into the water source when the irrigation system shuts down because of mechanical or power failures.*

2. *The chemigation system could continue to inject chemical into the irrigation pipeline when the irrigation system shuts down causing the chemical solution to flow back into the water source or spill onto the ground. Continued injection of concentrated chemicals into a non-flowing irrigation line can also result in toxic solutions to be applied in a small areas of the field when the irrigation system is restarted creating a potential for runoff into surface water supplies as well as crop damage.*

3. *The chemigation system could shut down while the irrigation system continues to operate and force water back into the chemical supply tank causing it to overflow and spill concentrated chemicals onto the ground.*

Chemigation can be safe and the environment will be protected if proper environmental protection measures are installed. A typical chemigation system with proper safety equipment is shown in Fig. 8.4.

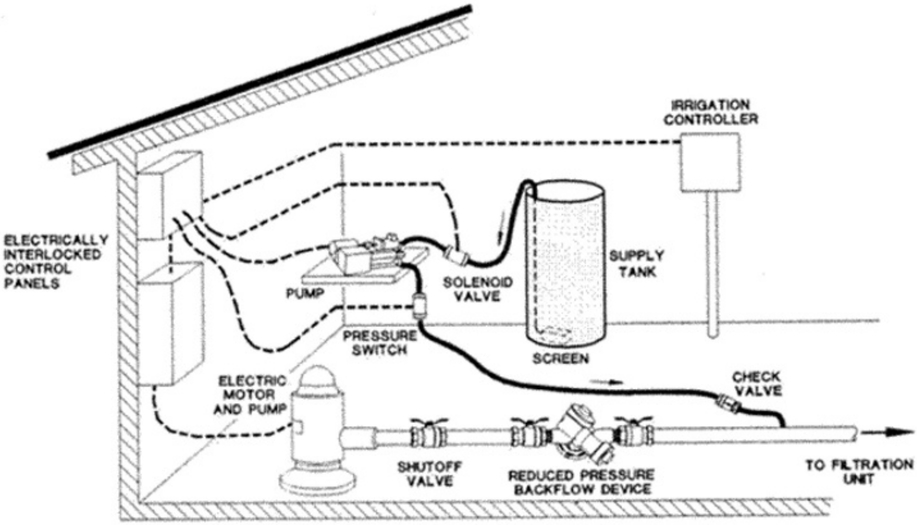


Figure 8.4. Chemigation safety equipment arrangement when applying a chemical with an irrigation system connected to an irrigation well. After Van der Gulik (1993).

8.2.2.1. Electrical and mechanical interlock system

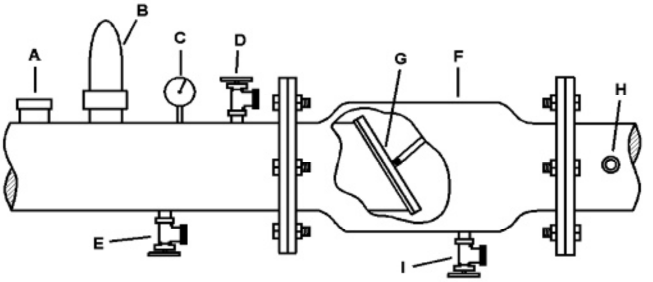
The injection pump must be shut off if the irrigation pump fails or is shut off. If the injection pump is electrical, then the control panels for the two pumps must include an electrical interlock so that the injection pump motor will not receive electrical power if the irrigation pump is off. For injection pumps systems powered by a drive belt connected to the irrigation pump/motor or those injector pumps powered by irrigation water pressure, the injection pump normally shuts off when the irrigation pump shuts off.

It is a good practice to place a solenoid valve on the chemical injection tank discharge line. The solenoid valve (normally closed) should be interlocked with the irrigation pump so that the chemical tank is isolated from the irrigation pipeline in case of malfunction. The solenoid valve can also be connected to pressure switches and flow sensors to provide extra protection.

8.2.2.2. Backflow prevention in the irrigation line

The irrigation system acts as a cross connection between the chemical supply tank and the water source. A backflow prevention device is required in the irrigation system between the water supply source and the point of chemical injection. The backflow prevention device should be automatic, quick-closing, and capable of preventing pollution of the water source. The device should provide for a watertight seal against reverse flow. Another reliable backflow prevention system is an air gap between the irrigation pump and the water source. The air gap must be at least twice the diameter of the inlet pipe and not less than 25 mm (Solomon and Zoldoske, 1998).

The backflow prevention device should be combined with a low-pressure drain, a vacuum relief device, and an inspection port. An atmospheric vacuum breaker (AVB) allows air to enter the downstream line when the line pressure is reduced to a gauge pressure of zero or less. The vacuum breaker should be installed upstream of the backflow prevention device. The vacuum breaker may also serve as an inspection port for the automatic low-pressure drain and the backflow prevention device. An inspection port allows for easy access to the internal components of the backflow prevention device for the purposes of testing, inspection and maintenance. The port should be installed on the upstream side of the backflow prevention device immediately above the opening to the low-pressure drain. The inspection port is common on larger (10- to 15-cm diameter pipe), but may not be practical for smaller installations where a double check valve assembly or a reduced pressure principle backflow prevention device is used although these devices typically have built-in testing ports. The low pressure drain will dispose of small volumes of fluid that leak past the check valve after an irrigation event. The details of a typical check valve assembly are shown in Fig. 8.5.



A .. Observation port
B.. Vacuum relief valve
C.. Pressure guage
D.. Fresh water supply valve
E.. Drain valve (manual) or an automatic drain valve
F.. Check valve assembly
G.. Check valve (interior)
H.. Injection port
I.. Low point drain valve (manual)

Figure 8.5. Details of an agricultural check valve and anti-siphon device. After Bausch (1985).

The California Center for Irrigation Technology (CIT) lists the following criteria for chemigation check valves that are connected to an agricultural water source (Solomon and Zoldoske, 1998)

> *"The chemigation valve's check shall be spring loaded so that a pressure greater than 2 kPa is required to open the valve. The check must be able to withstand for one minute an internal hydrostatic pressure of twice the rated pressure of the valve. It shall withstand for 16 h, without leakage at the valve seat, an internal hydrostatic pressure equivalent to the head of a 1.5 m column of water retained within the downstream portion of the valve body. No leakage past the valve seat is acceptable in either case. The combination air relief and vacuum relief valve shall have a nominal size at least 25 percent the nominal size of the chemigation valve. The vacuum relief valve must be open at pressures below 10 kPa. The automatic low pressure drain valve shall be a minimum 20 mm nominal size attaching to the chemigation valve at the lowest point of*

the upstream side of the check valve. It shall be pressure activated with an opening point of 10 ± 3 kPa. The drain valve must close above 7 kPa, and must be able to be closed externally to facilitate testing."

When the irrigation system water is from a municipal source or has a cross connection to a home water system, neither an atmospheric vacuum breaker nor a pressure vacuum breaker (spring check valve) provides adequate backflow prevention because of valves in the irrigation system that close off flow and create pressure. A double check valve is adequate protection against both backpressure and backsiphonage for a pollutant such as a fertilizer. However, protection is not considered adequate against a contaminant such as a pesticide. A properly functioning reduced pressure backflow prevention device is required for backflow prevention for any pollutant or contaminant because both backsiphonage and backpressure at a cross connection to a municipal or home water system are eliminated. Figure 8.6 shows a recommended installation of a reduced pressure principle backflow prevention device required by many municipalities.

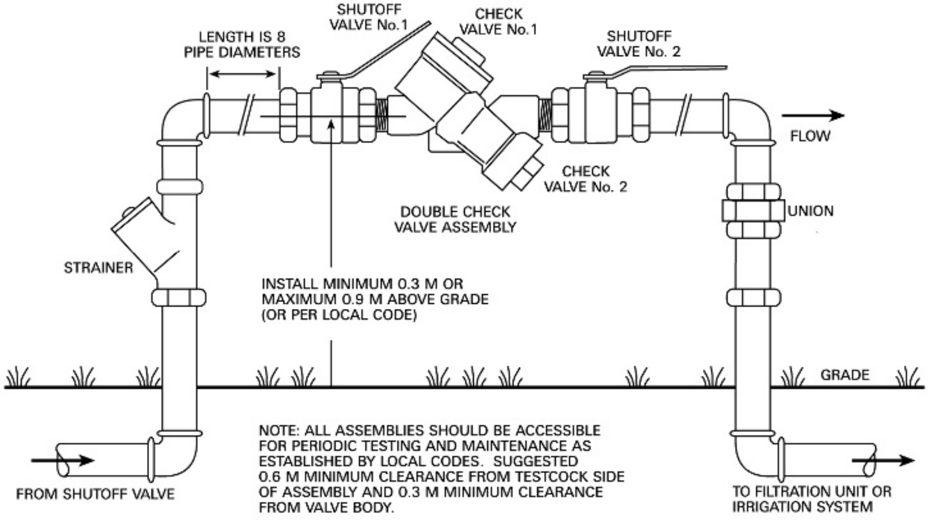


Figure 8.6 Typical installation of a reduced pressure principle backflow prevention device for municipal water supplies. After Van der Gulik (1993).

8.2.2.3. Injection line components

The injection line should include some or all of these components installed in the following order: chemical tank and calibration tube, manual valve, strainer, flowmeter, solenoid shut off valve, injection pump, air bleeder valve, flow sensor, pressure switch, and injection port check valve.

A calibration tube is a clear tube with volume markings such as milliliters attached to the side of the tank. A stopwatch is used in conjunction with changes in volume to calculate flowrate.

A manually operated valve should be installed on the chemical supply tank to allow the operator to manually stop the flow of chemical from the supply tank during equipment maintenance or in the case of malfunction.

A strainer should be installed on the suction side of the chemical injection pump. A strainer located upstream from the calibration device, chemical injection pump, air bleeder valve and injection line check valve is essential to prevent foreign materials from clogging or fouling these devices.

An in-line flowmeter can be installed at either the suction or discharge side of the injection device so the injection rate can be checked during a chemigation event. Its markings are typically expressed in flow units of volume per time (L/h).

A normally closed solenoid valve that is electrically interlocked with the engine or motor that drives the injection pump provides a positive shutoff in the chemical injection line, which can stop chemical or water flow in either direction if the injector pump stops.

The injection pump is placed in the injection line and normally includes check valves or other equipment required to pump solution from the tank to the irrigation line.

An in-line bleeder valve should be installed on the high-pressure side of the chemical injection pump. The air bleeder valve can be used to relieve trapped air and pressure in the high-pressure injection line that might otherwise affect the calibrated injection rate. Pressure should be relieved any time the injection line is to be disconnected.

A pressure switch shuts off the irrigation and/or the injection pump when pressure is lost in the pipeline. A pressure switch should be placed on the irrigation pipeline, but can also be placed before the injection port on the injection line. The pressure switch on the irrigation pipeline would shut down both pumps, and the pressure switch on the injection line would be designed to shut down the injection pump and possibly the irrigation pump. This safety measure would prevent continuous operation after a line/hose ruptures or disconnects, injection device loses prime or fails, supply tank is emptied or injection port becomes clogged.

A spring loaded check valve with an opening pressure of at least 70 kPa should be installed at the point of injection into the irrigation pipeline (Solomon and Zoldoske, 1998). This type of check valve prevents siphonage of chemical from the tank into the irrigation pipeline or backflow of irrigation water from the irrigation pipeline into the chemical injection tank. Backflow into the tank can cause a chemical spill onto the ground. Some check valves are designed in such a way that chemical is mixed rapidly within the irrigation pipeline.

Media filters or other irrigation system filters should be placed downstream from the chemical injection system in order to trap possible chemical precipitates before they reach the emitters. Whenever practical, filters should not be backflushed during chemigation, so it may be necessary to temporarily disable automatic backflush controllers. Whenever backflushing is required during the chemigation event, consideration must be given to proper handling and/or disposal of the backflush water.

8.2.3. Chemical Supply Tanks and Secondary Containment

Chemical tanks are used to contain hazardous chemicals and are generally regulated by state and Federal agencies to help protect water resources and for safety. Chemigation tanks are a special class of on-farm chemical tanks with specific conditions for use. The capacity of a container used in applying a bulk pesticide or bulk fertilizer through an irrigation system (chemigation) must be part of the total allowable onsite capacity regardless of whether the container is on a trailer, on the ground, or on a foundation. Once a container is connected to a chemigation system, it is considered storage.

The chemical holding tank must be constructed of a material that is resistant to corrosion. Because tanks are generally located outside, they also need to be resistant to weather and UV degradation from sunlight. The holding tank should provide an opening that is easily reached to minimize the risk of spills during tank mixing and to simplify checking chemical levels. Most chemigation tanks are constructed of high density polyethylene that provides excellent chemical resistance. If the tank is translucent, then the level of product can be easily seen from the outside. If the tank is not translucent, then a clear calibration tube should be installed for easy visibility of chemical tank fluid level. All components in contact with the chemical mixtures should be constructed of materials that are chemically resistant and resistant to sunlight degradation. The pressure rating of all components should be adequate to withstand all operating pressures. Hoses and fittings should be protected from mechanical damage. Several states also have regulations on the minimum distance of a chemical supply tank from a groundwater well.

Secondary containment (dike or another tank) to contain chemical spills or leaks is usually required. The injection pump should be placed within the chemical tank secondary containment area. A general rule is that secondary containment facility must be constructed to contain the sum of the maximum possible discharge from the largest container and the volume displaced by containers or equipment located within the containment area plus the expected precipitation from a 25-year, 24-h storm or at least 125% of the largest container capacity, whichever is largest. If the secondary containment is enclosed or covered, then it must be able to hold at least 110% of the combined volumes (Wright et al., 2002).

Greater caution is required for secondary containment of pesticide than for fertilizer. In general, acceptable materials for secondary containment include concrete, steel, bentonite liner or tank within a tank (Schulze and Buttermore, 1994). Check with local regulations for acceptable materials for the type of chemical that is stored.

8.2.4. Corrosion Resistance of Surfaces

All irrigation system components must be able to withstand the effects of corrosion from injected alkaline and acidic chemicals at the expected concentrations at each location. Consult material compatibility tables and match the materials with the chemicals. For example, concentrated sulfuric acid is not compatible with PVC tubing and will quickly create a hazardous situation, but PVC is acceptable when the acid is greatly diluted. As a general rule, uncoated metallic components (except specific stainless steels) should avoided as much as possible in microirrigation systems.

Corrosion of materials may be due to low pH; solution chemistry (i.e., sulfates, sodium, chlorides, and other ions); high flowrate within the piping systems; high water temperatures; presence of suspended solids (e.g., sand); and galvanic action of various combinations of dissimilar metals. Chemical and galvanic corrosions are usually minor problems in microirrigation systems because most of the components are made from plastic materials that are resistant to attack by many injected chemicals. Low-pH solutions tend to create the most concern. However, all microirrigation system components should be selected based on the types of injected chemicals and their concentration.

Chemical dissolution or precipitation is a complex series of reactions between a fluid, metal surfaces, and materials in which the fluid is stored or transported. The chemical process converts a processed material to a more stable state. The Langelier Saturation Index (LSI) or a modification of the LSI called the Rzynar Index (see Chapter 11) is often used to indicate the potential for chemical corrosion of a material. The LSI compares the actual pH of the water with the theoretical pH based on the chemical analysis. The LSI is typically either negative (corrosive) or positive (scale forming) and in rare instances zero (balanced).

Nearly all metals will corrode to some degree. The rate and extent of the corrosion depends on the degree of dissimilarity of the metals and the physical and chemical characteristics of the media, metal, and environment. Galvanization is a "sacrifice" coating material with a low-corrosion potential that extends the life of the metal underneath. Other coatings such as epoxy and vinyl are intended to create a barrier between the corrosive fluid mixture and the underlying materials. Certain types of stainless steel are resistant to corrosion by many chemicals, but the relatively high cost of stainless steel often precludes its use in many microirrigation system components.

Filters and flowmeters are usually the primary components subject to corrosion because almost all chemicals should be injected upstream of the filter system. Thus, stainless steel or epoxy-coated steel is usually used for these components. Corrosion can be managed by installing pretreatment systems, use of nonconductive fittings, and proper design and management of chemical injections. Table 8.1 presents the relative corrosion potential of some materials used in irrigation systems.

Table 8.1. Relative corrosion of various metals by fertilizer solutions (120 g of material in 1.0 liter of water). After Burt et al. (1995).

Type of metal	Calcium nitrate	Sodium nitrate	AN-20	NH_4 sulfate	Urea	Phosphoric acid	DAP*
Galvanized iron	2	1	4	3	1	4	1
Sheet aluminum	No	2	1	1	No	2	2
Stainless steel	No	No	No	No	No	1	No
Phospho-bronze	1	No	3	3	No	2	4
Yellow brass	1	No	3	2	No	2	4
pH of fertilizer solution	5.6	8.6	5.9	5.0	7.6	0.4	8.0

No, none; 1, slight; 2, moderate; 3, considerable; 4, severe.
*diammonium phosphate

8.2.5. Maintenance

Equipment maintenance is key to safe and reliable chemigation. Two water-supply hoses should be connected to the irrigation pipeline upstream from the backflow prevention device. One should be used to clean equipment and the other should be used for operator hygiene and rinsing. More details on maintenance procedures and concerns are presented in Chapter 11.

Injection and safety equipment such as the injection pump, injection lines and the injection line check valve should be flushed after each use. The irrigation system should be flushed after injection is complete. The operator should flush the irrigation system for at least 10 to 15 min. after each chemical injection period (Wright et al., 1993).

All injection and safety equipment should be inspected prior to each chemigation event. The operator should follow the manufacturer's recommendations for cleaning and maintenance of this equipment. Inspection of these devices will minimize the potential for failure. Moving parts should be lubricated as necessary before each chemigation event and before storage during the off-season to preserve the equipment (Wright et al., 1993).

The irrigation pipeline check valve should be repaired or replaced if leakage is observed. Operators should not chemigate if the check valve leaks. The low-pressure drain should be inspected before each chemigation event. If the drain is functioning properly, some water should discharge from the outlet immediately after start-up (Wright et al., 1993). The drain valve should close as the system pressure increases. The chemical injection line check valve should be inspected for wear and/or leakage prior to each chemigation event. The interlock should also be tested periodically throughout the season to determine functionality. Irrigation system components such as system joints, fittings, nozzles, etc. should be inspected to avoid leaks, over-application, or problems arising from insufficient coverage.

8.3. CHEMICALS AND CALCULATION OF INJECTION RATES

8.3.1. Fertigation

One of the advantages of microirrigation systems is its use in fertigation. Nutrients can be applied precisely to the root zone and spoon-fed to the crop. Thus, nutrients are applied at the right time and the right place, optimizing plant growth and minimizing leaching. Because the roots are concentrated in the vicinity of the emitter, fertilizer can be applied through the irrigation system directly to the roots. Many growers with microirrigation systems apply daily amounts of fertilizer. However, because of the lack of ability to distribute fertilizer beyond the vicinity of the emitter, some growers combine fertigation with conventional preplant fertilizer application. Thus, nutrients are distributed throughout the soil but are concentrated and replenished during the growing season by fertigation. In general, increased yield has been observed with fertigation. However, the increase in yield has not always adequate to offset the capital cost of the microirrigation and fertigation system equipment and the increased cost of liquid chemical formulations that are often used in fertigation systems (Bar-Yosef, 1999).

Plant growth rate is controlled by the nutrient with the lowest availability (Liebig's law of the minimum). Relationships have been developed between crop yield, nutrient uptake, nutrient surplus, and nutrient application. These relationships combined with economic models can help the grower optimize fertilizer application for maximum profit. Although, the models are complex, modern computers and precision agriculture equipment enable the grower to optimize fertilizer application amounts, even on a variable basis within the same field. Microirrigation systems are not typically conducive to site-specific fertigation, the scale of site-specific fertigation cannot be smaller than the size of individual blocks. However, preplant fertilization with variable rate fertilizer application systems (ground rigs) could allow growers to vary fertilization rates within a microirrigated block.

Effective fertigation requires calculation of nutrient requirements based on plant requirements and soil nutrients, selection of the most effective formulations, preparation of solutions for injection, and scheduling injections to ensure that essential nutrients are available as needed (Granberry et al., 2001). Fertilizer application rates depend on crop, soil, and time. Thus, individual growers and agronomists often use trial and error to develop fertilization schemes that are specifically tailored to elicit the desired crop response, yield, and quality. These fertilization timetables are often unavailable because of their proprietary nature. Fortunately, researchers have developed macronutrient utilization timetables for individual crops that can be the initial basis for a fertilization schedule.

8.3.1.1. Calculation of plant nutrient requirements

Soil tests are conducted in order to determine the availability of soil nutrients, and the required seasonal nutrient application is calculated based on the difference between plant requirements and soil nutrient concentration. Soil nutrient tests are usually conducted just before planting. Plant tissue analysis is used during the growing season to assess plant nutrient status. Many studies have shown that plant response to fertigation is generally higher than response to broadcast fertilization (Bar-Yosef, 1999), especially on sandy soils with low cation exchange capacities.

For many microirrigated crops, the rhizosphere (root zone) is concentrated in the vicinity of the emitter, and all water is supplied by the emitter at the center of this zone; plants may have limited access to nutrients in the soil that are far from the emitter. Similarly, fertilizer applied by conventional methods may be unavailable to microirrigated crops in arid areas unless it is placed within the irrigated zone. Thus, distribution of roots in the soil must be considered when determining the available nutrients in the soil and in determining the amount of nutrients that should be applied by broadcast methods over the entire soil surface and that are applied by fertigation.

Unlike tests for other nutrients, the nitrogen soil test gives the total amount of nitrate-nitrogen (NO_3-N) in soil (as N). Soil tests for nitrogen are conducted from 0- to 60-cm soil depth, and nitrogen content in soils is reported in mg/L. This number is converted to total nitrogen amount in kg/ha by multiplying by 2.2. For example, if nitrate content in soil is 10 mg/L, then there is 22 kg/ha of nitrogen in the soil. If the crop requires 100 kg/ha, then the amount of N that must be applied in fertilizer is 78 kg/ha (i.e., 100 minus 22). For nutrients other than nitrogen, such as potassium or phosphorous, extraction methods are used to determine the amount of available nutrient rather than the total amount of the nutrient in the soil.

Bar-Yosef (1999) published tables of nutrient uptake for various crop mostly grown under microirrigation with fertigation. The tabulated data are plotted in Figs. 8.7 to 8.17.

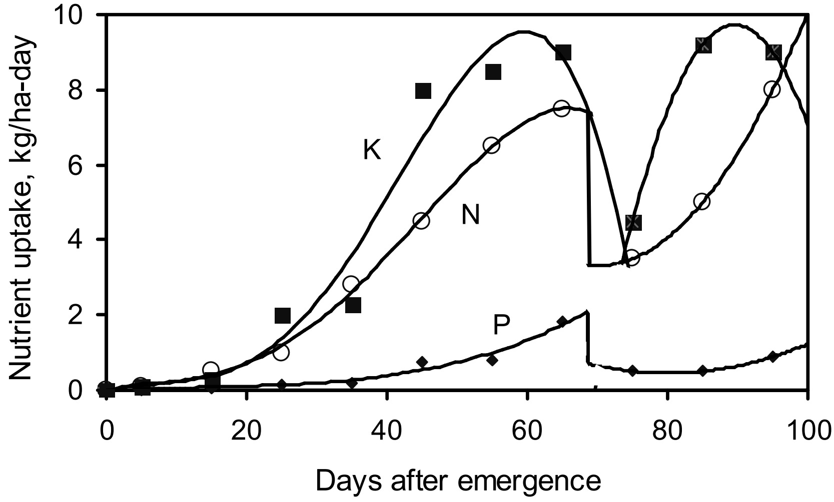


Figure 8.7. Nutrient uptake rate of N, P, and K as related to days after emergence for processing tomato. Data from Bar-Yosef (1999).

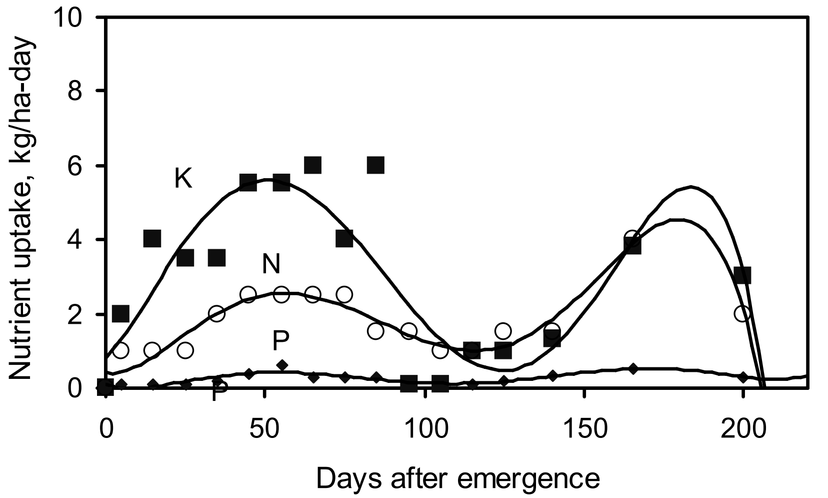


Figure 8.8. Nutrient uptake rate of N, P, and K as related to days after emergence for greenhouse tomato. Data from Bar-Yosef (1999).

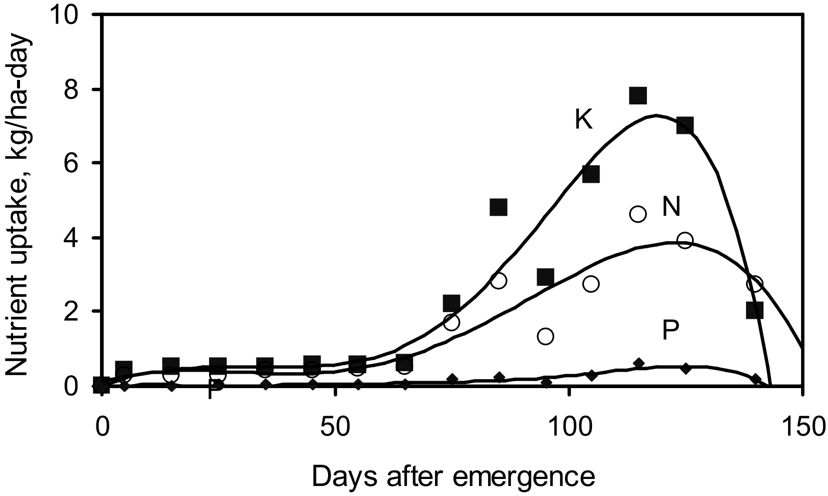


Figure 8.9. Nutrient uptake rate of N, P, and K as related to days after emergence for fresh tomato. Data from Bar-Yosef (1999).

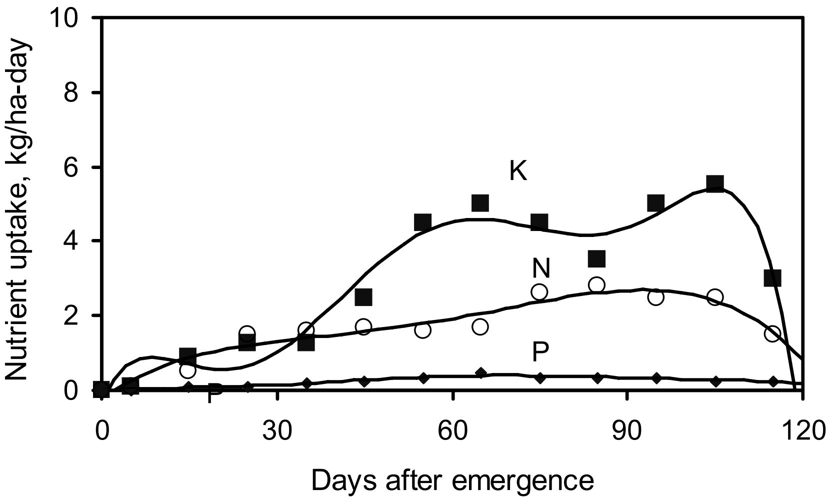


Figure 8.10. Nutrient uptake rate of N, P, and K as related to days after emergence for bell pepper. Data from Bar-Yosef (1999).

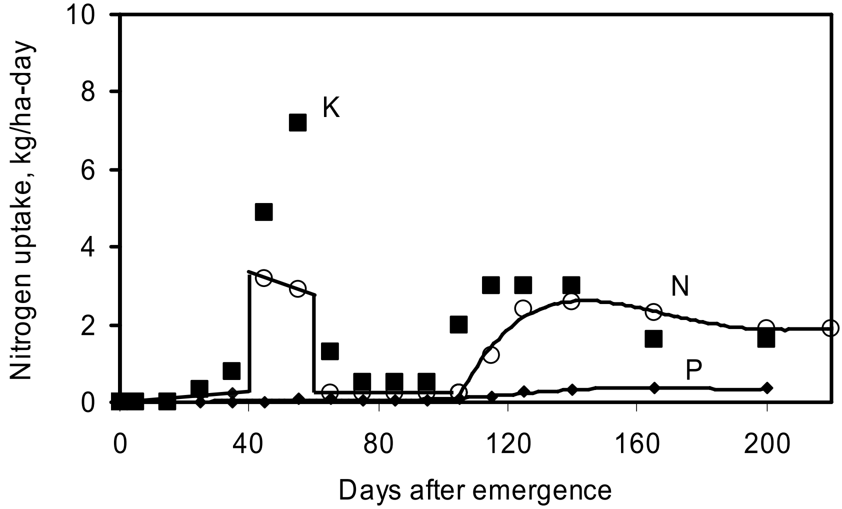


Figure 8.11. Nitrogen uptake rate as related to days after emergence for eggplant. Data from Bar-Yosef (1999).

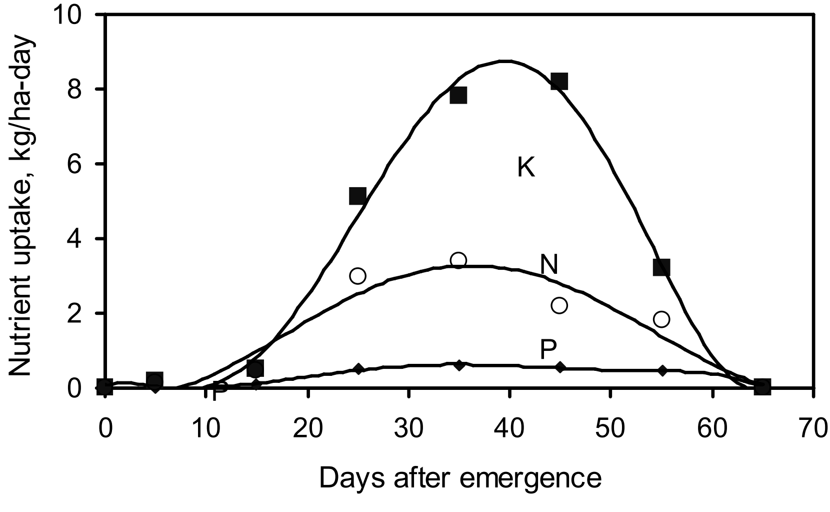


Figure 8.12. Nutrient uptake rate of N, P, and K as related to days after emergence for lettuce. Data from Bar-Yosef (1999).

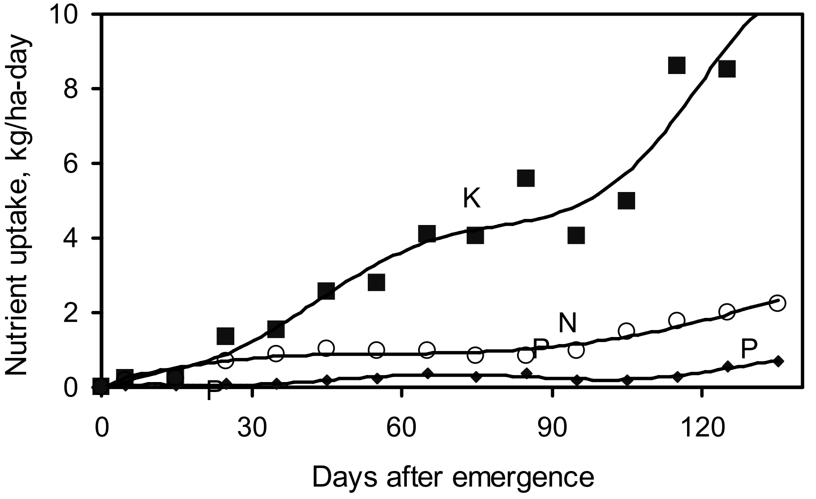


Figure 8.13. Nutrient uptake rate of N, P, and K as related to days after emergence for celery. Data from Bar-Yosef (1999).

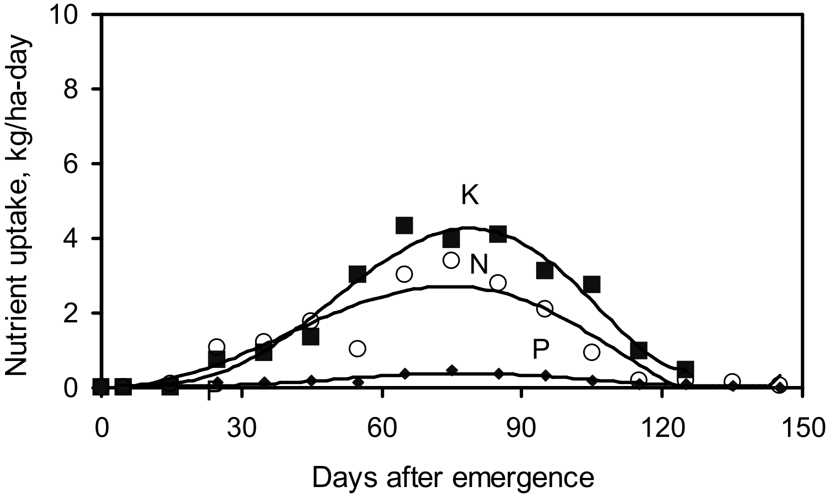


Figure 8.14. Nutrient uptake rate of N, P, and K as related to days after emergence for broccoli. Data from Bar-Yosef (1999).

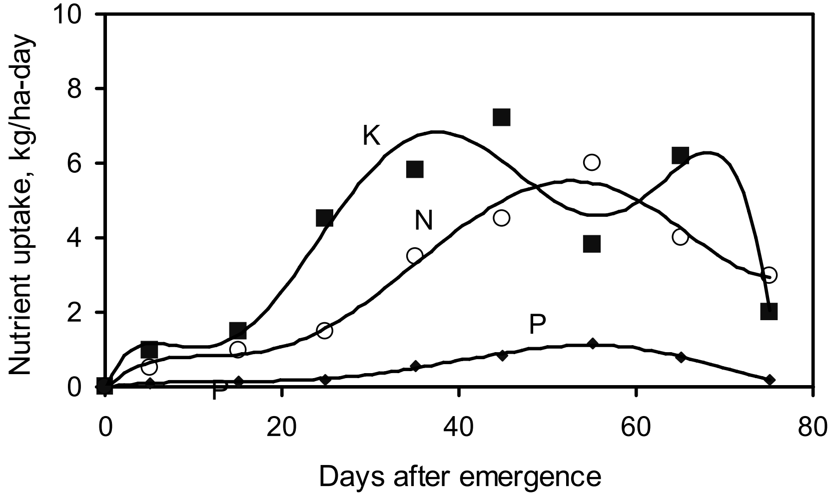


Figure 8.15. Nutrient uptake rate of N, P, and K as related to days after emergence for sweet corn. Data from Bar-Yosef (1999).

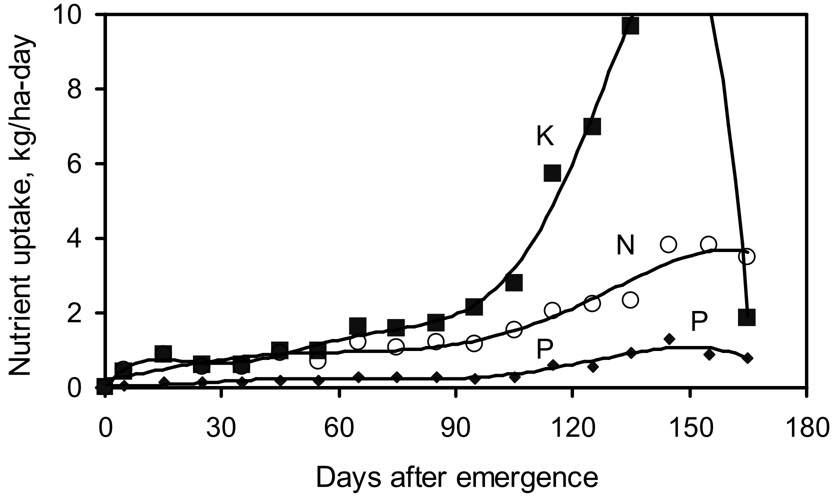


Figure 8.16. Nutrient uptake rate of N, P, and K as related to days after emergence for carrot. Data from Bar-Yosef (1999).

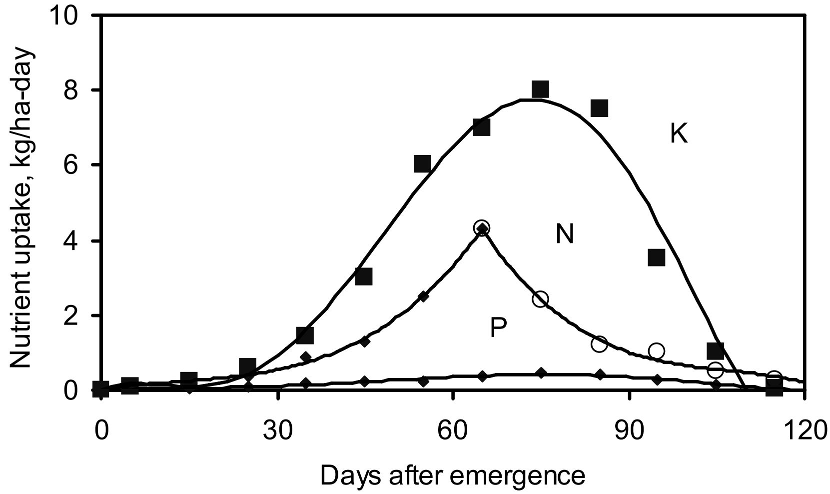


Figure 8.17. Nutrient uptake rate of N, P, and K as related to days after emergence for muskmelon (cantaloupe). Data from Bar-Yosef (1999).

Polynomial functions were generated for each nutrient of the form

$$F = C_0 + C_1 d + C_2 d^2 + C_3 d^3 + C_4 d^4 + C_5 d^5 + C_6 d^6 \tag{8.1}$$

where F is the fertigation rate in kg/ha-day, d is the days after the beginning of the growing season, and C_0 through C_6 are coefficients for various crops, various macronutrients (N, P and K) and time periods as listed in Tab. 8.2. Figures 8.7 to 8.17 also show the trend lines for each nutrient that were generated with the equations. The equations tend to smooth out the data; however, some of the data irregularities could represent changes in plant physiological condition or management strategy. For example, tomatoes are typically stressed during flowering (Fig. 8.7). Equation 8.1 can be integrated to enable the grower to calculate the amount of each fertilizer required during any given time period:

$$F_i = C_0 (d_2 - d_1) + C_1/2(d_2^2 - d_1^2) + C_2/3(d_2^3 - d_1^3) + C_3/4(d_2^4 - d_1^4) + C_4/5(d_2^5 - d_1^5) + C_5/6(d_2^6 - d_1^6) + C_6/7(d_2^7 - d_1^7) \tag{8.2}$$

where F_i is the fertilizer requirement during the interval d_2 minus d_1 in days and C_0 through C_6 are coefficients as listed in Tab. 8.2. Although the equations appear complex, third order to seventh order polynomials, they are simple to implement on computers. Bar-Yosef's (1999) data were based on crops grown in the Mediterranean region, and thus the nutrient consumption rates are specific for that region. The curves can be adjusted by multiplying by the ratio of the expected nutrient uptake in a specific region to the total nutrient uptake for the crop given in Tab. 8.3. Bar-Yosef (1999) emphasized, however, that great caution must be taken when trying to adjust the nutrient uptake rates for other regions.

Table 8.2. Coefficients used for calculating daily nutrient consumption (kg/ha) and cumulative nutrient use during a specified interval by various field crops as function of time after emergence or planting. Adapted from Bar-Yosef (1999).

Crop & time after planting	C_0	C_1	C_2	C_3	C_4	C_5	C_6
Muskmelon							
N1 (0-65)	5.5327E-03	2.6344E-02	-1.0489E-03	2.5471E-05			
N2 (65-120)	5.3110E+01	-1.4430E+00	1.3351E-02	-4.1667E-05			
P (0-120)	-1.4318E-03	6.6062E-03	-3.9107E-04	1.4201E-05	-1.6809E-07	6.0926E-10	
K (0-110)	1.6960E-02	6.3798E-02	-8.3179E-03	3.5853E-04	-4.4706E-06	1.6826E-08	
Carrot							
N (0-170)	2.1994E-01	1.4222E-02	5.0808E-04	-1.7633E-05	1.7399E-07	-5.1130E-10	
P (0-170)	5.0863E-02	-7.1123E-03	7.5581E-04	-1.6997E-05	1.4456E-07	-4.0456E-10	
K (0-170)	-3.4648E-02	1.5166E-01	-1.0510E-02	3.1679E-04	-4.4736E-06	2.9532E-08	-7.2153E-11
Sweet corn							
N (0-80)	5.1031E-02	1.1070E-01	-8.8205E-03	4.4525E-04	-7.2012E-06	3.5344E-08	
P (0-80)	1.9042E-03	2.4951E-02	-1.1709E-03	-2.2492E-05	3.0137E-06	-5.9328E-08	3.3619E-10
K (0-75)	-7.3084E-02	6.0485E-01	-1.0148E-01	7.0042E-03	-2.0268E-04	2.5918E-06	-1.2163E-08
Broccoli							
N1 (0-120)	1.0137E-02	-9.1582E-04	1.0574E-03	4.9441E-06	-2.5466E-07	1.1810E-09	
N2 (120-135)	1.5000E-01						
P (0-150)	-2.6557E-02	1.6496E-02	-1.2156E-03	3.9095E-05	-5.2593E-07	3.0956E-09	-6.6607E-12
K (0-140)	-1.7837E-02	2.1597E-02	-2.2648E-03	1.1445E-04	-1.4319E-06	5.2177E-09	
Chinese cabbage							
N (0-90)	1.4774E-01	3.8759E-02	4.1971E-03	-1.3582E-04	1.2880E-06	-3.9132E-09	
P (0-90)	-1.3947E-02	5.5364E-02	-6.8084E-03	3.4888E-04	-7.4226E-06	6.8804E-08	-2.3145E-10
K (0-75)	4.1280E-01	5.2000E-02	1.2595E-02	-3.3964E-04	2.1473E-06		
Celery							
N (0-140)	3.9118E-02	-4.1111E-03	2.3491E-03	-6.1871E-05	5.7548E-07	-1.7620E-09	
P (0-140)	-1.8816E-02	2.3248E-02	-2.0238E-03	7.0724E-05	-1.0609E-06	7.0739E-09	-1.7242E-11
K (0-140)	-6.3735E-02	9.0771E-02	-6.9441E-03	2.9860E-04	-5.0450E-06	3.6849E-08	-9.6917E-11
Lettuce							
N (0-60)	-2.6474E-01	9.5903E-02	1.2795E-03	-4.1966E-05			
P (0-60)	3.7608E-07	-1.3331E-02	2.2847E-03	-5.0070E-05	2.7858E-07		
K (0-60)	2.9323E-01	-2.7821E-01	2.8381E-02	-4.0656E-04			
Potato							
N1 (0-120)	7.7395E-02	3.3868E-03	-6.3029E-05	9.0638E-05	-2.2924E-06	1.9554E-08	-5.5737E-11
Bell pepper							
N (0-120)	-2.0800E-01	1.0900E-01	-3.0300E-03	4.1800E-05	-1.9600E-07		
P (0-120)	-1.2387E-02	1.4352E-02	-1.0617E-03	4.1940E-05	-6.9565E-07	5.0787E-09	-1.3673E-11
K (0-120)	-3.3149E-01	3.6574E-01	-3.6904E-02	1.4843E-03	-2.5982E-05	2.0620E-07	-6.1003E-10

Table 8.2. *(continued)*

Crop & time after planting	C_0	C_1	C_2	C_3	C_4	C_5	C_6
Cotton							
N1 (0-45)	2.5000E-01						
N2 (45-113)	-4.4243E+02	3.2138E+01	-9.0885E-01	1.2486E-02	-8.2956E-05	2.1308E-07	
N3 (113-150)	1.3000E-01						
P (0 - 140)	-1.3056E-02	1.2371E-02	-8.2662E-04	1.9598E-05	-1.5941E-07	4.0936E-10	
K1 (0 - 25)	1.0000E-01						
K2 (25-114)	2.8973E+00	-2.3080E-01	5.7727E-03	-3.4848E-05			
Eggplant							
N1 (0-40)	4.8800E-03	7.2000E-03					
N2 (40-60)	4.5500E+00	-3.0000E-02					
N3 (60-105)	2.5000E-01	0.0000E+00					
N4 (105-220)	-9.9566E+01	2.2505E+00	-1.8173E-02	6.3743E-05	-8.2305E-08		
P (25-200)	1.8091E-02	-7.5989E-03	5.3740E-04	-1.2519E-05	1.2946E-07	-5.9827E-10	1.0128E-12
K1 (25-55)	1.7500E-02	-1.1200E-01	4.5000E-03				
K2 (55-165)	7.9862E+01	-2.8638E+00	3.6560E-02	-1.9432E-04	3.6669E-07		
K3 (165-220)	1.6000E+00						
Fresh tomato							
N (0-150)	-8.7100E-03	5.6400E-02	-2.4300E-03	3.6800E-05	-1.5200E-07		
P1 (0-140)	-6.1077E-03	7.9270E-03	-6.6030E-04	2.2590E-05	-3.5780E-07	2.6840E-09	-7.5547E-12
P2 (140-150)	8.5000E-02						
K (0-150)	1.4100E-01	1.7000E-02	7.4500E-04	-5.0400E-05	8.2500E-07	-3.6000E-09	
Greenhouse tomato							
N1 (0-200)	4.0500E-01	-9.3200E-03	3.5800E-03	-7.4200E-05	5.1900E-07	-1.1800E-09	
N2 (200-220)	2.0000E+00						
P1 (0-20)	1.0000E-01						
P2 (20-200)	7.5700E-02	-2.2400E-02	1.8300E-03	-3.9700E-05	3.6200E-07	-1.4800E-09	2.2400E-12
K1 (0-200)	8.2251E-01	9.0821E-02	3.4609E-03	-1.0052E-04	7.4905E-07	-1.7149E-09	
K2 (200-220)	3.0000E+00						
Processing tomato							
N1 (0-70)	7.1100E-04	3.0600E-02	-2.1400E-03	1.4900E-04	-1.4800E-06		
N2 (70-100)	4.0100E+01	-1.0500E+00	7.5000E-03				
P1 (0-70)	-1.6100E-02	1.0800E-02	-4.5600E-04	1.0800E-05	0.0000E+00		
P2 (70-100)	1.2900E+01	-3.1200E-01	1.9500E-03				
K1 (0-70)	-2.6500E-02	6.5300E-02	-7.3400E-03	3.7200E-04	-3.7300E-06		
K2 (70-100)	-1.8700E+02	4.3900E+00	-2.4500E-02				

Table 8.3. Calculated seasonal nutrient uptake amounts for various crops based on Eq. 8.2.

Crop	Calculated N kg/ha	Calculated P kg/ha	Calculated K kg/ha
Muskmelon (cantaloupe)	148	25	389
Carrot	277	72	592
Sweet corn	237	40	323
Broccoli	183	25	255
Chinese cabbage	137	38	281
Celery	151	36	588
Lettuce	113	22	244
Cotton	233	45	186
Potato	166	n/a	n/a
Eggplant	296	33	399
Bell pepper	206	30	372
Fresh tomato	248	25	367
Greenhouse tomato	431	49	709
Processing tomato	395	56	517

The injection rate during any time period must be calculated based on the irrigation rate and the type of fertilizer applied. Growers can either vary fertilizer injection rate continuously to meet crop demands or irrigate in a uniform manner over a period of time. Many growers calculate fertilization needs for every stage of crop growth. For each growth stage, the fertilization rate and the fertilizer formulation remains constant, and thus only irrigation period is varied during the fertigation event. An example using the nutrient functions is given as follows:

Example 8.1

A crop consultant wishes to calculate the nutrient requirements for muskmelon (cantaloupe). The growing season will be split into five stages: (0-25 days), (25-50 days), (50-75 days), (75-100 days), and (100-120 days).

The amount of fertilizer that is required during the first 25 day stage for muskmelon is calculated using Eq 8.2 with C coefficients from the Tab. 8.2. Note only 4 of 7 degrees of the polynomial are required.

$$F_{0\text{-}25} = 5.5327E\text{-}03\,(d_2 - d_1) + (2.6344E\text{-}02\,/2\,(d_2^2 - d_1^2)) + (-1.0489E\text{-}03\,/3\,(d_2^3 - d_1^3)) + (2.5471E\text{-}05\,/4\,(d_2^4 - d_1^4))$$

$$F_{0\text{-}25} = 5.5327E\text{-}03\,(25 - 0) + (2.6344E\text{-}02\,/2\,(25^2 - 0^2)) + (-1.0489E\text{-}03\,/3\,(25^3 - 0^3)) + (2.5471E\text{-}05\,/4\,(25^4 - 0^4))$$

$$F_{0\text{-}25} = 5\ kg\,/\,ha$$

For the second stage, lasting from 25 to 50 days, the amount of N required is

$$F_{25\text{-}50} = 5.5327E\text{-}03\ (50 - 25) + (2.6344E\text{-}02\ /2\ (50^2\text{-}25^2)) +$$

$$(-\ 1.0489E\text{-}03\ /3\ (50^3\text{-}25^3)) + (\ 2.5471E\text{-}05\ /4\ (50^4\text{-}25^4))$$

$$F_{25\text{-}50} = 24\ kg\ /\ ha$$

For the third stage 50 to 75 days, the total N for 50 to 65 days is calculated and then the amount for 65 to 75 days is calculated. Different coefficients are used for the two periods (Tab 8.2).

$$F_{50\text{-}65} = 5.5327E\text{-}03\ (65 - 50) + (2.6344E\text{-}02\ /2\ (65^2\text{-}50^2)) +$$

$$(-\ 1.0489E\text{-}03\ /3\ (65^3\text{-}50^3)) + (\ 2.5471E\text{-}05\ /4\ (65^4\text{-}50^4))$$

$$F_{50\text{-}65} = 44\ kg\ /\ ha$$

$$F_{65\text{-}75} = 5.3110E{+}01\ (75 - 65) + (-1.4430E\text{-}00\ /2\ (75^2\text{-}65^2)) +$$

$$(1.3351E\text{-}02\ /3\ (75^3\text{-}65^3)) + (-4.1667E\text{-}05\ /4\ (75^4\text{-}65^4))$$

$$F_{65\text{-}75} = 33\ kg\ /\ ha$$

Total required during third stage = 44 kg/ha + 33 kg/ha = 77 kg/ha

For the fourth stage, 75 to 100 days, the amount of N required is

$$F_{75\text{-}100} = 5.3110E{+}01\ (100 - 75) + (-1.4430E\text{-}00\ /2\ (100^2\text{-}75^2)) +$$

$$(1.3351E\text{-}02\ /3\ (100^3\text{-}75^3)) + (-4.1667E\text{-}05\ /4\ (100^4\text{-}75^4))$$

$$F_{75\text{-}100} = 32\ kg\ /\ ha$$

For the fifth stage, 100 to 120 days, the amount of N required is

$$F_{100\text{-}120} = 5.3110E{+}01\ (120 - 100) + (-1.4430E\text{-}00\ /2\ (120^2\text{-}100^2)) +$$

$$(1.3351E\text{-}02\ /3\ (120^3\text{-}100^3)) + (-4.1667E\text{-}05\ /4\ (120^4\text{-}100^4))$$

$$F_{100\text{-}120} = 9\ kg\ /\ ha$$

The total seasonal N requirement is

$$F_{0\text{-}120} = F_{0\text{-}25} + F_{25\text{-}50} + F_{50\text{-}75} + F_{75\text{-}100} + F_{100\text{-}120}$$

$$F_{0\text{-}120} = 5 + 24 + 77 + 32 + 9 = 147\ kg\ /\ ha$$

Equation 8.2 and the appropriate coefficients in Tab. 8.2 were also used to calculate the amount of P and K required for the muskmelon crop. The combined N, P, and K results are shown in Tab. 8.4. Often, there are differences between the required fertilizer amounts and the amounts applied by the grower. The grower makes decisions about applications during each stage based on soil nutrient reserves, fertilizer formulations, preplant fertilization, irrigation schedules, criteria for maximum nutrient concentration in irrigation water, and other factors. In addition, the grower may decide to change the fertilization rate during the growing season based on leaf tissue analysis. Soils at Yuma are typically not limited in potassium, so no potassium was applied. The grower adds phosphorous during early fruiting (Stage 3).

Table 8.4. N, P, and K requirements for a muskmelon crop in Yuma, Arizona for each of the five growth stages and the applied amounts used in Example 8.3.

Stage	Nitrogen N (kg/ha)		Phosphorus P (kg/ha)		Potassium K (kg/ha)	
	required	applied	required	applied	required	applied
1 (0-25 days)	5	5	1	0	4	0
2 (25-50 days)	24	35	4	0	55	0
3 (50-75 days)	77	35	9	20	166	0
4 (75-100 days)	32	35	9	0	150	0
5 (100-120 days)	9	9	2	0	14	0

8.3.1.2. Fertilizer selection and calculation of injection rates

Fertilizers for fertigation systems are selected based on plant response, solubility, cost, effect on soil pH, formulation, and potential for reaction with other chemicals within the distribution system. Liquid fertilizers can be purchased in liquid form or stock solutions can be mixed on farm. Fertilizer formulation labels for nitrogen (N), phosphorous (P), and potassium (K) are based on percent N, P_2O_5, and K_2O, respectively (Rosen, 1994).

Fertilizer is often available in premixed liquid form for fertigation systems. Transportation costs are higher for liquid fertilizers than for solid forms. However, premixed fertilizer often save time and labor, and avoid problems associated with poorly prepared onfarm mixes (Granberry et al., 2001). Solid fertilizers used in making liquid fertilizer formulations should be in the granular form. However, some granular fertilizers are not completely soluble in water and should not be injected into microirrigation systems. The maximum amount of a solid that can be dissolved in water is referred to in the fertilizer industry as the solubility (kg/L). The solubility changes with temperature and with the concentration of other ions in solution. Fertilizers should not be mixed at the maximum solubility because temperature change can cause chemical precipitation and because the mixing time is extensive.

Plants can take up nitrogen as ammonium, NH_4^+, or as nitrate, NO_3^-. Nitrogen applied as ammonium (a cation or positively charged ion) is less likely to be leached from soil than nitrogen applied as nitrate (anion) because cations are adsorbed by the clay particles in the soil by Coulombic forces. The type of nitrogen that is used by the plant has an effect on both the plant and the soil environment. Because the plant must maintain electroneutrality (same number of anions and cations), plants tend to secrete cations (hydrogen ions) when most of the nitrogen is taken up as ammonium. This process tends to acidify the soil. Fertilizers are often applied as ammonium-N with the expectation that nitrifying bacteria will slowly convert the ammonium to nitrate during the growing season. Thus, the nitrogen will not be leached out of the soil immediately and will slowly become available to the plant in the nitrate form.

Nitrogen can be lost to the atmosphere by ammonia volatilization or by conversion of nitrate to nitrous oxide gas or nitrogen gas. At higher pH, the ammonium/ammonia equilibrium goes toward ammonia, and thus volatilization of ammonium is more likely at high pH. For surface drip irrigation, ammonia volatilization may result in a significant loss of nitrogen.

One source of nitrogen in the soil is microbial mineralization of organic matter to ammonium and subsequently nitrate. Nitrogen may also be present in the irrigation water and in some cases may be so high in nitrate-N, that fertilization is not needed. Calculations of nitrogen requirements should take mineralization and nitrogen in irrigation water into account.

Because only a small percentage of the root zone is wetted, combining microirrigation and fertigation affects soil water and nutrient distributions, and consequently, root development. Acidification of some soils may be a problem with acid-based fertilizers, and alternatives such as calcium nitrate should be considered. A balanced fertilization program may require supplemental foliar applications of micronutrients.

Typically soil tests report phosphorus (P), and potassium (K) availability in soils as the oxidized forms, P_2O_5 and K_2O, respectively. Equation 8.1 and 8.2 are in terms of elemental N, P, and K instead of the oxide forms of potassium and phosphorus. Applicable conversion factors are given in Tab. 8.5.

Table 8.5. Conversions of relevant nutrient units of measurements. After Burt et al. (1995).

Unit	Multiplier		Result
Any compound (mg/L)	x 2.0	∍	Same compound (lb./acre)
N (mg/L) (elemental N)	x 4.42	∍	NO_3 (mg/L) if the nitrogen analyzed is nitrate
NO_3-N (mg/L) (elemental N)	x 4.42	∍	NO_3 (mg/L)
N (mg/L)	x 1.29	∍	NH_4 (mg/L) if the nitrogen analyzed is ammonium
NH_4-N (mg/L) (elemental N)	x 1.29	∍	NH_4 (mg/L)
NH_4 (mg/L)	x 0.78	∍	NH_4-N (mg/L)
NO_3 (mg/L)	x 0.226	∍	NO_3-N (mg/L)
P_2O_5 (mg/L)	x 0.67	∍	PO_4 (mg/L)
P_2O_5 (mg/L)	x 0.44	∍	PO_4-P (mg/L)
PO_4-P (mg/L)	x 3.07	∍	PO_4 (mg/L)
K_2O (mg/L)	x 0.83	∍	K (mg/L)
NO_3-N (%)	x 71.4	∍	NO_3-N meq/100 g of soil
K (%)	x 25.57	∍	K meq/100 g of soil
Ca (%)	x 49.9	∍	Ca meq/100 g of soil
Mg (%)	x 82.24	∍	Mg meq/100 g of soil
NH_4-N (%)	x 71.4	∍	NH_4-N meq/100 g of soil

A large variety of fertilizers are injected into microirrigation systems (Tab. 8.6). Fertilizer company representatives or other experts should always be consulted when mixing or using chemical formulations for the first time to ensure compatibility with other chemicals and with the irrigation water.

Table 8.6. Types of fertilizer and suitability for fertigation through microirrigation systems. After Burt et al. (1995).

Fertilizer	Compound	Precaution	Characteristics
Anhydrous ammonia	82-0-0	Never inject into microirrigation systems.	n/a
Aqua ammonia	20-0-0	Never inject into microirrigation systems.	n/a
Ammonium nitrate solution (AN-20) $NH_4NO_3 * H_2O$	20-0-0	Never mix solution with concentrated acids.	Density – 1.29 kg/L Commonly used for fertigation
Urea ammonium nitrate (UAN32) $(NH_2)_2CO*NH_4NO_3$	32-0-0	Don't mix with CAN17 or calcium nitrate solutions.	Density – 1.33 kg/L Commonly used liquid fertilizer with highest N.
Calcium ammonium nitrate (CAN17) $Ca(NO_3)_2*NH_4NO_3$	17-0-0 8.8% Ca	Do not combine with solutions containing sulfates/thiosulfate.	Density – 1.55 kg/L Effective for obtaining high fruit quality in some crops.
Ammonium phosphate $(NH_4)H_2PO_4$	8-24-0	Can precipitate if injected at high rates or into hard water.	Density – 1.26 kg/L Not commonly used for fertigation.
Ammonium polyphosphate $(NH_4)_2H_2P_2O_7$	9-30-0, 10-34-0, 11-37-0	Can precipitate with carbonates in high pH water.	9-30-0, Density – 1.36 kg/L 10-34-0, Density – 1.37 kg/L 11-37-0, Density – 1.41 kg/L
Ammonium polysulfide $(NH_4)_2S_x$	20-0-0 45% S	Dangerous hydrogen sulfide gas results from contact with acid.	Density – 1.05 kg/L Solution has very high pH, but can act as soil acidifying agent.
Ammonium thiosulfate $(NH_4)_2S_2O_3$	12-0-0 26% S	Do not mix with acids or apply to low pH soils.	Density – 1.33 kg/L Acidifying agent, ideal for treatment of calcareous soils.
Metal chelates	Most metal micronutrients must be chelated with EDTA, DTPA, or EDDHA to prevent precipitation.		Chelated metals are very effective in alkaline soils.

Table 8.6. Continued.

Fertilizer	Compound	Precaution	Characteristics
Phosphoric acid H_3PO_4	0-54-0	Never mix phosphoric acid with calcium fertilizer.	Density – 1.69 kg/L Green acid is most common, but is less pure than white acid.
Potassium chloride KCl	0-0-60 Dry form	Not recommended for Cl sensitive crops.	Solubility – 0.347 kg/L Highest used potassium fertilizer.
Potassium nitrate KNO_3	13-0-44	None	Solubility – 0.133 kg/L Second most popular source of potassium fertilizer.
Potassium phosphate KH_2SO_4	0-52-34	None	Density – 1.26 kg/L Used in greenhouse and nursery
Potassium sulfate K_2SO_4	0-0-50	None	Solubility – 0.12 kg/L Popular for fertigation as good source of sulfur
Potassium thiosulfate (KTS) $K_2S_2O_3$	0-0-25 17% S 0-0-22 23% S	KTS blends should have pH less than 6.	Contains 0.36 kg/L K_2O and 0.25 kg/L S
Sulfuric acid H_2SO_4	0-0-0	Very hazardous. Injection w/ CAN17 results in clogging.	Density – 1.83 kg/L
Urea solid $(NH_2)_2CO$	46-0-0	Never mix urea with sulfuric acid.	Solubility – 1 kg/L
Urea phosphate $(NH_2)_2CO*H_3PO_4$	17-44-0		The acidity prevents ammonia volatilization
Urea sulfuric acid $(NH_2)_2CO*H_2SO_4$	10-55-18 15-49-16 28-27-9	Never mix urea and sulfuric acid in the field – harms plants.	10-55-18 Density – 1.54 kg/L 15-49-16 Density – 1.53 kg/L 28-27-9 Density – 1.42 kg/L

Proper mixing procedures should always be followed with all fertilizer formulations. Mixing procedures (after Burt et al., 1995) are listed as follows:

1. Always fill the mixing container with 50 to 75% of the required water to be used in the mix.
2. Always add the liquid materials to the water before adding the dry, soluble fertilizers.
3. Always add the dry ingredients slowly with circulation or agitation to prevent the formation of large, insoluble, or slowly soluble lumps.
4. Always add acid into water, not water into acid.

5. Never mix an acid or acidified fertilizer with chlorine (gas, liquid, or solid).
6. Do not mix concentrated fertilizer solutions with other concentrated fertilizer solutions.
7. Because fertilizer solutions are applied in very small dosages, and if injected at different locations in the irrigation line, many incompatibility problems are avoided.

Urea sulfuric acid can be mixed with other solutions such as phosphoric acid, muriate of potash, and sulfate of potash. Urea sulfuric acid mixtures should always be mixed in the correct order and only with approved fertilizers as specified by the manufacturer (Burt et al., 1995).

Mixing of liquid fertilizer stock tank solutions from solid fertilizer (granular) requires some basic knowledge of chemistry including unit conversion, molarity, concentration, density and molecular weights of cations and anions in the fertilizer.

Molarity	*mol/L*	=	*moles of solute (dissolved substance) / 1.0 L of water.*
Concentration	*mg/L*	=	*mass of solute / volume of water.*
Density, ρ	*kg/m^3*	=	*mass of solute, kg / 1.0 m^3 of volume*

Solid granular fertilizers such as KNO_3 (potassium nitrate) consist of a positively charged ion (cation) and a negatively charged ion (anion). When granular KNO_3 dissolves in water, the potassium and the nitrate exist as ions with a positive and negative charge, respectively. The molecular weights (number of grams in one mole of substance) and ionic charge (valence) for common salts in water are shown in Tab. 8.7.

Table 8.7. Common salts their molecular weights and electrical charges.

Cations			Anions		
Name	Symbol & charge	Molecular wt (g/mol)	Name	Symbol & charge	Molecular wt (g/mol)
Ammonium	NH_4^+	17.0	Bicarbonate	HCO_3^-	61.0
Calcium	Ca^{2+}	40.1	Carbonate	CO_3^{2-}	60.0
Hydrogen	H^+	1.0	Nitrate	NO_3^-	62.0
Magnesium	Mg^{2+}	24.3	Phosphate	PO_4^{3-}	95.0
Sodium	Na^+	23.0	Sulfate	SO_4^{2-}	96.1
Potassium	K^+	39.1	Chloride	Cl^-	35.5

Example 8.2.

A grower wants to apply 4 kg/ha of potassium (K) as K_2O and 2 kg/ha of nitrate-N to a 20 ha field during a one-week period. Calculate the mass of KNO_3 fertilizer that must be dissolved and the amount of solution required for the one-week period.

Total potassium required as K_2O is 4 kg/ha x 20 ha = 80 kg.

Total potassium required as K is found by taking the ratio of K to K_2O (0.83 from Tab. 8.5)

Mass K = 80 x 0.83 = 66.4 kg

Now solve for the number of moles of K required using information from Tab. 8.7.

Mol. K = 66.4 kg x 1000 g/kg x 1/39.1 mol./g = 1,698 mol. K

Solve for the number of moles of nitrogen required.

Mol. N = 2 kg/ha x 20 ha x 1,000 g/kg x 1/14 mol N/g = 2,857 mol. N

The number of moles of N and number of moles of K that are applied must be the same because there is a one to one ratio of NO_3 and K in the fertilizer. Thus, excess potassium will be applied.

Solve for the mass of fertilizer required.

Molecular weight of fertilizer = Mol. wt. NO_3 + Mol wt. K = 62 + 39.1 = 101.1 g/mol.

Mass of fertilizer = 2,857 moles x 101.1 g/mol. x 0.001 kg/g = 289 kg.

The solubility of potassium nitrate is 0.133 kg/L (Tab. 8.6). However, it is easier to dissolve potassium nitrate at a concentration less than the maximum concentration (0.133 kg/L).

Volume of water required based on solubility of potassium nitrate

289 kg / (0.133 kg/L) = 2,172 L

The grower decides that doubling the volume of liquid used to dissolve the fertilizer to approximately 5,000 L might be a wise idea.

If irrigation occurred on daily basis and fertilizer injection was conducted for 2 h for each irrigation, then the injection rate for the 20 ha block would be calculated as follows.

*5,000 L / (2 h/day * 7 days) = 357 L/h*

The grower could adjust the relative amounts of N and K by mixing a fertilizer that is higher in nitrogen and lower in potassium. One possible combination would be ammonium nitrate and potassium nitrate.

Example 8.3.

A grower plans to use the nutrient application rates specified in the applied columns of Tab 8.3 for irrigation of muskmelon in Yuma, Arizona to develop a seasonal fertigation schedule. The 75 ha field is divided into 5 blocks of 15 ha each. In addition to N and P fertilization, the grower also adds 20 kg/ha calcium during the fourth and fifth stages. Nutrient application *rates per block were the product of kg/ha for each stage (Tab. 8.4) and the area of each block. The results are shown in Tab. 8.8.*

Irrigation water was applied to each block at a rate of 4 mm/h for a 4-h period during each irrigation event. The number of irrigations per stage were scheduled using a climatic-based water budget and is shown in Tab. 8.8. The flowrate per block is calculated as follows:

4 mm/h / 60 min/h x 15 ha x 10,000 L/ha-mm = 10,000 L/min

The grower begins each fertigation event after irrigation is started and finishes well before irrigation has concluded in order to ensure high distribution uniformity and complete flushing of fertilizer from microirrigation laterals. In this case, the grower injects the fertilizer during the middle 2 h of each 4 h irrigation event. The volume of water applied per block during the 2 h of fertilizer injection is 10,000 L/min x 120 min = 1,200,000 L/block for each fertigation event. The volume of water applied during the entire irrigation event is 10,000 L/min x 240 min = 2,400,000 L/block for each irrigation event. Relevant irrigation and fertigation parameters are shown in Tab. 8.8.

Table 8.8. Irrigation and nutrient amounts per stage for muskmelon crop in Yuma as used in Example 8.3.

Stage	Nutrients - kg/block/stage				Water –			
	N	P	K	Ca	Irr. events per stage	Fertigation h/stage	Irrigation h/stage	Water applied per block per stage - (L)
1 (0-25 days)	75	0	0	0	6	12	24	$1.44 * 10^7$
2 (25-50 days)	525	0	0	0	12	24	48	$2.88 * 10^7$
3 (50-75 days)	525	300	0	0	16	32	64	$3.84 * 10^7$
4 (75-100 days)	525	0	0	300	16	32	64	$3.84 * 10^7$
5 (100-120 days)	135	0	0	300	16	32	64	$3.84 * 10^7$

The grower must then select or mix fertilizer formulations. In order to save time and avoid possible problems, the grower decides to purchase premixed liquid formulations. Urea-ammonium nitrate (UAN32) is selected during the first 2 stages because only nitrogen is required. For the third stage, liquid formulations of UAN32 and ammonium polyphosphate (10-34-0) are selected and will be injected at two ports into the irrigation pipeline. Ammonium polyphosphate would not normally be selected for injection into Colorado River water (pH ~ 8) because of the danger of precipitation of calcium phosphate ($CaPO_4$). However, the grower injects sulfuric acid in order to lower irrigation water pH to 6.5 at an injection port upstream from the two fertilizer injection ports. Thus, the grower can avoid precipitation of fertilizers with Ca in the Colorado River water source. The soil is alkaline so that soil acidification is not a hazard, and acidity may actually make some calcium in the soil available to the plant. For the last two stages, the grower decides to use CAN17 as the calcium source. CAN17 cannot be injected with urea-ammonium nitrate so the grower decides to use ammonium nitrate as the nitrogen source if CAN17 does not supply the nitrogen required during the fourth and fifth stages.

UAN32 will supply 75 kg N per block over 12 h of fertigation (Tab. 8.8) during the first stage. The density of UAN32 is 1.33 kg/L and the formulation is 32-0-0 (Tab 8.5).

Volumetric N content of UAN32 = 1.33 kg/L x 0.32 = 0.425 kg/L of N

UAN32 volume per block during stage 1 = 75 kg / 0.425 kg/L = 176 L UAN32

Injection rate = 176 L / 12 h of fertigation = 14.7 L/h.

UAN32 will supply 525 kg N per block over 24 h of fertigation during stage 2.

UAN32 volume per block during stage 2 = 525 kg / 0.425 kg/L = 1,235 L UAN32

Injection rate = 1,235 L / 24 h of fertigation = 51.5 L/h.

Ammonium polyphosphate will supply 300 kg per block over 32 h of fertigation during the third stage. The density of ammonium polyphosphate (APP) fertilizer is 1.37 and the formulation is 10-34-0 (Tab. 8.6). Thus, 34% of the mass of the fertilizer is phosphorous as P_2O_5. P_2O_5 is multiplied by 0.44 (Tab. 8.5) to convert to elemental P (PO_4-P).

Volumetric P content of APP = 1.37 kg/L x 0.34 x 0.44 = 0.205 kg/L of P

APP volume per block during stage 3 = 300 kg / 0.205 kg/L = 1,463 L of APP

APP Injection rate = 1,463 L / (32 h of fertigation) = 46 L/h of APP

The nitrogen supplied by the ammonium polyphosphate during stage 3 is calculated as follows:

Volumetric N content of APP = 1.37 kg/L x 0.10 = 0.137 kg/L of N

Mass N applied as APP = 1,463 L x 0.137 kg/L = 200 kg of N

If 200 kg N is applied as ammonium phosphate, then the remainder of the nitrogen requirement (525-200 = 325 kg/block) during stage 3 must be supplied by UAN32.

UAN32 volume per block during stage 3 = 300 kg / (0.425 kg/L) = 705 L of UAN32

Injection rate = 705 L / (32 h of fertigation) = 22 L/h of UAN32

Calcium ammonium nitrate (CAN17) will supply 300 kg Ca per block over 32 h of fertigation during the fourth stage and fifth stages. The density of calcium fertilizer is 1.55 and the formulation is 17-0-0-8.8 Ca (Tab. 8.6). Thus, 8.8% of the mass of the fertilizer is calcium.

Volumetric Ca content for CAN17 = 1.55 kg/L x 0.088 = 0.136 kg/L of Ca

CAN 17 volume per block during stage 3 = 300 kg / (0.136 kg/L) = 2,205 L of CAN17

Injection rate of CAN17 = 2,205 L / (32 h of fertigation) = 69 L/h of CAN17

The amount of nitrogen supplied by CAN17 during stage 3 is calculated as follows.

Volumetric N Content of CAN17 = 1.55 kg/L x 0.17 = 0.264 kg/L of N

Mass N applied as CAN17 = 2,205 L CAN17 x 0.264 kg/L = 582 kg of N

Thus, CAN17 will supply slightly more N per block, 582 kg, than is required during the fourth stage, 525 kg, and much more than is required during the fifth stage, 135 kg. As a result, the grower may decide to apply less N during the third stage and the application of UAN32 during the third stage may not be necessary.

The final step in assessing a fertigation strategy is to check the concentration of nutrients in irrigation water and the impact on the root zone soil nutrient concentration. Excessive amounts of nutrients can lead to salinization or other types of phytotoxicity. The dynamic nature of root zone salinity and nutrient distribution and nutrient uptake is discussed by Bar Yosef (1999). The mass of nutrient application is divided by the total water applied during each stage rather than the volume of water applied during fertigation. The natural salinity in the irrigation water is not accounted for in this calculation.

Example 8.4
The grower decides to check the average increase in salinity concentration in irrigation water during the growing season. Information from Example 8.3 is used here. For example, mass of salts applied during stage 1 are calculated as follows.

*Mass of UAN32 applied = 176 L * 1.33 kg/L = 234 kg UAN32/block*

The total depth of irrigation water applied to the field during the season is

*4 mm/h * 66 irrigations * 4 h/irrigation = 1,056 mm.*

The total volume of irrigation water applied to the 75 ha field is

$1.056\ m * 75\ ha * 10{,}000\ m^2/ha = 792{,}000\ m^3$

*The total mass of fertilizer (salts) applied is the sum of the fertilizer mass applied per block * 5 blocks*

*5 * (234 + 1,642 + 2,500 + 860 + 3,418 + 3,418) = 60,360 kg salts*

The average increase in salinity concentration in irrigation water is

$60{,}360\ kg/792{,}000\ m^3 = 0.076\ kg/m^3 = 76\ mg/L$

It is unlikely that an additional 76 mg/L in the irrigation water will harm the crop.

It should be mentioned that experience with crops in local areas, leaf tissue analyses, and monitoring of other forms of stress such as pest infestations will play a large role in selecting a fertigation schedule. The previous examples were an effort to demonstrate how to utilize the Bar-Yosef (1999) nutrient curves, and to show the mechanics of calculation of fertilizer injection rates.

8.3.2. Chemigation of Non-Fertilizer Materials

Pesticides must be applied according to label instructions. If pesticides are not labeled for chemigation, then they should not be applied with microirrigation systems. The pesticide application may also be subjected to additional state regulations above label specifications.

Chemigation of pesticides may lead to leaching and ground water contamination if chemicals are used improperly. Overirrigation may lead to leaching. Pesticides have different leaching properties. The United States Environmental Protection Agency has established criteria for evaluating the leaching potential of pesticides. Pesticides are considered less likely to leach if they have a short life in the soil before degrading, are not very soluble in water, and are likely to be adsorbed onto soils and organic matter.

Some systemic insecticides, soil fumigants, nematicides, and fungicides are labeled for application through microirrigation systems. Nematicides have been shown to be very effective when applied through a subsurface drip irrigation system [Vapam® (metham sodium), Nemacur®, Furadan 4F®, which is also a insecticide]. Experience has shown that close spacing of emitters gives better control of nematodes. Weeds should be killed first to reduce uptake of pest control chemicals. Insecticides used effectively in microirrigation include Vydate®, Imidicloprid–Provado® and Admire®. Soil fumigants such as Telone® and Vapam® are often applied through microirrigation systems for control of nematodes, soil borne diseases, weeds, and crop termination. Application rates ranging from 1/6 to 1/15 of the maximum labeled rates have been found to be sufficient to control nematodes and soil-borne diseases when applied with a subsurface drip irrigation system. This is probably due to the fact that roots and fumigant application are localized in the vicinity of the drip emitter. For example, the labeled maximum application rate of Vapam, a soil fumigant, is 700 L/ha. However, some experienced growers have found that an application rate of 47 L/ha through a subsurface drip irrigation system is sufficient (Wuertz and Ozuna, 2002).

Trifluralin and acid have been recommended as a root growth inhibitor to reduce root growth into subsurface drip irrigation systems. However, recent controlled experiments (Suarez-Rey, 2002) indicated that injection of chemicals into microirrigation systems is not an effective method of preventing root intrusion into emitters. Instead, embedding trifluralin in plastic emitters has been shown to effectively control root growth into emitters. The trifluralin is slowly released in emitter outlets and prevents root growth.

Pesticide injection rate can be calculated based on irrigation system area and time of application. A typical pesticide application might include one h of water application before pesticide is injected, 3 h of pesticide injection, and then one h of water application after pesticide application in order to flush all pesticides from the irrigation system. Flushing is especially important with the application of soil fumigants in order to prevent crop damage when irrigation is resumed after planting.

The concentration of the pesticide in the irrigation water must also be checked in order to ensure that the concentration of pesticide in the irrigation system is not corrosive to irrigation system components. Because of the possibility of injection pump malfunction or other potential problems, it is a good practice to not exceed pesticide concentrations in irrigation water that are in excess of one-half of the concentration that has been found to be corrosive.

Example 8.5.

A grower wants to apply Telone EC at a rate of 45 L/ha over a period of 3 h to an irrigation zone that covers 10 ha. The irrigation water flowrate to the irrigation zone is 5,000 L/min. The density of Telone EC is 1.1 kg/L. The required injection rate is

$$\text{Injection rate, L/h} = 45 \text{ L/ha} \times 10 \text{ ha} / 3 \text{ h} = 150 \text{ L/h} = 2.5 \text{ L/min}$$

It has been found that Telone EC at concentrations greater than 1,500 mg/L is corrosive to irrigation system components. In order to avoid exceeding one-half of the corrosive concentration, the concentration of Telone EC in irrigation water should not exceed 750 mg/L.

$$\text{Telone EC Concentration} = 2.5 \text{ L/min Telone} / 5{,}000 \text{ L/min water} \times 1.1 \text{ kg/L Telone} \times 1 \times 10^6 \text{ mg/kg} = 550 \text{ mg/L Telone}$$

Thus, at an injection rate of 2.5 L/min, the concentration of Telone in irrigation water is less than 750 mg/L and is acceptable.

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Microirrigation for Crop Production
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9. APPLICATION OF BIOLOGICAL EFFLUENT

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9.1. INTRODUCTION

This chapter addresses a specialized application of microirrigation systems, namely use of biological effluent for crop production. The term "biological effluent" refers to wastewater that contains impurities derived from biological sources. Typical sources include human and animal metabolic waste and domestic and industrial food processing waste. Effluents from these sources contain organic and inorganic matter, in contrast to fresh water, which contains primarily inorganic matter of riparian origin.

Different factors have converged in various areas of the world to stimulate the increased use of biological effluent with microirrigation systems. Virtually all of the nations in the Mediterranean basin use biological effluent for irrigation (Marecos do Monte et al., 1996) and effluent reuse is expected to increase in the near future (Angelakis et al., 1999). In Israel, shortage of fresh water resources has spurred the reuse of treated municipal effluents for many types of crops under irrigation (Shelef, 1991). In Florida, USA, treated municipal effluent from the City of Orlando is now part of a large development (Conserve II) for application for citrus production and is considered to be a way to help meet irrigation needs (Parsons et al., 2001). In Hawaii, USA, guidelines have restricted the application of treated effluent with sprinkler systems, and subsurface drip irrigation systems provide a viable application alternative (Gushiken, 1995). In the Great Plains of the USA, large numbers of animals on feed have generated biological effluent in areas heavily developed with irrigated feed grain production (Forster, 1998). The application of the effluent back onto the grain-producing lands has conserved fresh water resources and reduced some fertilizer applications. Commonly, the livestock wastewater is applied with sprinkler or surface irrigation systems. Subsurface drip irrigation is a new technology for livestock wastewater application (Trooien et al., 2000).

This chapter considers biological effluent to be a resource. Consequently, the approach will be to emphasize the efficient use of the resource rather than disposal of a waste product. Application of biological effluent at disposal rates causes another set of challenges (Kirkham, 1986) that are beyond the scope of this presentation.

Traditionally, most effluents have been applied by sprinkler or surface irrigation systems. However, continued advances in microirrigation system design, management, monitoring, and especially in water treatment have expanded the use of biological effluent through microirrigation systems. Even though effluents contain many types of materials that can readily clog emitters, the advantages strongly favor the use of such effluents for agricultural irrigation.

9.1.1. Advantages of Applying Biological Effluent

Many potential advantages exist for irrigating crops with biological effluent instead of fresh water, regardless of the irrigation system type. The advantages include:

- potable water resources are conserved
- nutrients can be utilized by the crop
- cost/benefit ratio is favorable in some situations.

Additionally, advantages to using microirrigation systems, particularly drip irrigation systems, to apply the effluent include (Gushiken, 1995; Trooien et al., 2000):

- plant damage is minimized because effluent is not applied to plant tissues
- small flow rates are usable
- pressure requirements are low
- unusual field shapes and sizes are easier to irrigate
- irrigation system corrosion is reduced because most of the system is plastic
- tailwater control is unnecessary
- shallow soil profiles and erodible soils can be irrigated
- reduced exposure to humans associated with overspray and drift, especially in populated areas.

Finally, other additional advantages to applying the biological effluent with subsurface drip irrigation (SDI) systems include (Gushiken, 1995; Trooien et al. 2000):

- human contact with the effluent is reduced
- separation (setback) distance is decreased
- effluent is distributed uniformly,
- runoff of applied effluent is minimized
- weed germination and bacteria survival near the soil surface are reduced because the soil surface stays dry
- vandalism is reduced because the application system is underground
- odor is minimized
- weather constraints such as high wind or low temperature are reduced
- air humidity is minimized
- most crops and soils can be irrigated
- septic tank effluent can be applied in some situations where conventional systems fail.

9.1.2. Disadvantages of Applying Biological Effluent

Potential disadvantages of applying biological effluent also exist, regardless of microirrigation system type, including:

- system (especially emitter) clogging or root intrusion could cause nonuniformity or system failure
- land area requirements could be increased
- installation costs could be increased
- maintenance requirements and costs may be increased
- system performance monitoring requirements may be increased
- soil degradation could interfere with system operation or plant growth
- management may require more expertise
- limited experience could result in improper system design or management criteria.

9.2. CHARACTERISTICS OF BIOLOGICAL EFFLUENTS

9.2.1. Effluent Source and Degree of Treatment

Biological effluent quality is strongly affected by its source and the degree of treatment (Table 9.1). Conventional wastewater treatment may entail three steps—primary, secondary, and tertiary. Primary treatment generally is a screening or settling process that removes organic and inorganic solids from the effluent. Secondary treatment is a biological process with three steps. First, complex organic matter is broken down to dissolved nutrients and less complex material. Second, the nutrients and other materials are absorbed and utilized by bacteria. Third, the bacteria are removed from the effluent in settling chambers. Activated sludge and trickling filters are the most common secondary treatment processes. The discharge from these treatment plants contains dissolved nitrogen, phosphorus, and other plant nutrients. Oxidation ponds provide combined primary and secondary treatment. These ponds are large and shallow, and the waste is retained for sufficient time for sedimentation and decomposition to take place. Due to presence of plant nutrients, water, and sunlight, small aquatic plants (algae) grow in these ponds, so discharge from oxidation ponds may contain algae as well as nutrients.

In tertiary treatment, plant nutrients (primarily nitrogen and phosphorus) are removed from the effluent. Tertiary treatment facilities are expensive to build and operate and are only used when the plant’s discharge flows into a sensitive ecosystem. Secondary treatment discharges are usually adequate for agricultural microirrigation systems. Primary treatment discharges may also be used, but additional pretreatment may be required prior to effluent use. Before implementing an irrigation program with biological effluent, its characteristics must be analyzed. It may be necessary to modify the treatment process to make the effluent compatible for long-term use in agricultural irrigation.

Table 9.1. Characteristics of some biological effluents used in selected microirrigation studies.

	Oron and DeMalach (1987a and b)	Taylor et al. (1989)	Adin and Sacks (1991)	Tajrishy et al. (1994)	Hills and Brenes (2001)	Jnad et al. (2001a)	Trooien et al. (2000)
Source	municipal	municipal	municipal	municipal	municipal	residential	beef feedlot
Treatment method	oxidation ponds/ reservoir	aerated lagoon/ oxidation ponds/ screen filter	oxidation ponds/ screen filter	activated sludge/ clarifier	activated sludge/ clarifier	septic tank	pen runoff/ lagoon
BOD_5, mg/L	15 to 320		6 to 26	8 to 39	5 to 21	8 to 15	96 to 1,033
COD, mg/L		85 ± 38	96 to 204				
TSS, mg/L	39 to 315	32 ± 14	3 to 163	2 to 30	2 to 24	5 to 30	190 to 1,320
Turbidity, NTU			7 to 100	1 to 15	1 to 8		
TDS, mg/L		1,151 ± 104					
EC, dS/m	1.3 to 2.2		1.1 to 1.7	1.0 to 1.1		0.9 to 1.5	2.5 to 5.3
Alkalinity as $CaCO_3$, mg/L		387 ± 72	350 to 450	410 to 570			650 to 771
NH_4-N, mg/L	23 to 80	21.9 ± 6.6				12 to 40	
Total N, mg/L							60 to 170
P, mg/L	2.3 to 9.5					0.6 to 0.9	30 to 39
Ca, mg/L		74 ± 5.2	198 to 347			41 to 113	105 to 160
pH	7.5 to 7.8	8.3 ± 0.2	7.1 to 8.5	7.1 to 7.9	7.0 to 8.0		7.6 to 8.2

9.2.2. Composition of Effluent

The composition of effluents applied with microirrigation systems will depend upon public health considerations, environmental protection criteria, and the water quality needed for crop use. The important constituents are generally total dissolved and suspended solids, organic matter, nitrogen, inorganic ions, exchangeable cations, and microorganisms.

Total dissolved solids (TDS) is the aggregate of the dissolved solid components and is a measure of the total amount of salts in the effluent and is usually determined by electrical conductivity (EC). Primarily, TDS or EC is more important than the concentration of any specific ion. Irrigation with effluent high in TDS or EC results in a salinity hazard to crops, especially in areas where annual evapotranspiration exceeds annual precipitation.

Total suspended solids (TSS) is the measure of larger undissolved particles in the effluent and is primarily organic matter. Removal of TSS is critical and is most often accomplished by sand media or disk filtration prior to pumping the effluent into the microirrigation system. If not adequately removed, the suspended solids can readily clog emitters and other components in the system. Ideally, all suspended solids should be removed by filtration, but in practice only the larger particles are removed. The smaller particles that pass through the filter must be able to pass through all other system components, including the emitters. System performance must be monitored to assure that these small solids do not coagulate within the system and clog emitters or other components.

The amount of organic matter content is commonly assessed by the 5-day biochemical oxygen demand test (BOD_5). Organic matter is present in dissolved form as well as in suspended and colloidal solids. The concentration of organic matter in secondary effluent is usually low enough that it is not harmful to plants. However, organic compounds in high concentrations, including pesticides, may be found in primary treated effluents and can be toxic to soil microorganisms and plants. If the organic matter is primarily in suspended solids, a good portion of it can be removed by filtration within the microirrigation system. If the organic matter is primarily in a dissolved state, its removal is more difficult because biological oxidation is the usual procedure, which requires special equipment and expense.

Nitrogen in primary treated effluent exists in organic and inorganic forms. Organic nitrogen is generally contained in the suspended solids, and its removal by filtration is fairly effective. Nitrogen in secondary treated effluent is usually in the oxidized form, nitrate. In animal wastewaters, nitrogen is usually in the ammonium and organic forms. Although any effluent may contain various forms of nitrogen, all forms are considered beneficial to agricultural plants. The nutritional value of nitrogen and how improper management, especially excessive applications, can lead to environmental degradation are discussed in the next section.

Phosphorus is often present in effluents in the organic form. Some inorganic phosphorus may also be absorbed to soil particles, especially in effluents that capture runoff from soil-based animal pens.

When applied to agricultural land over long periods, some inorganic constituents in effluent can cause problems through the effect of specific ions on soil, plants, and groundwater. Problems of high sodium adsorption ratios are perhaps the most common, although heavy metals and trace elements can also cause problems. Boron is an essential plant nutrient, but is toxic to some plants at relatively low levels. Similarly, some heavy metals are essential for plant growth at low concentrations, but are toxic at higher levels to both plants and microorganisms. Water quality criteria for agricultural crops are applicable to all waters, irrespective of their source.

Exchangeable cations (e.g., sodium, calcium, magnesium) typically increase in concentration whenever water is used, whether for domestic or industrial purposes. Primary or secondary treatment does not remove these cations. Therefore, concentrations of exchangeable cations are higher in biological effluents than in fresh waters. In irrigation water, high amounts of sodium relative to calcium and magnesium can lead to permeability problems in soils that are high in clay content. When using effluents on agricultural soils, the concentrations of exchangeable cations must be closely monitored to maintain soil quality.

Microorganisms are contained primarily in the suspended solids of biological effluents and are typically found in primary, secondary, and tertiary treated discharges. While pathogenic bacteria and viruses pose health hazards, all bacteria in effluent pose irrigation system clogging hazards. These hazards create management problems necessitating special maintenance requirements, as discussed later in the chapter.

An emerging issue that may have an indirect impact on crop production is the release of antibacterial and other pharmaceutical agents to the environment via reclaimed effluent application. Many antibacterial agents are water soluble and have the capacity to pass through animals unchanged. These antibacterials may be released into and then affect the environment in various ways. They may change the microbial population in the soil, and thereby, change the biogeochemical cycles such as herbicide degradation (either increasing or decreasing the degradation rate). They may contribute to the development of antibiotic-resistant microbes in the field or in the waste stream that is subsequently released to a field. Finally, they may become environmental contaminants.

9.2.3. Characteristics of Effluents Used in Some Microirrigation Studies

Biological effluents available for microirrigation of crops may originate from municipal wastewater treatment plants, food industrial discharges, or outflow from livestock confinement areas. The majority of studies to date have investigated use of municipal effluents because these effluents are readily available in large quantities and have already been treated to local wastewater quality control standards. Studies involving irrigation systems have focused primarily on surface and sprinkler systems. Only since the mid-1970s have microirrigation systems received attention. By its nature, microirrigation hardware (an emitter, for example) requires relatively clean effluents to function properly, whereas effluent quality is not as critical for surface and sprinkler irrigation systems.

Early trials of municipal effluents in microirrigation systems occurred in the arid regions of the world. Municipal effluent, following primary treatment and high rate bio-filtration, was used successfully for four years to drip irrigate grapes in Australia (Read et al., 1977). Oron et al. (1979) used trickling filter effluent and clarified high rate algae pond effluent to irrigate cotton with in-line labyrinth type emitters. In a later study, treated effluent from facultative-oxidation ponds was successfully used to microirrigate cotton for one growing season (Oron et al., 1982). Microirrigation studies with food processing effluents were conducted in Hawaii. Effluent from oxidation ponds treating sugarcane processing wastes was mixed with fresh water and pumped into microirrigation systems to irrigate sugarcane. These studies were initiated in 1979 and continued through the 1980s (Bui, 1992). Microirrigation studies with animal confinement runoff were initiated in Kansas during the late 1990s (Trooien et al., 2000). Rain runoff from a beef feedlot received secondary treatment in an anaerobic lagoon before being used in a subsurface drip irrigation system for corn. These early studies have indicated the feasibility and provided initial guidelines for using effluents from a variety of sources for watering crops with microirrigation systems.

A summary of selected effluent characteristics pertinent to microirrigation systems for several types of effluents used in microirrigation research studies is presented in Table 9.1. These characteristics can provide comparative values to serve as a preliminary guide when assessing the feasibility of using biological effluents in microirrigation systems.

9.3. BIOLOGICAL EFFLUENT CONSTITUENT BEHAVIOR IN SOILS

Fertilizer content can be significant when biological effluent is used for irrigation of agricultural crops. Nutrient concentrations vary for the different effluent sources and treatment levels. Supplemental applications of fertilizer may or may not be required depending on the crop and soil material. For example, when treated municipal effluent was applied by microsprinklers to citrus trees in Florida, USA, phosphorus, calcium, and boron were each provided in adequate concentrations to meet plant requirements (Parsons et al., 1995). Application of other nutrients, however, was required to meet crop needs. Treated municipal effluent in Israel contained about 200 kg N/ha in the form of ammonia, which was adequate to supply the needs of the wheat crop, yielding greater than 7000 kg/ha (Oron and DeMalach, 1987b). The value of this nitrogen was estimated to be $195/ha per y.

When irrigating with reclaimed water to meet either crop fertilizer needs or crop water requirements, caution must be exercised so that certain effluent constituents are not applied in excessive amounts. Nitrogen and phosphorus are two fertilizer constituents applied to agricultural crops. Both are typically found in varying degrees in effluents. Trace elements required by crops may also be contained in biological effluent, but some may be in high concentrations that are detrimental to plants. Effluents generally have a higher salt content than the original fresh water and, if not applied correctly, may lead to saline soils and poor crop yield. Pathogenic organisms may be present in effluents and should be of concern when effluents are applied to edible crops.

9.3.1. Nitrogen Uptake by Plants and Potential Loss Mechanisms

All soils that support vegetative cover have a reservoir of nitrogen-containing organic matter, a small proportion of which is continually being mineralized and nitrified by the activity of microorganisms. This nitrogen fraction is removed from the soil by plant uptake, leaching, and denitrification. Effluent irrigation schemes must be designed and managed to maximize nitrogen plant uptake and minimize nitrate losses by leaching. In the absence of significant denitrification, the proportion of mineralized nitrogen absorbed by plants will depend on the plant type, distribution and amount of rainfall or irrigation water application, efficiency of drainage, soil type and fertility, and season. Maximum nitrogen uptake would be expected for a crop having a high nitrogen requirement, where both nitrogen and water are supplied to the soil regularly and in relatively small quantities during periods of vigorous growth. If the vegetative cover is not harvested and removed, the nitrogen taken up by the plants will ultimately be returned to the soil nitrogen reservoir, from which considerable nitrate leaching may occur, particularly during dormant seasons or other periods when precipitation exceeds evapotranspiration. If the amount of rainfall or effluent applied to the land does not raise the soil water content sufficiently to cause rapid drainage from the soil, nitrate originating from the applied effluent tends to remain in the root zone of the vegetative cover. This water retention facilitates nitrogen uptake by the plants, giving a relatively high removal of nitrogen from the biological effluent.

Nitrogen compounds other than nitrate, urea, and nitrite are retained relatively strongly by most soils, and are therefore not lost in significant amounts to percolating water. Nitrate is freely mobile in soils and may be lost (leached) in large amounts in drainage waters. Nitrate leaching represents an economic loss, and high nitrate concentrations can be a health hazard if the water resources are used for domestic supply. The process of nitrification puts all nitrogen compounds in soils at risk for loss by leaching. Nitrification is the conversion by microorganisms of ammonia to nitrate, via nitrite. Aerobic soil conditions are necessary for this conversion; therefore, the soil type and profile, the efficiency of drainage, and the amount of degradable organic material present will affect conversion rates. Nitrification generally occurs rapidly in open-textured, well-drained soils, but may be very slow or absent in heavy, poorly-drained soils. Nitrate leaching, denitrification, and nitrogen uptake by plants all depend on the occurrence of nitrification, or on the existence of aerobic soil conditions suitable for nitrification to occur. Under anaerobic conditions, denitrifying organisms are capable of using nitrate in place of oxygen. In the process, nitrate and nitrite are converted to gaseous nitrogen, which is lost from the soil. Usually, nitrification must have occurred before denitrification is possible.

Excess effluent application can cause leaching of nitrate. Although it is not possible to prevent nitrate leaching under conditions of high rainfall, effluent should not be applied at a rate great enough to cause leaching.

Nitrogen in the ammonia form (NH_3) can volatilize (i.e., it can be lost to the atmosphere as a gas). The gas transfer of ammonia requires considerable contact between the effluent and air; thus, ammonia loss can be enhanced by spraying the effluent through the air with sprinklers or by allowing effluent to remain on the soil surface. Conversely, volatilization losses can be reduced or eliminated by placing the effluent beneath the soil surface such as with SDI. Little research has been performed to measure the ammonia volatilization losses from applied effluent, but such volatilization losses have been measured from applied animal waste slurry. Slurry is similar to effluent but has a higher solids content. If slurry is allowed to remain on the soil surface, NH_3-N volatilization losses as great as 27 kg/ha, representing 48% of the NH_3-N applied in the slurry (Klarenbeek and Bruins, 1991) and 78 kg/ha, representing 40% of the NH_3-N applied (Vlassak et al., 1991) have been measured. Incorporation of the slurry with sprinkler irrigation following the slurry application reduced the NH_3-N volatilization losses to 9 kg/ha (Klarenbeek and Bruins, 1991). Injecting the slurry directly into the soil, similar in principle to irrigating with SDI, reduced NH_3-N volatilization losses to less than 0.5 kg/ha, representing less than 0.5% of the applied NH_3-N (Klarenbeek and Bruins, 1991). In a direct comparison of surface slurry application with hoses and slurry injection at a depth of 50 mm, surface application of slurry resulted in a two-year average volatilization loss of 29 kg N/ha representing 35% of the applied ammonia, whereas injection resulted in loss of 10 kg N/ha, representing 7% of the ammonia applied in the slurry (Rubaek et al., 1996). These published values of volatilization losses may overestimate losses when irrigating with effluent because ammonia volatilization has been shown to vary directly with slurry dry matter content (Moal et al., 1995), but the differences are small at dry matter content less than 4% (Sommer and Olesen, 1991). Ammonia volatilization losses can be expected when applying effluent with surface irrigation methods. Irrigation with SDI may minimize or eliminate those volatilization losses.

9.3.2. Phosphorus Uptake by Plants and Potential Loss Mechanisms

Phosphorus added to the soil from irrigation with biological effluent may be consumed by the crop, accumulated in the soil through sorption and precipitation reactions, or lost from the system via transport in percolating or runoff water or attached to eroding soil particles. The largest fraction of the added phosphorus is removed with the crop or by reaction with the soil. Plants have specific phosphorus requirements that depend on their species and stage of growth. Phosphorus stimulates early crop growth and root formation. It also hastens maturity and promotes seed production. Generally, nitrogen and phosphorus work in a synergistic fashion; as nitrogen uptake by plants increases, so does phosphorus uptake.

When applied to soils, inorganic forms of phosphorus combine chemically to form compounds of limited solubility. In neutral to alkaline soils, calcium phosphate is formed, whereas in acid soils, iron and aluminum phosphates are produced. Available soil phosphorus is typically less than one percent of the amount present. Solubility of phosphate is controlled primarily by its concentration in the soil solution. As plant roots extract the soluble phosphate, it is replaced from the solid-phase phosphorus in contact with the soil solution. Other factors affecting the availability of inorganic phosphorus are soil microorganisms, soil temperature, and soil pH. Through their metabolism, microorganisms convert inorganic phosphorus into organic acids and cell material. The speed of chemical and biological reactions generally increases with increasing temperatures; however, the overall net increase or decrease of soluble phosphate depends on a number of site conditions. For most soils, phosphorus availability is highest in the pH range 6.0 to 7.5 (Follett et al., 1981).

In many cases, the majority of phosphorus loss is due to attachment to eroding soil particles because of the strong sorption of inorganic forms to soil particles and the application of the phosphorus to the soil surface. Under some conditions, however, environmentally significant amounts of phosphorus can be leached in drainage water (Sims et al., 1998). Phosphorus is more mobile in soils that are anaerobic or that contain very large amounts of organic material. For example, the phosphorus concentration in water percolating through such soils may be as high as 1 mg/L (Papadopoulos and Stylianou, 1991). Phosphorus concentrations in waters that have percolated through agricultural soils under aerobic conditions, and which do not carry significant amounts of soil particulates, are usually 0.05-0.2 mg/L (Papadopoulos and Stylianou, 1991). Most significantly, these phosphorus leaching losses can be exacerbated by the use of biological effluent because the organic phosphorus often contained in the effluent is more mobile than inorganic phosphorus (Lucero et al., 1995). Reduction or elimination of leaching, therefore limits leaching loss of phosphorus.

Biological effluents from animal sources are regulated in the USA based on phosphorus. Each State may adopt its own animal effluent regulations, but many have already adopted the US-EPA regulations. The EPA regulations restrict or disallow effluent application when the phosphorus concentration in the surface soil layer exceeds a target value.

9.3.3. Trace Element Uptake by Plants and Potential Loss Mechanisms

Biological effluent can be a good source of micronutrients required for plant growth. For example, boron, iron, manganese, selenium, and zinc are essential for plant growth. At high concentrations, however, these elements are toxic to certain plants. There are also some elements (e.g., cadmium, mercury, and lead) that have no known physiological function and are considered biologically harmful to plants (Pettygrove and Asano, 1985). Because trace elements are found in various effluents, they should be analyzed before use for potentially harmful and beneficial constituents. Once in the soil, trace elements accumulate and in most cases they are difficult to remove. Trace elements can accumulate to harmful concentrations, which leads to (1) toxicity to plants grown on the affected soils, (2) absorption by crops, resulting in trace element levels in the plant tissue considered harmful to the health of humans or animals who consume the crops, and (3) transport from soils to underground or surface water, thereby rendering the water unfit for its intended use (Page and Chang, 1985). Maximum trace element concentration recommendations (Tab. 9.2) are based on plant toxicity in most cases. Notable exceptions are molybdenum and selenium. Selenium, in particular, has been found to be less toxic to some plants than was previously indicated by the original research that based recommendations on plant response to selenium in nutrient solutions. For example, coffee showed no decrease of plant growth (mass) in solutions with Se concentrations at 7.9 mg Se/L or less; plant growth was reduced at 79 mg Se/L (Mazzafera, 1998). In addition, white clover yield was not decreased at Se concentrations of 4 mg/L when applied as selenate or 2 mg/L when applied as selenite (Smith and Watkinson, 1984). The other element exception, molybdenum, is not toxic to plants at concentrations usually found in soils and waters, but molybdenum can become toxic to animals that consume plants grown on soils with high levels of available molybdenum. The recommendation is based on the potential toxicity to animals (National Academy of Sciences, 1972).

Trace elements contained in suspended solids usually filter out in the soil matrix near the soil surface and combine with other soil constituents. Soluble trace elements commonly found in filtered effluent usually are not removed due to cost, but can be removed from solution by chemical reactions such as ion exchange, precipitation, surface adsorption, and organic complexing.

Beneficial trace elements are present in most domestic sewage effluents, whereas most harmful trace elements typically are found in industrial effluents originating from processes used in manufacture of consumer goods. Conventional wastewater treatment systems do not remove trace elements. Knowledge of the waste streams contributing to a treatment facility's effluent is therefore important. For irrigation with other reclaimed wastewaters relatively high in trace elements, it is important to monitor periodically the element concentrations in the soil because the trace elements have the tendency to accumulate with time.

Table 9.2. Recommended maximum concentrations of trace elements in irrigation waters. Adapted from National Academy of Sciences (1972) and Pratt (1972).

Element	Recommended max. concentration (mg/L)	Remarks
Aluminum	5.0	Can cause nonproductivity in acid soils (pH<5.5), but alkaline soils will precipitate the ion and eliminate any toxicity.
Arsenic	0.10	Toxicity to plants varies widely, ranging from 12 mg/L for sudan grass to less than 0.05 mg/L for rice.
Beryllium	0.10	Toxicity to plants varies widely, ranging from 5 mg/L for kale to 0.5 mg/L for bush beans.
Cadmium	0.01	Toxic to beans, beets, and turnips at concentrations as low as 0.1 mg/L in nutrient solutions. Conservative limits recommended because of its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Chromium	0.1	Not generally recognized as an essential growth element. Conservative limits recommended because of lack of knowledge on toxicity to plants.
Cobalt	0.05	Toxic to tomato plants at 0.1 mg/L in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Copper	0.2	Toxic to many plants at 0.1 to 1.0 mg/L in nutrient solutions.
Fluoride	1.0	Inactivated by neutral and alkaline soils.
Iron	5.0	Nontoxic to plants in aerated soil, but can contribute to soil acidification and reduced availability of essential phosphorus and molybdenum.
Lead	5.0	Can inhibit plant cell growth at very high concentrations.
Lithium	2.5	Tolerated by most crops up to 5 mg/L. Mobile in soil. Toxic to citrus at low levels (>0.075 mg/L). Acts similar to boron.
Manganese	0.2	Toxic to a number of crops at a few tenths mg to a few mg/L, but usually only in acid soils.
Molybdenum	0.01	Nontoxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high levels.
Nickel	0.2	Toxic to a number of plants at 0.5 to 1.0 mg/L. Reduced toxicity at neutral or alkaline pH.
Selenium	0.02	Toxic [in nutrient solutions] to plants at concentrations as low as 0.025 mg/L; toxic to livestock if forage is grown in soils with relatively high levels of selenium. Elevated levels cause birth defects in wildlife.
Tin, Titanium, Tungsten		Effectively excluded by plants. Specific tolerance unknown.
Vanadium	0.1	Toxic to many plants at relatively low concentrations.
Zinc	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH>6 and in fine textured or organic soils.

9.3.4. Salinity Management

Although salinity effects are addressed in detail in Chapter 4, a brief discussion of salinity related to irrigation with effluent is warranted here. As is the case with trace elements, salt concentration in water typically increases with each water use, and is not reduced with wastewater treatment. Effluent from a wastewater treatment plant typically has higher salinity content than fresh water. In areas where evapotranspiration exceeds precipitation and irrigation is critical for crop production, reduction in soil water content by evapotranspiration concentrates the salt in the soil solution. If dormant season rainfall is low, these accumulated salts must be leached from the root soil profile through application of effluent or other irrigation water in excess of that required to meet evapotranspiration.

Plant toxicity may also occur when a specific ion is taken up by a plant and accumulates in amounts that result in tissue damage or reduced yield. The ions of most concern in biological effluent are sodium, chloride, and boron. These elements are present in domestic sewage and originate from household detergents and water softeners. Maximum plant damage occurs when these ions concentrate on plant foliage. Thus, microsprinklers are not recommended for irrigating biological effluent on sensitive plants. Drip emitters placed on the soil surface or buried in the root zone avoid this problem.

Sodium ions may also lower the hydraulic conductivity of soils with high clay content. When septic tank effluent with high sodium concentration was applied to soil that was pedogenically low in sodium, sodium accumulated in areas around the emitters (Jnad et al., 2001b). The dispersion and resulting decrease of soil hydraulic conductivity caused increased pressure around the emitters and decreased flowrates from the emitters (Shani et al., 1996). Application of calcium may be required to prevent soil hydraulic deterioration in such cases. Calcium, magnesium, and total salts did not accumulate in the soil profile over a five-year period (Jnad et al., 2001a).

9.3.5. Pathogenic Organisms

Local and state health departments regulate the use of biological effluent for irrigation. Although water shortages in various regions of the world necessitate water recycling, health concerns mandate regulations on effluent use. The primary health hazards of effluent used for irrigation are pathogenic bacteria and viruses. Prior to irrigation with effluent from human sources such as municipal wastewater, disinfection treatment such as chlorination is practiced to control pathogens and prevent nuisances such as odors during seasonal wastewater storage and field application.

Microirrigation equipment is especially well suited for applying sewage effluents with minimal health risk. Subsurface drip irrigation leaves the soil surface dry, reducing the potential for transfer of bacteria to people. However, high soil water content resulting from frequent irrigations lead to a greater survival time for enteric bacteria in soils (Gerba et al., 1975) so bacteria may accumulate deeper in the soil profile. Sunlight has been shown to reduce bacterial survival (Gerba et al., 1975), so surface placement of drip emitters may have the advantage of reducing bacteria by exposure to ultraviolet light. Using either subsurface or surface drip irrigation with treated municipal wastewater resulted in less viral and bacterial contamination of sweet corn, compared with sprinkler irrigation (Oron et al., 1991, 1992). Subsurface drip irrigation resulted in relatively high bacterial concentrations near the dripline at a depth of 0.25 m. Because of this, applying effluent via SDI would not be suitable for irrigating subsurface crops such as potatoes.

Viruses can also accumulate in the soil when effluent is applied with subsurface drip irrigation (Oron, 1996). Tests were conducted with both potable water and effluent that were enriched with high levels (1,000 to 10,000 PFU/mL) of poliovirus. All treatments resulted in virus-contaminated soil except for the first sampling period when high soil temperatures (30°C) may have hindered virus survival. Some virus contamination was detected in the leaves, indicating some virus uptake by the plant roots. No poliovirus was found in the fruit of the tomato plants when irrigating with either the enriched potable water or enriched wastewater. This experiment applied very high virus concentrations of 1,000 to 10,000 PFU/mL. More normal concentrations might be 0.1 PFU/mL; even epidemic concentrations are only about 10 PFU/mL (Oron, 1996).

9.4. HEALTH CONSIDERATIONS

Pathogen transfer hazards from biological effluents and their harmful effects on humans have been recognized as health issues for about a century, since it was found that eating raw vegetables grown on soil fertilized with raw sewage resulted in outbreaks of typhoid fever (Gerba et al., 1975).

When irrigating with effluent, laws and regulations may require additional compliance measures by the irrigator. The regulations usually are written to prevent adverse health effects in humans but some also address environmental impacts. Before irrigating with biological effluent, consult with local, state, or national authorities to obtain complete information on regulations governing the application process. This discussion of regulations is presented only to provide a very brief overview of some regulatory requirements for irrigation effluent quality and should not be considered complete.

Various crops present differing health hazards based on criteria including the uses of the crops, the time elapsed between harvest (or last irrigation) and consumption, and the extent of processing following harvest. Crops that will be consumed by humans without cooking, peeling, or other processing pose the greatest hazard to human health. Also, areas of landscape irrigation to which humans are frequently exposed, such as parks and lawns, pose a relatively high hazard of pathogen transfer to humans. These crops are sometimes called “unrestricted crops” or “unrestricted irrigation crops.” Conversely, crops that are not ingested by humans such as trees and fiber crops pose less risk because of lower probability of pathogen transfer to humans. The discussion presented in the remainder of Section 9.4 addresses the regulation of municipal effluents used for irrigation.

9.4.1. Typical Regulations

Three examples of regulations will be presented covering regulations for the state of California, USA, criteria for Israel, and criteria advanced by the World Health Organization (WHO).

In the USA, effluent irrigation is regulated by states or municipalities. In California, for effluent applied to landscapes such as golf courses, cemeteries, and freeway medians, the seven-day median number of coliforms may not exceed 23 per 100 mL and the number of coliforms may not exceed 240 per 100 mL in two consecutive samples (State of California, 1978). Effluent used for surface irrigation of food crops must have a seven-day median number of coliforms not exceeding 2.2 per 100 mL. When effluent is applied to food crops via sprinkler irrigation or when applied to landscapes such as parks or playgrounds, the same seven-day median of 2.2 coliforms per 100 mL applies, but the maximum number of coliforms must not exceed 23 per 100 mL in more than one sample in any 30-day period.

In Israel, microbiological criteria for irrigation with effluent are based on coliform counts (Tab. 9.3). When irrigating vegetables that will be peeled and cooked or when irrigating green belts, for example, coliform counts must not exceed 250 per 100 mL. For irrigation of unrestricted crops (e.g., vegetables to be eaten raw, parks, and lawns), coliform counts must not exceed 12 per 100 mL in 80% of the samples and must not exceed 2.2 per 100 mL in one-half of the samples.

Table 9.3. Microbiological quality guidelines from WHO and criteria for irrigation with biological effluent in California, USA and Israel. California and WHO summarized from Asano and Levine (1996), Israel from Shelef (1991).

Entity	Conditions/Crops	Intestinal nematodes †	Fecal or total coliforms
California	Spray and surface irrigation of food crops, high exposure landscape irrigation such as parks.	No standard recommended	< 2.2/100 mL ‡
California	Irrigation of pasture for milking animals, landscape impoundment.	No standard recommended	< 23/100 mL ‡
WHO	Irrigation of crops likely to be eaten uncooked, sports fields, public parks.	< 1 per L	< 1000/ 100 mL
WHO	Landscape irrigation where there is public access, such as hotels.	< 1 per L	< 200/100 mL
WHO	Irrigation of cereal crops, industrial crops, fodder crops, pasture, and trees.	< 1 per L	No standard recommended
Israel	Group C. Deciduous fruits §, conserved vegetables, cooked and peeled vegetables, green belts, sports fields, and golf courses.	No standard recommended	250 / 100 mL
Israel	Group D. Unrestricted crops, including vegetables eaten uncooked (raw), parks, and lawns.	No standard recommended	12 / 100 mL (80%) 2.2 / 100 mL (50%)

† Intestinal nematode concentrations are expressed as arithmetic mean number of eggs per liter during the irrigation period.
‡ Median number of coliforms per 100 mL, as determined from the bacteriological results of the last seven days for which analyses have been completed.
§ Irrigation must stop two weeks before picking; no fruit should be picked from the ground.

The guidelines proposed by the WHO represent a shift of hazard focus from coliform bacteria to intestinal nematodes (Mara and Cairncross, 1989). For example, the maximum concentration of fecal coliforms was raised to a geometric mean of 1000 per 100 mL for crops likely to be eaten uncooked (Table 9.3). For landscape irrigation where there is public access, the maximum coliform concentration should not exceed 200 per 100 mL. At the same time, the standard for intestinal nematode eggs was tightened to <1 viable egg per liter for unrestricted or restricted irrigation (e.g., trees, forages, and industrial crops).

This relaxation of the coliform standards has not been without controversy. Shelef (1991) raised objections concerning the epidemiological evidence presented, issues with health risk assessment methods used, inattention to bacterial survival, lack of consideration of farming practices such as wetting harvested fresh produce prior to delivery to market, and others.

9.4.2. Practices to Meet the Regulations

Crop selection is one of the management choices available to growers to comply with effluent irrigation quality criteria or regulations. Effluent quality must meet much higher standards for application to crops in the unrestricted category. Even when the effluent available to an irrigator does not meet quality criteria for irrigation of unrestricted crops, the effluent may still be appropriate for application to crops such as trees or industrial crops.

In California, secondary treatment and disinfection are used to meet the coliform standards of 23 per 100 mL (Asano and Levine, 1996). Meeting the coliform requirement of 2.2 per 100 mL requires tertiary treatment (secondary treatment plus filtration and chlorination). Chlorination is the usual disinfection method. Asano and Levine (1996) also stated that “virtually pathogen-free effluents” (i.e., free from bacteria and viruses) could be produced with tertiary treatment and extended chlorination.

Treatment practices to meet the WHO guidelines usually include stabilization ponds. Retention time of about 11 days is required to get adequate nematode egg removal (Mara and Cairncross, 1989). Retention time must be doubled to achieve the coliform concentration guideline. Secondary treatment followed by disinfection is required to meet the nematode and coliform criteria for landscape irrigation where there is public access (Asano and Levine, 1996).

9.5. SITE CONSIDERATIONS

Perhaps the most important factor to consider when using effluent for irrigation of agricultural lands is its availability in both time and place. Ideally, the effluent should be available according to the water needs of the crop. If the enterprise that manufactures the effluent relies solely on its disposal through irrigation of annual crops, discharge is restricted only to the growing season, and storage will be required for the non-irrigated period ranging from about three months in moderate climates to seven months or longer in colder climates. The distance and elevation of the effluent collection site relative to the agricultural land are important when determining the economic feasibility of using the effluent for irrigation purposes, due to the pumping cost. Ideally, agricultural lands receiving effluent should be located close to the effluent source and at a similar elevation.

From a farmer's perspective, the primary objective in irrigating crops is to maximize yield or maximize profit. Effluent use can meet either irrigation objective, with a possible added benefit of providing a portion of the plant's nutrient requirement. From the effluent producer's perspective, the objective in using effluent for irrigation purposes is primarily for the additional treatment it receives and its ultimate disposal. For treatment to be successful, the effluent must enter and be retained in intimate contact with the soil long enough to permit retention, uptake, and degradation of undesirable constituents. Thus, the ideal site for microirrigation of effluents must have appropriate soils, climate, and vegetation. The soil properties are perhaps the most important single site factor, but suitable soil properties do not usually exist unless the other site characteristics are also satisfactory.

9.5.1. Soils

The following soil conditions are necessary for successful microirrigation treatment of effluents:

- sufficient infiltration and/or soil water redistribution capacity to accommodate the microirrigated effluent under the expected range of operating conditions with minimal ponding and surface runoff
- soil profile permeable enough to permit vertical drainage and maintain aerobic soil conditions, yet capable of retaining water long enough to allow interaction of the waste constituents with the soil minerals, plants, and organisms
- sufficient exchange capacity to temporarily hold effluent constituents for use by plants and soil organisms and minimize migration of these constituents to groundwaters, especially during periods of slow biological activity
- sufficient soil thickness to provide adequate purification of the effluent.

It is important that the site has favorable characteristics for water movement within the soil. Basic properties of structure, texture, and porosity are critical for maintaining an aerobic soil environment. Cropped soils, however, often have reduced permeability, as fibrous organic matter is lost, aggregates are weakened, and soils are compacted by machinery. Once compacted, the soil may become overloaded with soluble organic matter from the effluent. Anaerobic conditions then develop, the types of microorganisms change, and the breakdown of effluent is retarded. For similar reasons, the agricultural field must also be sufficiently well drained to prevent water accumulation and waterlogging of the soil.

9.5.2. Climate

There are two main climatic features affecting effluent application, namely precipitation and temperature. In drier regions, the water component of irrigated effluents gives the greatest return in plant growth. The greatest benefit in wetter areas may be the nutrients. The majority of the world's agricultural regions are in temperate climates, where effluent organic matter is easily broken down by soil organisms. Typically, evapotranspiration for these areas is relatively high and the organic content supplied by the effluent is readily assimilated. In cooler regions, the organic content in the soil must be monitored so that carbon buildup does not lead to depletion of oxygen and an anaerobic plant root environment, which can be detrimental to the plant.

9.5.3. Crops

As discussed in section 9.2.2, the concentrations and types of dissolved constituents in effluents determine their suitability as irrigation water. The effects of these constituents on soil chemistry and on plants and plant products must be considered. Effluents are generally of lower quality than the original source water. As a result, microirrigation with effluent requires better management than with water from traditional sources. Some of the problems associated with effluent irrigation are the result of its use as a disposal operation rather than an irrigation operation (Tanji, 1997). Under excess irrigation, high soil water content conditions prevail. This can reduce soil aeration and result in poor plant growth and plant disease problems.

Adequate nutrient levels must be maintained for proper plant growth. Effluents may satisfy all or part of the plant nutrient requirements. However, effluents may also add excess plant nutrients. Nitrogen is an important nutrient that can also build up to excessive levels in some plants. For example, excess nitrogen in cereal crops can cause the plants to lodge. The nutrients available in effluents are beneficial in that they reduce the need for commercial fertilizers. However, they can be detrimental if not properly managed.

The previous section on health considerations suggests the types of agricultural crops that may be suitable for irrigation with effluent. Presently, health regulations generally refer to surface and sprinkler irrigation of effluents, with few guidelines specifically for microirrigation systems. Because microirrigation systems have the capability of applying effluent precisely and with little environmental contamination, the crops categorized in the previous section would also be suitable for microirrigation. Additional crops may also be approved for microirrigation application, once data indicate minimal health risks.

Only in recent years has there been interest in developing appropriate hardware and practices for effluent use in microirrigation. One early Israeli study focused on municipal effluent irrigation of wheat (Oron et al., 1986). Subsurface drip irrigation produced higher yields than sprinkler irrigation. By increasing the length of the irrigation season (resulting in higher applications of effluent) yields were higher yet. Oron and DeMalach (1987a) examined response of microirrigated cotton to treated domestic wastewater applied at different frequencies and emitter spacings. Maximum yield was obtained under twin row planting, irrigated twice a week at amounts equivalent to the evapotranspiration requirement. Yields were lower when irrigating only once a week with the effluent. Neilsen et al. (1989) in Canada used microirrigation with either well water or secondary effluent to irrigate tomato, sweet pepper, onion, cucumber, bush bean, and melon. Over their four-year study, yields with effluent irrigation were greater than or similar to yields with well water. Papadopoulos and Stylianou (1991) reported a three year study in Cyprus with a microirrigation system for applying municipal wastewater to sunflowers grown for edible seed. Their results indicated that, with treated wastewater, less nitrogen and no phosphorus fertilizers were needed by the sunflowers for high yield of good quality. Bastos and Mara (1995) used field and glasshouse trials for examining bacterial contamination of lettuce and radishes microirrigated with oxidation pond effluent. Their study, conducted in England, indicated that the *E. coli* bacterial count for their produce grown with the effluent was similar to that for crops grown using conventional practices. For citrus in Florida, USA, disposal-rate application of 2500 mm per year of biological effluent (secondary treated municipal effluent) resulted in increased tree growth and fruit production (Parsons et al., 2001). The total production of soluble solids per land area was also increased even though the concentration of soluble solids was usually reduced. While the effluent was not considered an important source of nutrition for most elements, it did supply all the calcium, phosphorous, and boron required by the trees (Parsons et al., 1995). With water scarcity in many regions of the world, interest in effluent resources will increase. Continuing research with a variety of crops will provide useful guidelines for use of effluents in microirrigation systems.

9.5.4. Land Area

The land area required to efficiently use any biological effluent for irrigation depends on the crop, climate, and effluent composition. The crop can influence the relative amounts of water or nutrients used, and therefore, how much can be applied in effluent. The climate will dictate how much water is required to meet crop water needs, and therefore, how much effluent can be applied. Effluent composition can vary depending on source, degree of treatment, and may also vary with time. Any of a number of effluent constituents can be the factor that limits the amount of effluent applied to a land area, but most often the limiting factor is water, nitrogen, or phosphorus. Examples 9.1 through 9.3 illustrate how these three different constituents can be the limiting factor under the same conditions but for different effluent sources and compositions.

Example 9.1

A grower plans to use secondary-treated municipal effluent to irrigate maize (Zea mays L.) for animal feed. The phosphorus concentration in the effluent is 7 mg/L and the total nitrogen concentration is 50 mg/L. The grower estimates 450 mm of effluent plus the average rainfall for the area will be needed to meet the annual water requirement for the maize. Similarly, the grower estimates the crop will require 45 kg P/ha annually, requiring 640 mm of effluent at the stated P concentration. Finally, the grower estimates the crop will need 340 kg N/ha, requiring 680 mm of effluent at the stated N concentration. Thus, the water requirement of the crop is met before the requirements of either phosphorus or nitrogen.

Example 9.2

A grower plans to use biological effluent from a beef cattle feedlot to irrigate maize (Zea mays L.) for animal feed. The phosphorus concentration in the effluent is 35 mg/L and the total nitrogen concentration is 120 mg/L. The grower estimates 450 mm of effluent plus the average rainfall for the area will be needed to meet the annual water requirement for the maize. Similarly, the grower estimates the crop will require 45 kg P/ha annually, requiring 130 mm of effluent at the stated P concentration. Finally, the grower estimates the crop will need 340 kg N/ha, requiring 280 mm of effluent at the stated N concentration. Thus, the phosphorus requirement of the crop is met before the requirements of either water or nitrogen.

Example 9.3

A grower plans to use biological effluent from a swine operation to irrigate maize (Zea mays L.) for animal feed. The phosphorus concentration in the effluent is 20 mg/L and the total nitrogen concentration is 400 mg/L. The grower estimates 450 mm of effluent plus the average rainfall for the area will be needed to meet the annual water requirement for the maize. Similarly, the grower estimates the crop will require 45 kg P/ha annually, requiring 225 mm of effluent at the stated P concentration. Finally, the grower estimates the crop will need 340 kg N/ha, requiring 85 mm of effluent at the stated N concentration. Thus, the nitrogen requirement of the crop is met before the requirements of either water or phosphorus.

Microirrigation can be a very uniform method of water application. Agricultural producers that have converted from other irrigation system types often state that they apply less water to their crops to generate the same or greater yields. Because of this uniformity and apparent efficiency of microirrigation, the land area required for efficient use of effluent with microirrigation systems may be greater than the land area required with other irrigation system types when excess water is the factor that limits effluent application. Greater land area may also be required for SDI systems if nitrogen is the factor that limits effluent application because above-ground irrigation systems allow ammonia volatilization losses from the effluent.

9.6. DESIGN AND MANAGEMENT CONSIDERATIONS

The greatest challenge for both irrigation system design and management, when applying biological effluents through microirrigation systems, is preventing emitter clogging to keep the system operating as designed. Because of their generally higher salt, nutrient, solids, and biological concentrations, effluents present increased hazards for clogging. This challenge of clogging prevention requires meeting these five criteria:

- selecting and installing the proper system components
- filtering the effluent properly and effectively
- effectively suppressing biological growth and chemical precipitation in the effluent
- flushing the materials that may accumulate in the distribution system
- monitoring system performance to assure that partial clogging can be treated before it becomes catastrophic.

9.6.1. System Components

In microirrigation design, using emitters with small flowrates is advantageous because zone sizes can be larger and less control hardware is required. However, biological effluents have greater potential for emitter clogging than do fresh surface or ground water. Within a single type, emitters with smaller flowrates are more susceptible to clogging even though neither emitter type nor emitter flowrate can be used individually to accurately assess clogging potential (Ravina et al., 1992). There also are differences of clogging susceptibility among different emitter types that are not directly correlated with emitter flowrate (Ravina et al., 1992). They presented a table of specific emitters (products) and compared their degree of clogging during a test. Of the 12 emitters tested, three were orifice-type emitters and two were labyrinth-type emitters. Two of the orifice-type emitters were ranked among the three emitters most vulnerable to clogging. The remaining orifice-type emitter was ranked as moderately vulnerable to clogging. Of the nine tested labyrinth type emitters, five were ranked as moderately vulnerable and three were ranked as least vulnerable to clogging. The three emitters ranked as least vulnerable were emitters integrated into the tube. Of these, one emitter was pressure-regulated and two were non-regulated. Adin and Sacks (1991) noted several emitter design features that could be implemented to reduce clogging potential. They included: shorten and widen the flow path, flowrate considerations; round the straight edges on the protruding teeth in the flow path; remove dead areas in the flow path; design the orifice entrance to act as a barrier to prevent large particles from entering the emitter flow path; and place seams away from the flow path or remove seams from the emitter.

Thin-walled collapsible emitting hose, sometimes referred to as drip tape, can be appropriate for use when applying effluents with low TSS such as activated sludge secondary treated effluent (Hills and Brenes, 2001). They tested products with flowrates between 0.9 and 1.4 L/h-emitter and of three different manufacturing methods, using two products manufactured by indentation and one each by attachment and molding. The two emitters manufactured by indentation were not acceptable for use with effluent. The indentation process of emitter manufacturing changed the physical characteristics of the plastic, resulting in increased variability among emitters after two months of use with effluent. The emitters formed by indentation were also more susceptible to changes of plastic elasticity because the manufacturing process reduced the thickness of the plastic forming the flow channel. The products manufactured by attachment and molding performed well. They did not clog and their emission variability did not increase with use during the two months of testing (Fig. 9.1). Biological effluent was pumped from a secondary clarifier, sodium hypochlorite was injected continuously at the rate of 3.7 mg/L to obtain a target free chlorine concentration of 0.4 mg/L, and the effluent was passed through a media filter of silica sand no. 20 and 105 μm screen filter. The system was operated continuously.

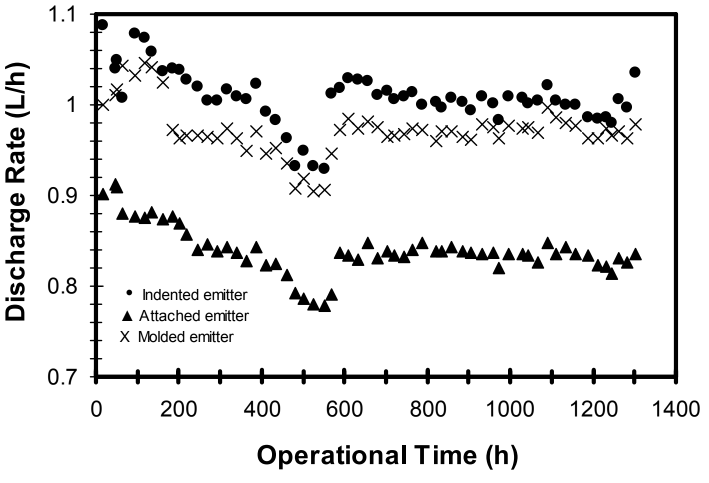

Figure 9.1. Decrease of flowrate for three emitter types. After Hills and Brenes (2001).

Five different emitters of varying sizes and flowrates were tested with beef feedlot runoff wastewater pumped directly from a storage lagoon (Trooien et al., 2000). By the end of the second year of operation, the flowrate of entire plots was reduced by 22% using 0.57 L/h emitters and reduced by 14% for 0.91 L/h emitters. These smallest emitters tested were manufactured by indentation. When using emitters of 1.5, 2.3, and 3.5 L/h, the flowrates were reduced by less than 5%. The emitters with flowrates of 1.5 and 2.3 L/h were manufactured by attachment. These results suggest that the smaller emitters manufactured by indentation are more prone to clogging when using wastewater and may be risky for use with wastewater. The management program included disk filtration (200 mesh, openings of 55 μm), periodic and simultaneous injection of acid to reduce wastewater pH to a target of about 6.5, chlorine, and dripline flushing at approximately two-week intervals. More aggressive management and wastewater treatment methods were not tested, but may be useful for maintaining the flowrates. Testing in subsequent years resulted in further clogging in the smallest emitters and partial clogging in the largest emitters in the test (Fig. 9.2). The flowrates of the pressure-compensated 3.5 L/h emitters had decreased by 13% by the end of the fourth season of operation (Lamm et al., 2002). Aggressive flushing at the termination of the project did not improve flowrates in these compensated emitters. The decrease of flowrate and lack of recovery after aggressive flushing might indicate that particles are becoming stuck in the elastic membrane used in pressure compensation. The aggressive flushing did result in flowrate recovery in the smallest emitters. The flowrate recovered to 80% of the original flowrate (up from a minimum of 62%) for the 0.57 L/h emitters and to 97% of the original flowrate (up from a minimum of 71%) for the 0.91 L/h emitters. Following the fourth and final season of this project, dripline sections from the lower 30 m of the 137 m long plots were excavated. Flowrates from individual emitters in 8-m sections were measured in the laboratory, including 69 of the 0.57 L/h emitters. Three of the tested emitters were completely clogged and 54 others showed partial clogging. Flowrates of the 1.5 L/h emitters that were laboratory-tested showed little evidence of clogging (Lamm et al., 2002).

9.6.2. Filtration Requirements

Physical clogging by inorganic particles in effluent begins at the distal ends of the driplines (Ravina et al., 1992) where flow velocities are reduced (Shannon et al., 1982). As the flowrate within the dripline decreases, the flow velocity also decreases to a speed that no longer keeps particles in suspension. The solids then accumulate into discrete piles on the bottom of the dripline. These piles slowly migrate downstream within the dripline as the upstream face erodes and deposits on the downstream face (Shannon et al., 1982). Still farther downstream, the sediment accumulates into a continuous deposit on the bottom of the dripline. The sediment deposition within the 120-m driplines began at about 61 m and increased steadily until about 110 m, then decreased in the last 10 m (Shannon et al., 1982). A model was subsequently developed to predict the spatial and temporal accumulation of sediment in driplines based on pipe diameter, flowrate, and concentration, particle density, and particle size distribution of the sediment (James and King, 1984).

Sand media filtration is often considered the standard for filtration protection of microirrigation systems. Testing showed that media filtration with uniform bed mean particle size of 1 mm provided the best protection, followed closely by disk filtration of 140 mesh (Ravina et al., 1997). Screen filtration at 155 to 200 mesh was not as effective in protecting downstream elements. If media filters become clogged with bacterial growth, chlorination with sodium hypochlorite at the rate of 150 mg/L for three hours improved flow associated with clogging (Hills and Brenes, 2001).

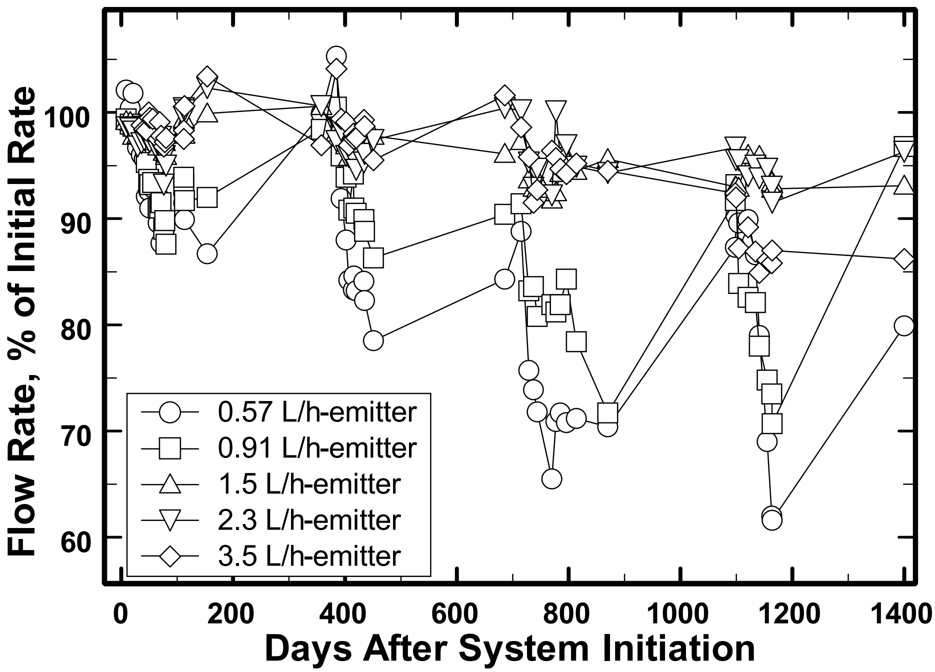

Figure 9.2. Decrease of flow rates during four seasons of operation of SDI system with biological effluent from beef feedyard. After Lamm et al. (2002).

A common procedure prior to installation of systems for utilization of livestock wastewater is a direct test of the wastewater, measuring the time required to clog a small filter with the same media or opening size that will be used in the final installed irrigation system. This method gives a direct measurement for the conditions present at the time of the test, but temporal variations of livestock wastewater characteristics can be considerable. Similarly, an in situ screen filter test and "dirtiness index" to rank the filtration requirements has been developed (van Niekerk, 1995). The measurement method was based on flow volume through a small screen filter within pressure drop parameters. The initial pressure was 50 kPa.

When using secondary treated municipal effluent, filtration with 80 mesh (openings of 180 μm), daily chlorination, and bimonthly lateral flushing were adequate to maintain clean emitters and reliable long-term system operation (Ravina et al., 1992). Disk filtration at 80 mesh was found to be slightly better than screen filtration for removal of total chemical oxygen demand (Oron et al., 1980).

Always consult the dripline manufacturer's specifications for the necessary filtration requirements.

9.6.3. Chemical Treatment Requirements

When irrigating with biological effluent, emitters can be clogged by a mixture of organic and inorganic particles (Ravina et al., 1995). Bacterial slimes initiate the clogging process. Suspended inorganic particles adhere to the slimes and cause the physical clogging (Adin and Sacks, 1991). Other emitter-clogging agents that have been identified include sulfur bacteria and colonial protozoa (Sagi et al., 1995) and protozoa (Ravina et al., 1992).

Filtration alone is not adequate in preventing algal and bacterial growth that clogs emitters (Tajrishy et al., 1994). Chlorination is the most common method for preventing biomass accumulation and maintaining adequate flowrates in emitters of SDI systems when using treated municipal wastewater. Chlorination is most efficient when performed before emitter clogging is extensive (Ravina et al., 1992).

All microirrigation emitters require adequate protection to prevent clogging, but use of biological effluent mandates even greater protection and caution to prevent clogging. Even though emitters of self-cleaning designs did not clog due to inorganic impurities as large as about 400 μm, organic impurities such as algae up to about 150 μm were conducive to bacterial growth that could clog the emitters (Hills and El-Ebaby, 1990). Such bacterial growth required periodic control with acid or chlorine injection. The clogging rate is often affected by the particle sizes more than by the particle-number density (Adin and Sacks, 1991).

Control of biological growth in nutrient-rich biological effluents can be a challenge, especially when the effluent has a high ammonia concentration. Chlorine reacts with ammonia to form chloramines (Chapter 11 and Feigin et al., 1991). Chloramines are up to 80 times less effective than the hypochlorite form for biological control.

Two management methods exist for injecting chlorine into microirrigation systems: continuous and intermittent (or "shock" treatment). Intermittent chlorination with free residual chlorine at 2 mg/L was equally effective as continuous chlorination at 0.4 mg/L (Tajrishy et al., 1994). Intermittent chlorination with 1 mg/L free residual chlorine and filtration with number 20 sand media were adequate to maintain good uniformity with turbulent flow emitters (Hills and Tajrishy, 1995). The same result was obtained with 2 mg/L free residual chlorine injected intermittently and 150 mesh (100 μm openings) screen filtration.

Methods other than chlorination have been tested for effectiveness of control of biological growth. Ultraviolet disinfection without chlorination required filtration of all particles greater than 40 μm to prevent emitter clogging (Hills and Tajrishy, 1995). Chlorine dioxide was at least as good as chlorine at controlling bacteria and was better at controlling virus growth (Narkis and Kott, 1992).

Biological growth within driplines may lead to the formation of biofilms. These biofilms can accumulate and increase the resistance to flow within the dripline. The biofilms include the interactions of microorganisms and the polysaccharide slime layer they produce (Picologlou et al., 1980). Increased resistance to flow led to increased pressure loss due to friction along the length of the dripline and decreasing the emission uniformity. Based on measured biofilm thickness, the expected pressure loss due to flow area constriction accounted for only 10% of the measured pressure loss (Picologlou et al., 1980). An unquantified portion of the friction was attributed to the oscillation of filaments attached to the biofilm at the tube wall. The remainder of the friction loss was attributed to increased roughness at the tube wall. Frictional resistance of the biofilm was similar to that of a hydraulically rough surface. That is, resistance showed a similar dependence on Reynolds number, was dependent on biofilm thickness, and did not increase above that of a smooth pipe until a critical biofilm thickness threshold was reached. The thickness threshold was approximately equal to the thickness of the viscous (laminar) sublayer of flowing liquid at the pipe wall. The frictional effects of the biofilm were considered analogous to equivalent sand grain size roughness of the same order of magnitude as the biofilm thickness.

Biofilms can be difficult to control with chlorination because of the protective and shielding nature of the biofilm. The chlorine concentration within the biofilm may be 20% or less of the concentration of chlorine in the liquid (DeBeer et al., 1994). To prevent biofilm formation and attachment, the driplines or emitters themselves may be treated to inhibit biological growth. Diiodomethyl-p-tolyl sulfone has been incorporated in the interior walls of driplines of products available from one company. Another company impregnates emitters with a biocide in their driplines marketed for use with biological effluent.

Although biological growth is the more immediate concern, chemical clogging of emitters by precipitating salts could be caused by irrigation with biological effluents, especially for surface-installed driplines. Many effluents carry high salt loads so prevention of chemical precipitation may be required. Acid injection to reduce pH from 7.6 to 6.8 was effective in preventing chemical precipitation-induced clogging in saline fresh water (Hills et al., 1989). Salinity issues in microirrigation are covered in detail in Chapter 4 and acid treatment in Chapter 11.

9.6.4. Dripline Flushing

Dripline flushing is required to remove particles and organisms that pass through the filters and accumulate within the driplines (Adin and Sacks, 1991; Ravina et al., 1992). Flushing requirements can be reduced with adequate filtration (Tajrishy et al., 1994). Thin walled collapsible hose should be flushed at least every two weeks to prevent accumulation of materials that may clog the emitters (Hills and Brenes, 2001). Flushing velocity within the dripline should be at least 0.5 m/s to assure that all particles are removed (Hills and Brenes, 2001). In an extreme case, daily flushing was performed when applying dairy lagoon wastewater through an SDI system in its first year of operation (Norum et al., 2001).

9.6.5. Monitoring Procedures

Frequent monitoring of system performance can detect clogging before it becomes catastrophic. Emitter clogging is progressive and continuous rather than a discrete event (Ravina et al., 1992 and Trooien et al., 2000) and partial clogging of emitters is more common than complete clogging (Ravina et al., 1992). Early detection of clogging is important because remediation of partially clogged emitters is more successful than severely clogged emitters (Ravina et al., 1992). Other monitoring and maintenance procedures are presented in Chapters 10 and 11.

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

10. FIELD PERFORMANCE AND EVALUATION

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University of Hawaii, Honolulu, Hawaii, USA
"Water is only as good as its application method and is priceless when it is not available."

JAVIER BARRAGAN
University of Lleida, Lleida, Catalunya, SPAIN
"Save water and protect water quality, the new culture of water."

VINCENT F. BRALTS
Purdue University, West Lafayette, Indiana, USA
"Evaluation and performance are the keys to sustainable irrigation systems."

10.1. INTRODUCTION

A microirrigation system is defined as a localized irrigation system that can deliver water directly into the crop root zone. The system, if properly designed, can eliminate surface runoff and minimize deep percolation. In addition, both high uniformity of water application and high irrigation application efficiency can be achieved. Historically, the development of microirrigation in the late 1960s marked a period of tremendous improvement in irrigation science and technology and resulted in more efficient water use in agricultural production.

Microirrigation will play an even greater role in the future with the increasing significance of limited water resources and the increasing need for environmental protection. The key factors in future agricultural production are microirrigation system operation, irrigation scheduling, crop response, and economic considerations. Microirrigation can be used for all kinds of agricultural production ranging from trees, fruits, vegetables, ornamentals, pastures, and a variety of commodity-type crops.

10.1.1. Uniformity of Water Application

A microirrigation system is designed based on the uniformity of water application with respect to the crops in the field. There are two types of microirrigation uniformity considerations; one is the system uniformity and the other is the spatial uniformity in the field. The system uniformity implies how uniformly the system can distribute water into the field. When a microirrigation system is designed for crops that are widely spaced such as trees, the system uniformity is equivalent to the water application uniformity in the field. For densely planted crops, the emitter spacing should be designed with overlapped wetting patterns and the spatial uniformity will be the basis for design. The uniformity of the microirrigation system depends not only on the hydraulic design, but also the manufacturer's variation, temperature effects, and potential clogging. When using turbulent flow emitters, the temperature effect can be considered as insignificant (Wu and Phene, 1984), and clogging can be controlled at less than 20% even when using biological effluent (Wu et al., 1991). The clogging percentage can be maintained at less than 10% using regular agricultural water for some labyrinth emitters with turbulent flow patterns.

The overall system uniformity as affected by hydraulic design, manufacturer's variation and clogging was evaluated statistically (Bralts et al., 1981a) and verified through computer simulation (Wu et al., 1985). The uniformity of the water application with respect to the crop can be improved (Wu et al., 1988) when a number of emitters are grouped together and considered as a unit, such as several overlapping emitters designed to irrigate a tree or a plant's root system.

In summary, the design parameters affecting the system uniformity are hydraulic design, manufacturer's variation, temperature, clogging, and the number of emitters per plant. The design parameters affecting the spatial uniformity are hydraulic design, manufacturer's variation, temperature, clogging, soil wetting pattern, and emitter spacing.

10.1.2. Order of Significance of Design Parameters

A computer simulation (Wu, 1993a) determined that clogging was the most significant factor affecting the uniformity followed next by emitter grouping. The microirrigation system uniformity can be controlled to a coefficient of variation of 10% when clogging is zero and when two or more emitters are used as a group. Even when clogging is 20%, the system coefficient of variation can still be less than 30% when four or more emitters are grouped together.

A superposition technique (Wu et al., 1989) was proposed to evaluate the spatial uniformity along the lateral by adding soil water patterns from all emitters with various specified spacings. The wetted soil water pattern under a single emitter along a lateral line can be expressed as a hemisphere, and the total infiltration expressed as depth of water along the lateral line can be expressed in a triangular or quasi-triangular pattern depending on the soil water gradient within the wetting pattern. The total infiltration pattern along the lateral line was used to determine the spatial uniformity in the field. A computer simulation was conducted to determine the spatial uniformity expressed by a uniformity coefficient along a lateral line for various hydraulic designs, manufacturer's variations, soil infiltration patterns, clogging percentages, and clogging patterns (Wu et al., 1989). The simulation results showed that clogging is also the most significant factor affecting spatial uniformity, followed by emitter spacing. However, when emitter spacing is sufficient for overlapping soil water patterns, both the soil water wetting patterns and the clogging distributions were not significant factors. When the hydraulic design of a microirrigation system allows for 20% emitter flow variation, which is equivalent to 6% coefficient of variation (CV_H) of emitter flow and a manufacturer's variation of less than 10% (CV_M), uniformity coefficients of 90% and 70% (10% and 30% coefficient of variation) can be achieved for 0 and 20% clogging, respectively, as long as the emitter spacing is designed for 0.5 of the wetted diameter of the single selected emitter (Wu, 1993b). Both the hydraulic design and manufacturer's variation are less significant than the clogging, grouping, and emitter spacing as long as they are individually designed within 10% in coefficient of variation.

10.1.3. The Goal of Microirrigation Application

The main goal of irrigation is to achieve optimal agricultural production and maximum economic return. A well-designed microirrigation system can help achieve the goal through its highly uniform water application. There are two other items that are equally significant in achieving the goal of irrigation, appropriate irrigation scheduling, and knowledge of the amount of water required for maximum yield. A well-designed microirrigation system cannot achieve its goal if the decision on irrigation scheduling is not properly made. Additionally, uniformity of water application will not be important when too much or too little water is applied compared with the required amount.

Although the microirrigation application can achieve high uniformity, it is, in fact, nonuniform. When a fixed irrigation application is used, the nonuniform nature of the irrigation system will overirrigate some portions of the field and underirrigate the remainder. Overirrigation will waste water and create deep percolation, which may cause contamination of underlying groundwater resources. The underirrigated area, which is subject to deficit irrigation, will experience yield reduction. An optimal microirrigation scheduling to achieve the maximum possible return can be determined based on the cost of water, price of the yield, and the groundwater contamination cost related to deep percolation.

10.2. VARIATIONS OF IRRIGATION APPLICATION

10.2.1. Variations from Hydraulic Design

The hydraulic design of a microirrigation system involves either designing the lateral line and submain separately, or designing a submain unit that combines the laterals and submain. Early research in microirrigation hydraulic design concentrated mainly on the single lateral line approach (Myers and Bucks, 1972; Howell and Hiler, 1974; Wu and Gitlin, 1974). A method to design a submain unit using the finite element method was developed by Bralts and Segerlind (1985). The hydraulic design is based on the energy relations in the microirrigation laterals, which involve the friction drop and energy changes due to field slope. Direct calculations of water pressures along a lateral line or in a submain unit can be made by using an energy gradient line approach (Wu and Gitlin, 1974; Feng and Wu, 1990). All emitter flows along a lateral line and in a submain can be determined based on their corresponding water pressures along the lateral line or in the submain unit. When all the emitter flows are determined, the emitter flow variation, q_{var}, of a lateral or a submain unit can be expressed by

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \tag{10.1}$$

where q_{max} is the maximum emitter flow and q_{min} the minimum emitter flow.

Other uniformity parameters also useful as design criterion include Christiansen's uniformity coefficient, *UCC*, (Christiansen, 1941), and the coefficient of variation, *CV*. All the uniformity parameters mentioned are related and can be expressed by the following the regression equations (Wu and Irudayaraj, 1987):

$$UCC = 1 - 0.865\,CV \qquad (R^2 = 0.9985) \qquad (10.2)$$

$$CV = -0.0095 + 0.4288\,q_{var} \qquad (R^2 = 0.9736) \qquad (10.3)$$

$$UCC = 1.0085 - 0.3702\,q_{var} \qquad (R^2 = 0.9689) \qquad (10.4)$$

The high correlation between any pair of the uniformity parameters expressed in Eqs. 10.2, 10.3, and 10.4 indicates that all three uniformity parameters can be used as design criteria for hydraulic design. This justifies using the simple uniformity parameter, q_{var}, which is determined by only the maximum and minimum emitter flows for a lateral line or submain unit. In general, the emitter flow variation *(q_{var})* is used for hydraulic design and can be converted to the coefficient of variation for emitter flow *(CV)* when combined with other design considerations. The design criterion for q_{var} for microirrigation design is often arbitrarily set as 10% to 20%, which is equivalent to *CV* from 0.033 to 0.076, respectively.

10.2.2. Manufacturer's Variation

The manufacturer's variation is the variation of emitter flows determined from a controlled constant hydraulic pressure applied to a number of emitters. It is expressed statistically by,

$$CV_M = \frac{S}{\bar{q}} \qquad (10.5)$$

where CV_M is the coefficient of variation of emitter flow caused by manufacturer's variation, *S* is standard deviation of emitter flows, and $\bar{q}$ is mean emitter flow. The manufacturer's variation ranges from 0.03 to 0.20 for various emitters (Solomon, 1979).

The combination of hydraulic variation and manufacturer's variation was first determined statistically (Bralts et al., 1981a) and verified through computer simulation (Wu et al., 1985). It is expressed by

$$CV_{HM}{}^2 = CV_H{}^2 + CV_M{}^2 \qquad (10.6)$$

where CV_{HM} is the coefficient of variation of emitter flows resulting from both the hydraulic and manufacturer's variation (CV_H), CV_H is the coefficient of variation of emitter flows caused by hydraulic design, and CV_M is the coefficient of variation of emitter flows caused by the manufacturer's variation.

10.2.3. Effects by Grouping of Emitters

As indicated in Section 10.1.2, the grouping of emitters will generally improve the uniformity of water application. The improvement depends on the magnitude of emitter flow variation caused by the hydraulic and manufacturer's variations. Under the extreme case in which the emitter flow variation is caused by hydraulics only and the manufacturer's variation is zero, there will be no grouping effect. That is

$$CV_{Hg} = CV_H \qquad (10.7)$$

where CV_{Hg} is the coefficient of variation of emitter flow by hydraulics after grouping, and CV_H is the coefficient of variation of emitter flow by hydraulics only. In another case where emitter flow variation is caused by manufacturer's variation only and hydraulic variation is zero, the emitter flows will follow a normal distribution and the grouping effect will be

$$CV_{Mg} = \frac{CV_M}{\sqrt{N}} \tag{10.8}$$

where CV_{Mg} is the coefficient of variation of emitter flow by manufacturer's variation after grouping, CV_M is the coefficient of variation of emitter flow by manufacturer's variation only, and N is the number of emitters grouped together. When the emitter flow is affected by both hydraulic and manufacturer's variations, the grouping effect can be expressed by the regression equation (Wu et al., 1988),

$$\begin{aligned} CV_{HMg} = {} & \frac{CV_M}{\sqrt{N}} + 1.2487(CV_{HM} - CV_M) - 5.3935(CV_{HM} - CV_M)^2 \\ & + 7.6749(CV_{HM} - CV_M)^3 + 2.3113CV_M(CV_{HM} - CV_M) \end{aligned} \qquad (R^2{=}0.9904) \tag{10.9}$$

where CV_{HMg} is the coefficient of variation of emitter flow caused by both hydraulic and manufacturer's variations after grouping and all other variables are as previously defined. Equation 10.9 can be used for N values ranging from 2 to 16.

10.2.4. Possible Clogging Effects

A major problem encountered in microirrigation is the clogging of emitters. Emitter clogging can adversely affect the rate of water application and the uniformity of water distribution. The combined effects of hydraulics, manufacturer's variation, and clogging were evaluated statistically (Bralts et al., 1981b). The coefficient of variation of emitter flow caused by hydraulics, manufacturer's variation, and clogging can be expressed as

$$CV_{HMC}^2 = \frac{CV_{HM}^2}{1-P} + \frac{P}{1-P} \tag{10.10}$$

where CV_{HMC} is the total emitter flow variation affected by all three factors; hydraulics, manufacturer's variation, and clogging (complete clogging only) and P is the fraction of emitters completely clogged. For the case where CV_{HM} is zero, the coefficient of variation caused by clogging *(CV_C)* can be expressed simply as a function of P

$$CV_C = \sqrt{\frac{P}{1-P}} \tag{10.11}$$

Equation 10.10 shows that the clogging can affect the uniformity tremendously; a 10% clogging will produce a 33% coefficient of variation of emitter flow as shown in Eq. 10.11.

By using a similar analysis to the grouping effect of emitters, a term called the contiguous clogging of emitters was evaluated (Wu et al., 1991). This work demonstrated that the probability of four or more emitters being clogged together (contiguously) is nearly zero and less than 1% for an emitter clogging rate of 10% or 20%, respectively. Therefore, when four or more emitters are designed to irrigate a tree, a 10% or 20% clogging rate will cause only certain trees to receive less than the required amount of irrigation water.

10.2.5. Total Variation

The overall variation of irrigation application for a single microirrigation event is affected by all the previously mentioned uniformity factors. These variations reflect the uniformity of irrigation water in the field. The total emitter flow variation caused by both hydraulic and manufacturer's variation can be determined by Eq. 10.6. When the grouping effect is included, the total variation can be determined by Eq. 10.9. However, the study of clogging effects on total emitter flow variation was not complete because partial clogging was not evaluated. The combined effects of hydraulic, manufacturer's and clogging (only complete clogged emitters) on total variation can be expressed by Eq. 10.10. When several emitters can be grouped as a unit, the total variation can be expressed by extending Eq. 10.10 to

$$CV_{HMgC}{}^{2} = \frac{CV_{HMg}{}^{2}}{1-P} + \frac{P}{1-P} \tag{10.12}$$

where CV^{2}_{HMgC} is the coefficient of variation for emitter flow affected by all four factors, hydraulics, manufacturer's variation, grouping, and clogging.

10.3. UNIFORMITY CONSIDERATIONS

10.3.1. Uniformity Parameters

Uniformity is a measurement of the nonuniform pattern of emitter flow of a microirrigation system. There are many uniformity parameters used for design and evaluating the microirrigation system. Some of the more common uniformity parameters are:

- Emitter flow variation (Wu and Gitlin, 1974)
- Christiansen uniformity coefficient (Christiansen, 1941)
- Coefficient of variation
- Statistical uniformity coefficient (Bralts et al., 1981a)

The system uniformity (or emitter flow uniformity) can be simply expressed as emitter flow variation, q_{var}, as previously discussed in Eq. 10.1 to show only the range of variation (Wu and Gitlin, 1974).

When more emitter flows are used in determining the uniformity, three uniformity parameters are generally used, the Christiansen uniformity coefficient, the coefficient of variation, and the statistical uniformity coefficient.

The Christiansen uniformity coefficient (Christiansen, 1941) is given by

$$UCC = 1 - \frac{\overline{\Delta q}}{\overline{q}} \tag{10.13}$$

where UCC is the Christiansen uniformity coefficient, $\overline{q}$ is the mean emitter flow and $\overline{\Delta q}$ is the mean deviation of emitter flow from the mean value.

The coefficient of variation is

$$CV = \frac{S}{\overline{q}} \tag{10.14}$$

where CV is the coefficient of variation of emitter flow, $\overline{q}$ is the mean emitter flow, and S is the standard deviation of emitter flow.

The statistical uniformity coefficient (Bralts et al., 1981a) is

$$UCS = 1 - CV \tag{10.15}$$

where UCS is the statistical uniformity and CV is the coefficient of variation of emitter flow.

The three statistical uniformity parameters, UCC, CV and UCS are interrelated (Wu and Irudayaraj, 1987). Therefore, any one of the three can be used to describe the microirrigation system uniformity. The simple uniformity parameter, q_{var}, is also highly correlated to CV or UCC. The grouping effect on microirrigation uniformity was previously reported by researchers (Keller and Karmeli, 1974; Solomon, 1979; Bralts et al., 1981a) considering a normal distribution for all emitter flow as follows:

$$CV_g = \frac{CV}{\sqrt{N}} \tag{10.16}$$

where CV_g is the coefficient of variation of emitter flow calculated based on grouping a number of consecutive emitters together as a unit, CV is the coefficient of variation calculated based on all emitters, and N is the number of emitters grouped together. A design emission uniformity, EU_k, which considers emitter flow variation, manufacturer's variation, and grouping was introduced for microirrigation system design by Keller and Karmeli (1974) as

$$EU_k = \left[1 - \frac{1.27 CV_M}{\sqrt{N}}\right] \frac{q_{min}}{\overline{q}} \tag{10.17}$$

where all the variables have been previously defined.

10.3.2. A Linearized Water Application Function

When the uniformity of a microirrigation system is designed for 70% or more in UCC (or 30% or less in CV), the irrigation application can be expressed (Fig. 10.1) as a straight line distribution

(Karmeli et al., 1978; Seginer, 1978; Wu, 1988). Figure 10.1 was plotted using the percent of area, P_A, against a relative irrigation depth, X, which is the ratio of a required irrigation depth to the mean irrigation application. The straight line distribution in the dimensionless plot can be specified by a minimum value, a, a maximum value, $a+b$, in the X-scale, and a slope b. The b value specifies the uniformity of water application and can be determined by (Wu, 1988)

$$CV = 0.29b \tag{10.18}$$

or

$$UCC = 1 - 0.25b \tag{10.19}$$

The value of a can be simply determined as

$$a = 1 - \frac{b}{2} \tag{10.20}$$

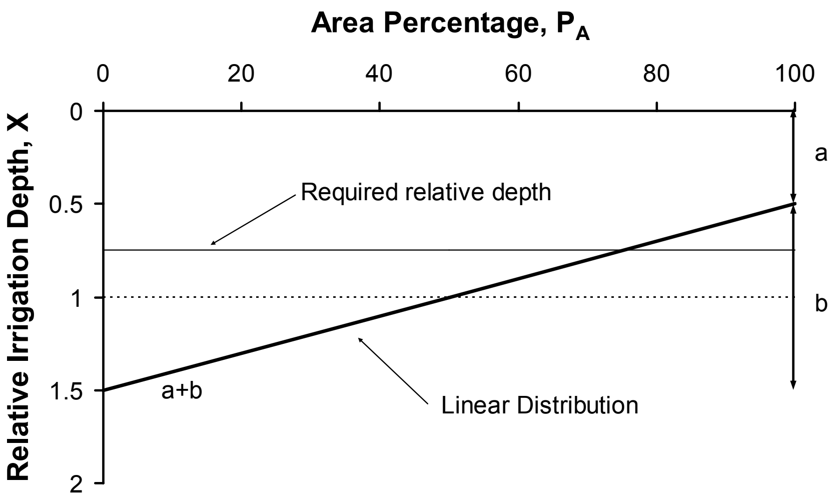

Figure10.1. A linear water application model for microirrigation; X, relative irrigation depth; P_A, percentage of area where the X-value is equaled or exceeded.

When the required irrigation depth is determined by the depth to achieve maximum yield, the relative irrigation depth, X, can also be shown as

$$X = \frac{W_m}{QT} \tag{10.21}$$

where W_m is the required amount of water per unit of surface area to achieve maximum yield and QT is the total amount applied, and where Q is the capacity of irrigation system per unit of surface area and T is the irrigation time for the whole crop season. The dimensionless value, X, is in fact a parameter for irrigation scheduling. Each X-value will be presented as a horizontal line which intersects the sloped straight line to form deficit and overirrigation areas expressed by two triangles as shown in Fig. 10.1. The triangle above the horizontal line specifies the deficit area and percentage of deficit. The triangle below the horizontal line presents the overirrigation area and volume of overirrigation. The percent of area, A_D, under deficit is

$$A_D = \frac{X - a}{b} \tag{10.22}$$

The area undergoing overirrigation, A_{dp}, which may cause deep percolation is simply $1 - A_D$ and is

$$A_{dp} = 1 - \frac{X - a}{b} \tag{10.23}$$

The percent of deficit, P_D, is defined as the ratio of deficit volume to the required volume of irrigation and can be expressed as

$$P_D = \frac{(X - a)^2}{2bX} \tag{10.24}$$

and the volume of deep percolation per unit surface area, V_{dp}, is determined by the volume below the horizontal line X *as*

$$V_{dp} = \frac{1}{2b}(a + b - X)QT \tag{10.25}$$

Equations 10.22, 10.23, 10.24, and 10.25 are all expressed as a function of a, b, and X. When an X value is selected in the range between a and $(a + b)$, different amounts of A_D, A_{dp}, P_D and V_{dp} can be shown in Fig. 10.1 and calculated by simple algebraic equations (Eqs. 10.22, 10.23, 10.24, and 10.25).

10.3.3. Uniformity and Total Yield

The effects of deficit irrigation on crop yield can be shown by a linear response model (Doorenbos and Kassam, 1979; Warrick and Gardner, 1983; Martin et al., 1984; Sammis and Wu 1985) and can be expressed as follows:

$$\left(1 - \frac{Y}{Y_m}\right) = K_y\left(1 - \frac{W}{W_m}\right) \tag{10.26}$$

or

$$1 - \frac{Y}{Y_m} = K_y P_D \tag{10.27}$$

where Y_m is the maximum yield and W_m its corresponding maximum water application per unit of surface area, Y is the yield and W its corresponding water application under deficit condition per unit of surface area; P_D is the fraction of deficit (Eq. 10.24), and K_y is a reduction coefficient, which is a constant for a given crop.

The linear model results in a sloped straight line for deficit water applications and a horizontal asymptote for overirrigation indicating no yield reduction by overirrigation.

When a microirrigation system is designed with a fixed uniformity, the sloped straight line with known values of *a* and *b* can be determined. An *X* can be selected between values of *a* and *a+b* and plotted as shown in Fig.10.1. The triangle formed above the horizontal line, *X*, will cause yield reduction. The total yield in the field, as affected by the uniformity of irrigation system, *UCC* or *CV*, and the value of *X* for irrigation scheduling, can be determined by combining Eqs. 10.24 and 10.27 to give

$$Y = Y_m - \frac{Y_m K_y}{2b}\left(X - 2a + \frac{a^2}{X} \right) \tag{10.28}$$

Equation 10.28 is applicable when the *X*-value ranges between *a* and $(a + b)$. When $X < a$, there will be no deficit and the volume of deep percolation will be

$$V_{dp} = (1 - X)QT \tag{10.29}$$

In the case where $X > (a + b)$, there will be no deep percolation. The fraction of deficit can be represented by

$$P_D = \frac{X-1}{X} \tag{10.30}$$

The total yield by this deficit condition, $X > (a + b)$, can be expressed as

$$Y = Y_m - Y_m K_y \left(\frac{X-1}{X}\right) \tag{10.31}$$

Equation 10.31 shows that the total yield is a function of *X* and is not affected by the uniformity of the microirrigation system. Therefore, when irrigation schedules are made for $X > (a + b)$, the uniformity of irrigation application will not be important. It is also interesting to note that in overirrigation cases ($X < a$), uniformity of the irrigation application will not affect the total deep percolation as shown in Eq. 10.29.

The relationship between total yield and uniformity (expressed as *CV*) for a given known K_y is determined by Eqs. 10.28 and 10.31 and plotted in Fig. 10.2.

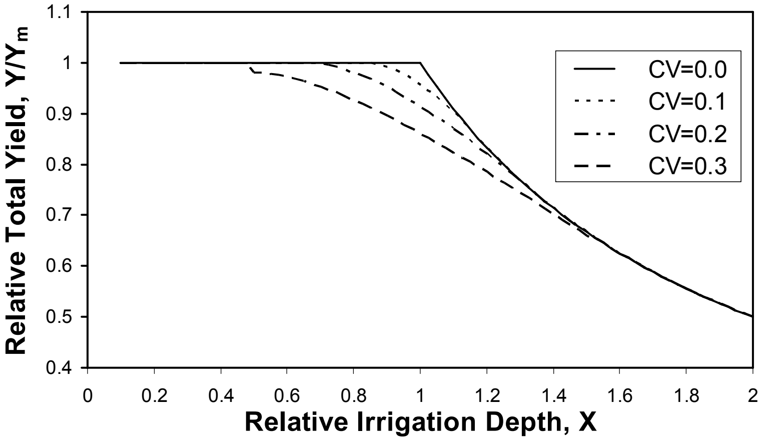

Figure 10.2. Relationship between relative total yield, Y/Y_m, and relative irrigation depth, X, for four CV conditions.

10.3.4. Uniformity and Total Economic Return

The horizontal line expressed by a value of X can be moved up and down within the limits between a and $(a + b)$ (Fig. 10.1). Each X value represents an irrigation schedule that can be determined by Eq. 10.32

$$QT = \frac{W_m}{X} \tag{10.32}$$

where QT is the total amount applied. The irrigation time T can be determined based on the discharge Q of the microirrigation system. Different X values will create different sets of triangles to show the deficit and overirrigation conditions.

Based on an overall analysis that includes the cost of water, price of crop, yield reduction by deficit irrigation, cost of the loss of fertilizer by overirrigation, and remediation cost for environmental pollution (Wu, 1995), the total return, Z, can be expressed as

$$Z = Y\rho_y - QT\rho_w - V_{dp}\ \rho_{dp} \tag{10.33}$$

where ρ_y is the unit cost of production, ρ_w is the unit cost of water, and ρ_{dp} is the price of the loss of fertilizer and remediation cost of environmental pollution per unit volume of deep percolation.

By substituting Eqs. 10.28 and 10.32 into Eq. 10.33, the total return Z is

$$Z = Y_m\rho_y\left[1 - \frac{K_y(X-a)^2}{2bX} - \frac{1}{X}C_{r1} - \frac{1}{2bX}(a+b-X)^2 C_{r2}\right] \tag{10.34}$$

where Cr_1 and Cr_2 are the two cost ratios defined as

$$C_{r1} = \frac{W_m \rho_w}{Y_m \rho_y} \tag{10.35}$$

and

$$C_{r2} = \frac{W_m \rho_{dp}}{Y_m \rho_y} \tag{10.36}$$

Equation 10.34 can be rearranged to give

$$\frac{Z}{Y_m \rho_y} = 1 - \frac{K_y (X-a)^2}{2bX} - \frac{1}{X} Cr_1 - \frac{1}{2bX}(a+b-X)^2 Cr_2 \tag{10.37}$$

where $\frac{Z}{Y_m \rho_y}$ is the total relative return.

The relationship between total relative return and X for $Ky=1.3$, $C_{r1}=0.1$, and $C_{r2}=1$ for four different CV values are shown in Fig. 10.3. This figure illustrates the combined effects of irrigation uniformity and scheduling on the economic return of the crop. More specifically, it shows that uniformity is only relevant when the relative irrigation depth X is between 0.6 and 1.4. Uniformity becomes irrelevant for overirrigation and underirrigation beyond this range.

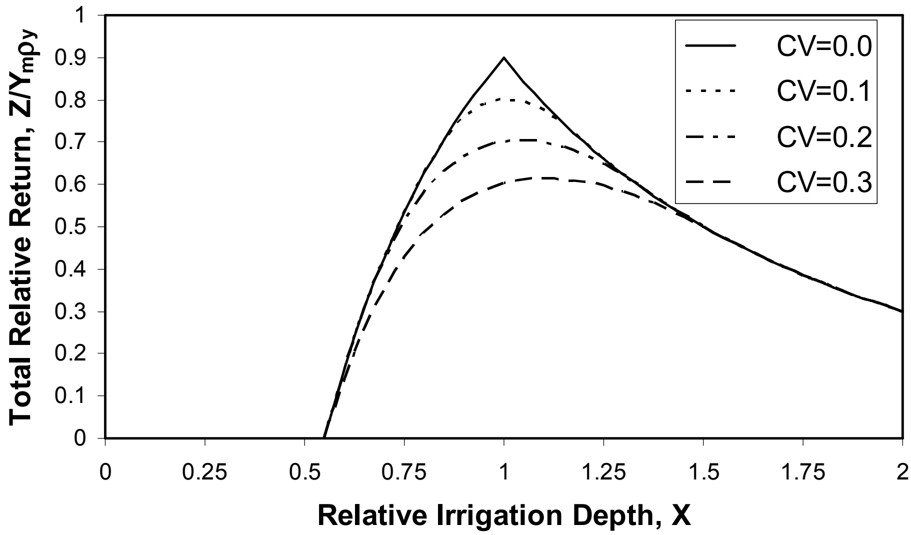

Figure 10.3. Relationship between relative return, $Z/Y_m \rho_y$, and relative irrigation depth, X, for $K_y=1.3$; $C_{r1}=0.1$; $C_{r2}=1$.

10.4. FIELD PERFORMANCE AND IRRIGATION STRATEGY

10.4.1. Significance of Irrigation Scheduling

The field performance of microirrigation systems is not only affected by the uniformity of irrigation application, but also by the irrigation amount and strategy of irrigation scheduling. Yield and total economic return are affected by both the uniformity of the microirrigation system (or irrigation water application) and the irrigation scheduling parameter X (Figs. 10.2 and 10.3). The irrigation scheduling parameter can also expressed as the ratio of depth of irrigation required (d) and the average depth applied $(\bar{d})$ for a single irrigation event

$$X = \frac{d}{\bar{d}} \tag{10.38}$$

or

$$X = \frac{d}{Qt} \tag{10.39}$$

The irrigation scheduling parameter (X) is considered to be a constant based on a selected irrigation strategy. When the irrigation depth (d) for a single irrigation event is known, the irrigation time (t) can be determined by rearranging Eq. 10.39

$$t = \frac{d}{QX} \tag{10.40}$$

As Eq. 10.21 shows, the volume of irrigation per unit area (QT) is determined by an irrigation scheduling parameter (X) when the water requirement for maximum yield (W_m) is known. A microirrigation schedule is any value of X within the range of a and $(a+b)$ or outside the range and which can be shown as a horizontal line in Fig. 10.1. Different microirrigation schedules expressed by X in Fig. 10.1 are explained as follows:

$X<a$ Overirrigation is scheduled with no deficit condition in the field.

$X=a$ This is a conventional irrigation schedule that is based on the minimum emitter or minimum water application. The field is fully irrigated and whole field is overirrigated except at the point of minimum irrigation application.

$X=X_o$ For an optimal return, there is a value of X for the irrigation scheduling parameter between a and $(a+b)$. The term X_0 is defined as the optimal irrigation scheduling parameter.

$X=1$ This is a simple irrigation schedule where the amount applied (QT) is the same as the amount required (W_m).

$X=(a+b)$ The irrigation schedule is based on the maximum emitter flow or maximum irrigation application. The whole field is under deficit condition except at the point of maximum water application. There is no deep percolation.

X>(a+b) Too little irrigation is scheduled. The whole field is under deficit irrigation conditions. There is no deep percolation for the whole field.

Among the various selections of X values, the $X<a$ and $X>(a+b)$ should not be used. These two strategies are improper irrigation practices, either too much or too little irrigation.

10.4.2. Optimal Irrigation

As Fig. 10.1 shows, the horizontal line expressed by a value of X can be moved up and down within the limits between a and $(a+b)$. Each X value represents an irrigation time that can be determined by Eq. 10.40

In an economic analysis where the cost of water, price of crop, yield reduction by deficit irrigation, the cost of fertilizer loss from overirrigation, and remedial cost for environmental pollution are considered (Wu, 1995), the total return Z can be expressed by Eq. 10.34. The optimum irrigation schedule can be determined by taking the first derivative with respect to X for Eq. 10.34 and setting the $dZ/dX=0$. The optimum value for the irrigation scheduling parameter, X_0, can be expressed as

$$X_0 = \sqrt{\frac{a^2 + 2b\left(\frac{C_{r1}}{K_y}\right) + (a+b)^2 \frac{C_{r2}}{K_y}}{1 + \frac{C_{r2}}{K_y}}} \tag{10.41}$$

The optimum return, Z_0, can be obtained by using X_0 for X in Eq. 10.34 and results in

$$Z_0 = Y_m \rho_y \left[1 - \frac{K_y (X_0 - a)^2}{2bX_0} - \frac{1}{X_0} C_{r1} - \frac{1}{2bX_0} (a + b - X_0)^2 C_{r2} \right] \tag{10.42}$$

The optimum irrigation amount and the optimum irrigation time can be determined from Eq. 10.32 as

$$QT_0 = \frac{W_m}{X_0} \tag{10.43}$$

where QT_0 is the irrigation water applied by the optimum irrigation schedule for the whole crop season per unit surface area.

10.4.3. Conventional Irrigation

The conventional irrigation schedule is determined by moving the horizontal line for required irrigation depth to $X=a$ in Fig. 10.1. This schedule will maintain the whole area fully irrigated with no deficit condition. The irrigation amount and the irrigation time for this case can be developed from Eq. 10.32 as

$$QT_a = \frac{W_m}{a} \tag{10.44}$$

where QT_a is the irrigation water applied for the conventional irrigation scheduling by the whole crop season per unit surface area.

The total return can be determined from Eq. 10.34,

$$Z_a = Y_m \rho_y \left[1 - \frac{1}{a} C_{r1} - \frac{b}{2a} C_{r2} \right] \tag{10.45}$$

where Z_a is the total return of conventional irrigation scheduling per unit surface area.

A conventional irrigation is generally applied by furrow and sprinkler irrigation to irrigate fully the whole area without any deficit condition. This irrigation strategy can achieve maximum yield based on the assumption that overirrigation will not reduce the yield. However, this irrigation practice uses too much water and the deep percolation caused by overirrigation may cause groundwater contamination.

10.4.4. A Simple Irrigation Schedule

The simple irrigation schedule can be determined by using $X=1$ in Eq. 10.32

$$QT_1 = W_m \tag{10.46}$$

where QT_1 is the total amount for simple irrigation schedule per unit surface area. The total return will be determined from Eq. 10.34 as

$$Z_1 = Y_m \rho_y \left[1 - \frac{K_y(1-a)^2}{2b} - C_{r1} - \frac{1}{2b}(a+b-1)^2 C_{r2} \right] \tag{10.47}$$

The simple irrigation schedule is to apply the same amount required for maximum yield. When the uniformity of irrigation application of microirrigation is designed for CV less the 20%, the simple irrigation schedule can always achieve a near optimal return (Fig. 10.3).

10.4.5. Irrigation Strategy for Environmental Protection

When environmental pollution from deep percolation is a major concern, the irrigation strategy can be set to eliminate or minimize deep percolation by using an irrigation schedule where $X = (a+b)$ by rearranging Eq. 10.32

$$QT_{a+b} = \frac{W_m}{a+b} \tag{10.48}$$

where QT_{a+b} is the irrigation amount for zero deep percolation. The total return will be determined by rearranging Eq. 10.34 to

$$Z_{a+b} = Y_m \rho_y \left[1 - \frac{K_y b}{2(a+b)} - \frac{1}{a+b} C_{r1} \right] \quad (10.49)$$

where Z_{a+b} is the total return for the irrigation schedule for zero deep percolation.

This schedule will result in the total field operating under deficit irrigation condition except at the point where $X = (a + b)$. There will be yield reduction in the deficit irrigation area according to the uniformity of water application. This irrigation schedule can be used to prevent environmental pollution by allowing an acceptable yield reduction.

10.4.6. Microirrigation for Water Conservation

Different irrigation strategies require different total applied irrigation amounts. Water conservation can be realized by comparing any two of the irrigation strategies.

10.4.6.1. Comparing optimal schedule with conventional irrigation schedule

Water saving by optimal irrigation schedule compared with conventional irrigation schedule can be obtained from Eqs. 10.43 and 10.44 as

$$\frac{QT_a - QT_0}{W_m} = \frac{1}{a} - \frac{1}{X_0} \quad (10.50)$$

The total returns difference of these two irrigation schedules can be determined from Eqs. 10.42 and 10.45 as

$$\frac{Z_0 - Z_a}{Y_m \rho_y} = \left(\frac{1}{a} - \frac{1}{X_0} \right) C_{r1} - K_y \frac{(X_0 - a)^2}{2bX_0} + \frac{1}{2} \left[\frac{b}{a} - \frac{1}{bX_0} (a + b - X_0)^2 \right] C_{r2} \quad (10.51)$$

10.4.6.2. Comparing simple irrigation schedule with conventional irrigation schedule

Water savings by the simple irrigation schedule compared with the conventional irrigation schedule can be obtained from Eqs. 10.44 and 10.46 as

$$\frac{QT_a - QT_1}{W_m} = \frac{1}{a} - 1 \quad (10.52)$$

The difference in total returns between these two schedules can be determined from Eqs. 10.45 and 10.47 as

$$\frac{Z_1 - Z_a}{Y_m \rho_y} = \left(\frac{1}{a} - 1 \right) C_{r1} - \frac{K_y (1-a)^2}{2b} + \frac{1}{2} \left[\frac{b}{a} - \frac{(a+b-1)^2}{b} \right] C_{r2} \quad (10.53)$$

10.4.6.3. Comparing simple irrigation schedule with the optimal irrigation schedule

The simple irrigation schedule can achieve water savings compared with the optimal schedule. This can be determined from Eqs. 10.43 and 10.46 as

$$\frac{QT_1 - QT_0}{W_m} = 1 - \frac{1}{X_0} \tag{10.54}$$

The total returns difference between these two schedules can be determined from Eqs. 10.42 and 10.47 as

$$\begin{aligned}\frac{Z_1 - Z_0}{Y_m \rho_y} = &\left(\frac{1}{X_0} - 1\right) C_{r1} + \frac{K_y}{2b}\left[\frac{(X_0 - a)^2}{X_0} - (1-a)^2\right] \\ &+ \frac{1}{2b}\left[\frac{(a+b-X_0)^2}{X_0} - (a+b-1)^2\right] C_{r2}\end{aligned} \tag{10.55}$$

10.4.6.4. Comparing the irrigation schedule for environmental protection with the optimal irrigation schedule

More water savings can be achieved by using the schedule for environmental protection because the whole area is under deficit irrigation. However, there will be yield reduction caused by deficit irrigation. Water savings can be determined from Eqs. 10.43 and 10.48 as

$$\frac{QT_{a+b} - QT_0}{W_m} = \frac{1}{a+b} - \frac{1}{X_0} \tag{10.56}$$

The total returns reduction can be determined from Eqs. 10.42 and 10.49 as

$$\begin{aligned}\frac{Z_0 - Z_{a+b}}{W_m} = &\frac{K_y}{2}\left[\frac{b}{a+b} - \frac{(X_0 - a)^2}{bX_0}\right] \\ &+ \left[\frac{1}{a+b} - \frac{1}{X_0}\right] C_{r1} - \frac{1}{2bX_0}(a+b-X_0)^2 C_{r2}\end{aligned} \tag{10.57}$$

10.4.6.5. Comparing the irrigation schedule for environmental protection with the simple irrigation schedule

Water savings by the irrigation schedule for environmental protection compared with the simple irrigation schedule can be determined from Eqs. 10.46 and 10.48 as

$$\frac{QT_1 - QT_{a+b}}{W_m} = 1 - \frac{1}{a+b} \tag{10.58}$$

The total returns reduction can be determined from Eqs. 10.47 and 10.49 as

$$\frac{Z_1 - Z_{a+b}}{W_m} = \frac{K_y}{2}\left[\frac{b}{a+b} - \frac{(1-a)^2}{b}\right] + \left[\frac{1}{a+b} - 1\right]C_{r1} - \frac{1}{2b}(a+b-1)^2 C_{r2} \tag{10.59}$$

Equations 10.50, 10.52, 10.54, 10.56, and 10.58 show that water savings can be achieved by comparing two irrigation schedules. Different irrigation schedules will also result in different total returns as shown in Eqs. 10.51, 10.53, 10.55, 10.57, and 10.59.

In comparing conventional irrigation with optimal irrigation (Tab 10.1), there is not only water savings, but also increased total returns by using the optimal schedule. More water savings and total returns can be obtained with higher values of CV, C_{r1} and C_{r2}. This analysis shows that the conventional irrigation concept of irrigating the whole field to the required irrigation depth is wasting water and reducing the total return.

Table 10.1. Comparing the conventional irrigation schedule with the optimal irrigation schedule for (a) Water saving (Eq. 10.50); (b) Total return (Eq. 10.51).

(a) Water saving by optimal irrigation schedule $\frac{QT_a - QT_0}{W_m}$

Cr1	Cr2=0			Cr2=0.2			Cr2=0.6			Cr2=1		
	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3
0.0000	0.0000	0.0000	0.0000	0.0902	0.2946	0.7560	0.1788	0.4984	1.0759	0.2229	0.5809	1.1832
0.0100	0.0060	0.0239	0.0862	0.0942	0.3052	0.7752	0.1812	0.5031	1.0822	0.2245	0.5838	1.1868
0.1000	0.0566	0.1985	0.5638	0.1283	0.3897	0.9170	0.2016	0.5423	1.1341	0.2390	0.6088	1.2174

(b) Total return increase by optimal irrigation schedule $\frac{Z_0 - Z_a}{Y_m \rho_y}$

Cr1	Cr2=0			Cr2=0.2			Cr2=0.6			Cr2=1		
	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3
0.0000	0.0000	0.0000	0.0000	0.0094	0.0326	0.0925	0.0579	0.1787	0.4360	0.1228	0.3587	0.8281
0.0100	0.0000	0.0001	0.0004	0.0103	0.0356	0.1001	0.0597	0.1837	0.4468	0.1250	0.3646	0.8400
0.1000	0.0029	0.0106	0.0326	0.0203	0.0670	0.1766	0.0770	0.2308	0.5466	0.1459	0.4183	0.9482

A comparison of the simple irrigation schedule with the optimal irrigation schedule indicates there will be water savings by the simple irrigation schedule when C_{r2} is less than 0.6 as shown in Table 10.2a (minus sign specifies water saving). The amount of water savings will increase with the increased CV value and decrease with the increased values of C_{r1} and C_{r2}. There will be total returns reduction by the simple irrigation schedule. It will decrease with respect to C_{r1} and C_{r2}, and increase with respect to larger CV (Table 10.2 b).

Table 10.2. Comparing the simple irrigation schedule with the optimal irrigation schedule for (a) Water saving (Eq. 10.54) and (b) Total return (Eq. 10.55).

a) Water saving by simple irrigation schedule $\dfrac{QT_1 - QT_0}{W_m}$

Cr1	Cr2=0			Cr2=0.2			Cr2=0.6			Cr2=1		
	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3
0.0000	-0.2083	-0.5263	-1.0714	-0.1181	-0.2317	-0.3155	-0.0295	-0.0279	0.0044	0.0145	0.0546	0.1118
0.0100	-0.2023	-0.5024	-0.9852	-0.1141	-0.2211	-0.2963	-0.0272	-0.0232	0.0107	0.0162	0.0575	0.1154
0.1000	-0.1517	-0.3278	-0.5076	-0.0800	-0.1366	-0.1545	-0.0068	0.0160	0.0627	0.0306	0.0825	0.1459

(minus sign indicates water saving)

(b) Total return increase by optimal irrigation schedule $\dfrac{Z_0 - Z_1}{Y_m \rho_y}$

Cr1	Cr2=0			Cr2=0.2			Cr2=0.6			Cr2=1		
	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3
0.0000	0.0431	0.0862	0.1293	0.0194	0.0308	0.0334	0.0019	0.0009	0.0000	0.0006	0.0048	0.0153
0.0100	0.0411	0.0811	0.1190	0.0183	0.0285	0.0303	0.0016	0.0006	0.0001	0.0008	0.0054	0.0164
0.1000	0.0252	0.0442	0.0548	0.0096	0.0126	0.0104	0.0001	0.0003	0.0035	0.0029	0.0117	0.0282

A comparison of the optimal irrigation schedule with the environmental protection irrigation schedule (Tab 10.3) indicates that there is definitely water savings in using the environmental protection irrigation schedule, but there will be decreased total returns. The water savings as well as total returns reduction will increase with the increased CV value, but will decrease with respect to increased C_{r1} and C_{r2} values.

The following three examples describe the results listed in the Tabs. 10.1, 10.2 and 10.3:

1. *In the case where CV=0.2, K_y=1, C_{r1}=0.1, and C_{r2}=0; the optimal irrigation schedule will not only save 20% of water, but also can increase 1% of total returns compared with the conventional irrigation schedule (Tab. 10.1).*

2. *In the case where CV=0.2, K_y=1, C_{r1}=0.1, and C_{r2}=0; the simple irrigation schedule can save 33% of water, but with only a 4% total returns reduction compared with the optimal irrigation schedule (Tab. 10.2).*

3. *In the case where CV=0.2, K_y=1, C_{r1}=0.1, and C_{r2}=1; the environmental irrigation schedule can save 17% of water, but will cause a 7% total returns reduction compared with the optimal irrigation schedule (Tab. 10.3).*

Table 10.3. Comparing the optimal irrigation schedule with the environmental protection irrigation schedule for (a) Water saving (Eq. 10.56); (b) Total return (Eq. 10.57).

(a) Water saving by environmental protection irrigation schedule $\dfrac{QT_0 - QT_{a+b}}{W_m}$

Cr1	Cr2=0			Cr2=0.2			Cr2=0.6			Cr2=1		
	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3
0.0000	0.3554	0.7827	1.4123	0.2652	0.4881	0.6564	0.1766	0.2843	0.3365	0.1325	0.2018	0.2291
0.0100	0.3494	0.7588	1.3261	0.2612	0.4775	0.6372	0.1742	0.2796	0.3302	0.1309	0.1989	0.2255
0.1000	0.2988	0.5842	0.8485	0.2271	0.3930	0.4954	0.1538	0.2405	0.2782	0.1164	0.1739	0.1950

(b) Total return increase by optimal irrigation schedule $\dfrac{Z_0 - Z_{a+b}}{Y_m \rho_y}$

Cr1	Cr2=0			Cr2=0.2			Cr2=0.6			Cr2=1		
	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3	CV=0.1	CV=0.2	CV=0.3
0.0000	0.1471	0.2564	0.3409	0.1148	0.1838	0.2191	0.0800	0.1193	0.1340	0.0615	0.0888	0.0976
0.0100	0.1435	0.2487	0.3272	0.1121	0.1789	0.2126	0.0782	0.1165	0.1307	0.0602	0.0868	0.0953
0.1000	0.1144	0.1888	0.2323	0.0902	0.1399	0.1620	0.0635	0.0931	0.1034	0.0490	0.0701	0.0764

The water savings and the total returns increase resulting from optimal irrigation compared with conventional irrigation are shown in Figs. 10.4 and 10.5 (Barragan and Wu, 2001).

10.5. FIELD EVALUATION AND ADJUSTMENT

10.5.1. Design Criteria of Microirrigation

10.5.1.1 Uniformity parameters

The purpose of field evaluation is to maintain the microirrigation system performance as close as possible to the system uniformity and original design irrigation strategy. The field evaluation can help the producer achieve the expected total economic return.

The design criteria of microirrigation is based on the uniformity of the emitter flow, which is mainly affected by hydraulic design, manufacturer's variation, and grouping effect depending on the emitter spacing with respect to the crop planting density in the field. This assumes that clogging is controlled to an acceptable level.

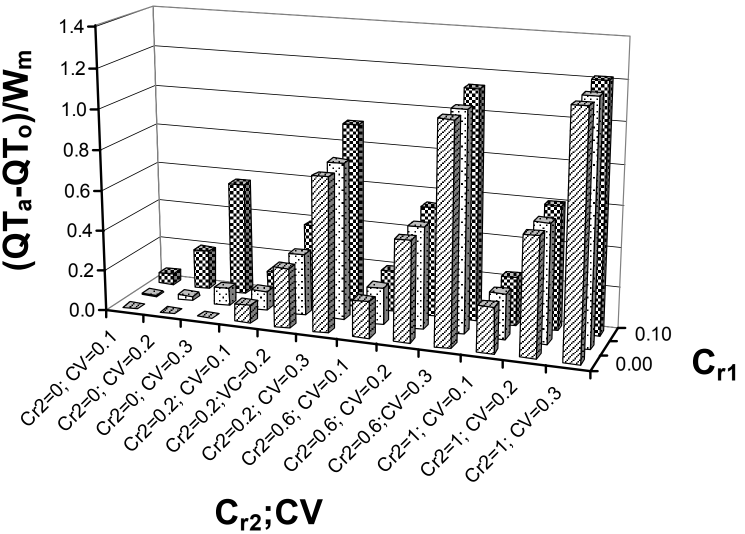

Figure 10.4. Amount of water saving by applying optimal irrigation schedule compared with the conventional one; $(QT_a\text{-}QT_o)/W_m$, water saving; CV, coefficient of variation; C_{r1}, water cost ratio, and C_{r2}, pollution cost ratio.

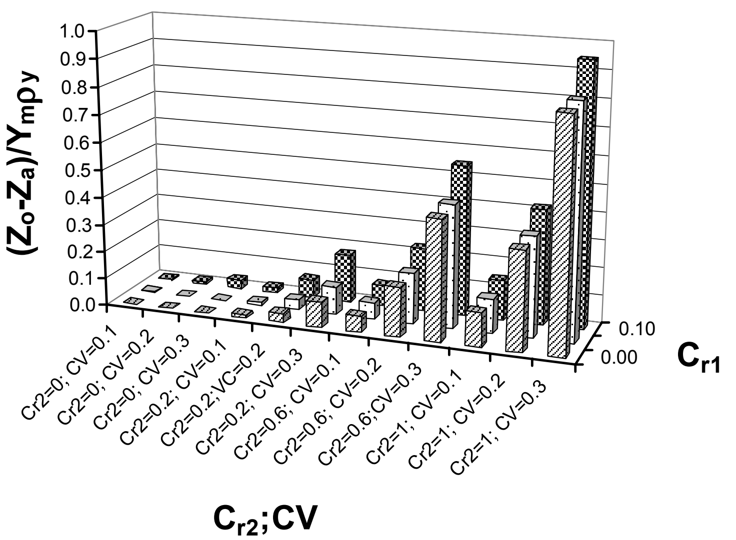

Figure 10.5. Total return increase by applying optimal irrigation schedule compared with the conventional one; $(Z_o\text{-}Z_a)/Y_m\rho_y$, increase in total return; CV, coefficient of variation; C_{r1}, water cost ratio, and C_{r2}, pollution cost ratio.

Uniformity is a measure of the degree of nonuniformity (or variation) in emitter flow or irrigation application of the microirrigation system. Different uniformity parameters are merely different ways of expressing the variation. The commonly used uniformity parameters are Uniformity Coefficient (*UCC),* Coefficient of Variation (*CV),* and Emission Uniformity (*EU)*. When the microirrigation system is designed for a *UCC* of 70% or more, or a *CV* of 30% or less, the emitter flow or irrigation application can be considered as a normal distribution and further simplified to a straight-line distribution.

When a straight line is used to show the emitter flow or water application function, the uniformity terms; *UCC*, *CV*, and *EU* can all be expressed by the slope of the straight line as expressed in Eq. 10.19, Eq. 10.18, and *EU* determined based on the lower quartile mean,

$$EU = 1 - 0.375b \tag{10.60}$$

The relationship between the Uniformity Coefficient and the Coefficient of Variation was given in Eq. 10.2. By combining Eqs. 10.19 and 10.60, the relationship between the Coefficient of Variation and the Emission Uniformity can be shown to be

$$CV = 0.77(1 - EU) \tag{10.61}$$

The relationship between *CV* and *UCC*, *CV* and *EU* can be calculated by combining Eqs. 10.2 and 10.61. The definite relationship between any two of uniformity parameters; *UCC*, *CV*, and *EU* as shown in Eqs.10.2 and 10.61, and Tab. 10.4 indicates that any one of the uniformity parameters can be used as a design criterion.

Table 10.4. The relationship among coefficient of variation, *CV,* and Christiansen uniformity coefficient, *UCC*, and design emission uniformity, EU, for a straight line distribution.

CV (%)	UCC (%)	EU (%)
5	96	94
10	91	87
15	87	81
20	83	74
25	79	67
30	74	61

10.5.1.2. Determination of design criteria

The design criterion for each of these uniformity expressions is arbitrary depending on a number of factors. For sprinkler irrigation design, an *UCC* less than 75% is considered low and an *UCC* larger than 85% is suggested for high-value crops. The design criterion of q_{var} is set as three levels for microirrigation design; less than 10% as desired design, between 10-20% as acceptable, and over 20% unacceptable. A more descriptive design criterion is *EU*, which is determined based on the types of emitters, field layout, and the topography of the field. The assigned range for each condition is quite large and overlapped so that it is still rather arbitrary when they are used in developing the design. An idea of *EU* design criteria selection, which is quite different from the one suggested for design by the ASAE Standard EP 405.1, was cited by Keller and Bliesner (1990) as follows:

> *"Selecting the ideal design EU requires economic trade off between factors. These are: Costs of systems having various EU values; water and water related cost; sensitivity of crop yield and quality to nonuniform irrigation; and market values of the crop. A complete economic analysis involving these factors is required to determine the optimal EU in any specific situation."*

Therefore, it is improper to simply assume or arbitrarily set a design criterion for microirrigation design. It should be determined with respect to certain aspects and goals. It can be set to achieve maximum yield, certain expected economic return, or with specific purpose such as water conservation or environmental protection. The conventional irrigation schedule in which the field is fully irrigated can achieve maximum yield (Fig. 10.2) if the cost of water is not considered and there are no environmental concerns. The optimal irrigation schedule can achieve optimal economic return based on the cost of water, price of yield, and the cost of environmental pollution caused by deep percolation through overirrigation. This can be seen in Fig. 10.3, which is plotted by Eq. 10.37 using selected values of $K_y=1.3$, $C_{r1}=0.1$, and $C_{r2}=1$ for different uniformity conditions expressed by *CV* and different *X* values. Graphs similar to Figs. 10.2 and 10.3 can be produced using different values of K_y, C_{r1}, and C_{r2} to set other design criterion to achieve a pre-set expected total return. Wu and Barragan (2000) determined the microirrigation system design criteria for various uniformity parameters necessary for achieving 80% or more of the maximum total return when the two cost ratio functions, C_{r1}, and C_{r2}, are matched with various degrees of water resources and environmental concerns (Tab. 10.5).

Table 10.5. Design criteria for uniformity of microirrigation system design.

Design consideration	CV (%)	UCC (%)	EU (%)
(1) Water is abundant with little or no environmental pollution problems (Cr_1=0-0.05; Cr_2=0-1.0)	30-20	75-85	60-75
(2) Water is abundant, but with environmental protection considerations (Cr_1=0-0.05; Cr_2=1-10)	20-10	80-90	75-85
(3) Limited water resources, but with little or no environmental pollution problems (Cr_1=0.05-0.10; Cr_2=0-1.0)	25-15	80-90	70-80
(4) Considerations for both water conservation and environmental protection (Cr_1=0.05-0.10; Cr_2=1-10)	15-5	85-95	80-95

10.5.1.3. Selection of design criteria

The selection of design criteria for microirrigation system design is based on the field situation and economic return, namely

- Cost of water, ρ_w
- Price of yield, ρ_y
- Total amount of water requirement, W_m, for maximum production, Y_m
- Crop reduction coefficient in deficit irrigation, K_y
- Cost of deep percolation produced by overirrigation including loss of fertilizer and chemicals, and remedial costs when the ground water is contaminated, ρ_{dp}
- An expected total economic return

The preceding information can be used to determine the two cost ratios, C_{r1}, and C_{r2}, and determine the relative return, $Z/Y_m \rho_y$, using Eq. 10.37 and Fig. 10.3. The uniformity producing the expected total relative return can be selected. All the items, except the cost of deep percolation ρ_{dp}, can be easily identified. There is not much information available for the cost of remediation. However, it is expected to be greater than the cost of water. A number to express the ratio of ρ_{dp} and ρ_w can be assumed to indicate degrees of environmental concerns and used in calculations in Eq. 10.37.

In general, the cost ratios, C_{r1}, and C_{r2}, can be related to the water resources situation and environmental protection considerations as follows:

- Abundant water resources.. $Cr_1 = 0 – 0.05$
- Limited water resources.. $Cr_1 = 0.05 – 0.10$
- Zero or little environmental pollution problems.................................. $Cr_2 = 0 – 1.0$
- Considerable concerns of environmental pollution............................. $Cr_2 = 1 – 10$

A design criteria considering availability of water resources, environmental protection based in economic returns of 80% maximum return can be selected from Tab. 10.5 for any of the three uniformity parameters *UCC*, *CV*, or *EU*.

10.5.2. Field Evaluation

10.5.2.1. Significance of field evaluation

The microirrigation system should be evaluated on a regular schedule to ensure that the system's performance is maintained at or near the originally designed uniformity. Such evaluation is a preventive program and any deviation found in the evaluation requires system adjustment to make the microirrigation system perform based on its designed capacity.

The items and procedures for evaluation should be designed to be practical for field use. The easily accessed items for evaluation are pressure gage readings to show the water pressure distribution in the system and the flowmeter to indicate the rate of flow applied into the system. If both pressure and flowmeter readings remain constant, or with only small variations, the microirrigation system is functioning as originally designed. When noticeable variation is found in pressure and flowmeter readings, a field evaluation of uniformity of emitter flow should be conducted and corrective measures taken if necessary.

10.5.2.2. Uniformity measurement

The field uniformity of microirrigation expressed by any one of the uniformity parameters, *UCC, CV,* or *EU* requires measurements of emitter flow and pressure in the field. From a practical standpoint, these uniformity measurements are only for surface microirrigation systems. Theoretically, all flows from all of the emitters should be collected, which is often impractical in the field evaluation. A random 18-sample set was proposed (Bralts and Kesner, 1983) for microirrigation field uniformity estimation and subsequently adopted as an ASAE Engineering Practice (EP-458). This evaluation is based on a statistical uniformity coefficient, which is defined as $UCS=1 - CV$, (Eq. 10.16). The random 18-sample size may cause a maximum difference ± 36% in the Coefficient of Variation determination (Wu and Irudayarij, 1989) based on a 95% confidence level. This means that the *CV* estimated by only 18 samples will be in a range of 0.064 and 0.136 when the actual *CV* is 0.10. This difference expressed in percentage seems high when the *CV* is used. However, if *UCC* is used as the design criteria and using $UCS=1-CV$ as an approximation, the actual *UCC* can be considered as 0.90 and the range that the *UCC* determined by 18 samples may fall in the range of 0.936 and 0.864. In this case, the difference will be only about 4% when *UCC* is used.

Large sample size will give a better estimation of microirrigation system uniformity. A computer simulation of up to 1000 samples showed the improvement of accuracy with large sample sizes (Wu and Irudayarij, 1989). The percentage of difference in *CV* is reduced from 0.36 for 18 samples to 0.20 for 54 samples. When *UCC* is used, the percentage of difference in *UCC* will be reduced from 4% for 18 samples to 2% when the actual $CV=0.1$ (or $UCS=0.90$) based on a 95% confidence level. The improvement in uniformity estimate will be less significant when the sample size is larger than 54.

Because taking 54 measurements requires three times more effort than 18 with only a slight improvement in the uniformity coefficient value, a sample size of 18 is recommended. The emitter flowrate can be measured as the time required filling a specific volume or as the volume collected for a given time. A simple nomograph can be used for uniformity estimation for *UCS* and *CV* (Bralts and Kesner, 1983). The nomograph is designed so that the horizontal scale is one-half the size of the vertical scale (Fig. 10.6).

10.5.3. Repairs and Adjustment

10.5.3.1. Repairing leaks in the system

When significant leaks in the microirrigation system occur, they can be detected by the presence of an increase in total flowrate and a corresponding decrease in system pressure. A field investigation should be conducted to locate the leaks and repair them. Leakage will not only waste water, but also affect the system uniformity.

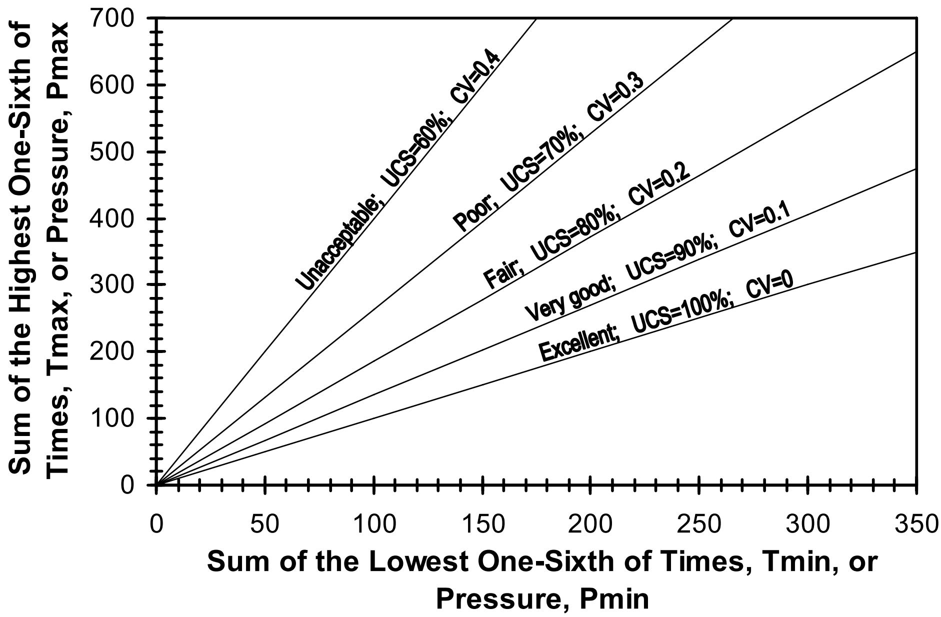

Figure 10.6. Nomograph for uniformity estimation in field evaluation by using 18 samples.

10.5.3.2. Adjustment of irrigation time

When there is a noticeable decline in total system or submain unit flowrates over a period of time, some emitters are either completely or partially clogged. There is usually a direct correlation between the percent of clogging and the percent reduction of the microirrigation system flowrates. A 10% clogging (complete and partial clogging combined) of total microirrigation emitters may cause about 10% flowrate reduction in the system (Bralts et al., 1981b). In this case, it may be necessary to evaluate the uniformity of the entire microirrigation system. If there is not much change in the system uniformity, adjustment can be made by simply increasing the irrigation time.

The adjustment of irrigation time can be determined by the relationship between a selected irrigation-scheduling parameter, X, and the total amount of irrigation, QT, based on a known water requirement for maximum yield, W_m, using Eq. 10.21. Assuming that the irrigation scheduling parameter, X, is constant and the water requirement for each irrigation event, d, as shown in Eq. 10.38 is determined based on a given evapotranspiration to contribute to the maximum yield, the time for any single irrigation event, t, can be determined by Eq. 10.40. Because X and d in Eq. 10.40 are known, the adjusted irrigation is only affected by the flowrate, Q, of the microirrigation system as follows:

$$t_1 = \frac{Q_0}{Q_1} t_0 \tag{10.62}$$

where t_1 is the adjusted time, Q_0 is the flowrate originally designed, Q_1 is the reduced flowrate determined through regular evaluation, and t_0 is the irrigation time based on the originally designed flowrate, Q_0. The adjusted irrigation time will be longer than the original time because of the reduced flowrate in the microirrigation system.

10.5.3.3. Adjustments for changes in uniformity

When there is a decrease of flowrate in the microirrigation system with a corresponding significant decrease in the uniformity, adjustments should be made to minimize the decrease in economic return. A significant drop in uniformity is considered to be an amount larger than the upper range of the uniformity as determined by the sample size of 18 emitters in the evaluation. For example, if the original design is based on a *CV* of 20% or Statistical Uniformity Coefficient, *UCS*, of 80%, the range of *CV* and *UCS* for a 95% confidence level will be 13% to 27% and 87% to 73%, respectively. Therefore, a significant uniformity decrease is present when the uniformity from the evaluation is $CV > 0.27$ and $UCS < 0.73$. When the decrease of uniformity is within the range, no adjustment is required for the uniformity change. When adjustments are required, they can be made by increasing the irrigation time to compensate for the decrease in microirrigation system flowrates as shown in the previous section.

When a significant change in uniformity occurs in the field evaluation, (i.e., the uniformity decreases from a *CV* from 0.15 to 0.25) then it is necessary to make adjustments for the uniformity changes. The adjustments can be made by determining a new optimal irrigation scheduling parameter, X_0, using Eq. 10.41. Then, using this new X_0 and the reduced flowrate, Q_1, a new irrigation time schedule can be estimated using Eq. 10.40. The new optimal irrigation scheduling parameter can also be determined graphically using Fig. 10.3. This adjustment will minimize the reduction of the total returns caused by the uniformity change.

The total relative returns can be calculated by using Eq. 10.37 or solved graphically from Fig. 10.3 as 0.66. This shows a 9% loss of total returns by the uniformity change. Because the graphs in Fig. 10.3 are plotted for a constant uniformity for the entire cropping season, the reduction of total returns for a uniformity change in only a part of the total season will be less than 9%.

LIST OF TERMS AND SYMBOLS

A_D	irrigation area under deficit condition, dimensionless (decimal)
A_{dp}	irrigation area under overirrigation, dimensionless (decimal)
a, b	coefficients of straight line distribution, dimensionless
Cr_1, Cr_2	two cost ratios used to determine appropriate irrigation schedule
CV	coefficient of variation, dimensionless (decimal)
CV_g	coefficient of variation on grouping a number of consecutive emitters as a unit, dimensionless (decimal)
CV_H	coefficient of variation caused by hydraulic variation, dimensionless (decimal)

CV_M	coefficient of variation caused by manufacturer's variation, dimensionless (decimal)
CV_C	coefficient of variation caused by clogging, dimensionless (decimal)
CV_{Hg}	coefficient of variation caused by hydraulic variation after grouping, dimensionless (decimal)
CV_{HM}	coefficient of variation caused by both hydraulic and manufacturer's variations, dimensionless (decimal)
CV_{Mg}	coefficient of variation caused by manufacturer's variation after grouping, dimensionless (decimal)
CV_{HMg}	coefficient of variation caused by both hydraulic and manufacturer's variations, after grouping, dimensionless (decimal)
CV_{HMC}	coefficient of variation caused by hydraulic, manufacturer's variation and clogging, dimensionless (decimal)
CV_{HMgC}	coefficient of variation caused by four factors: hydraulic, manufacturer's, grouping and clogging, dimensionless (decimal)
d	required irrigation depth, m^3/ha (or mm)
$\overline{d}$	average irrigation depth, m^3/ha (or mm)
EU	emission uniformity based on measurements from the lower quartile, dimensionless (decimal)
EU_K	design emission uniformity from Keller and Karmeli (1974), dimensionless (decimal)
K_y	crop reduction coefficient in deficit irrigation, dimensionless
N	number of emitters grouped together
P	fraction of emitter completely clogged, dimensionless
P_A	fraction of area, dimensionless
P_D	fraction of deficit area, dimensionless
Q	total discharge of the microirrigation system per unit of surface, m^3/h-ha
Q_0	flowrate as originally designed
Q_1	reduced flowrate
QT	irrigation water applied by the whole crop season, per unit of surface, m^3/ha
QT_0	irrigation water applied for the optimum irrigation schedule by the whole crop season, m^3/ha
QT_a	irrigation water applied for the conventional irrigation scheduling by the whole crop season, m^3/ha
QT_1	irrigation water applied for the simple irrigation scheduling by the whole crop season, m^3/ha

QT_{a+b}	irrigation water applied for zero deep percolation irrigation scheduling by the whole crop season, m^3/ha
q_{max}	minimum emitter flow, L/h
q_{min}	minimum emitter flow, L/h
q_{var}	emitter flow variation, dimensionless, (decimal)
$\bar{q}$	mean emitter flow, L/h
R^2	coefficient of correlation
S	standard deviation of emitter flow
T	total irrigation time by the whole crop season, h
t	irrigation time for one irrigation event, h
t_0	irrigation time based on the originally designed flowrate, h
t_1	adjusted time for reduced flowrate, h
UCC	uniformity coefficient of Christiansen, dimensionless (decimal)
UCS	statistical uniformity coefficient, dimensionless (decimal)
V_{dp}	volume of deep percolation per unit of surface, m^3/ha
W	seasonal irrigation water application under deficit condition per unit of surface, m^3/ha
W_m	seasonal irrigation water application for maximum yield per unit of surface, m^3/ha
X	relative irrigation depth, dimensionless
X_0	optimal relative irrigation depth, dimensionless
Y	crop yield under deficit condition per unit of surface, kg/ha
Y_m	maximum crop yield per unit of surface, kg/ha
Z	total economic return in deficit irrigation condition per unit of surface, \$/ha
Z_a	total economic return of conventional irrigation scheduling per unit of surface, \$/ha
Z_0	total economic return of optimal irrigation scheduling per unit of surface, \$/ha
Z_1	total economic return of simple irrigation scheduling per unit of surface, \$/ha
Z_{a+b}	total economic return for zero deep percolation irrigation scheduling per unit of surface, \$/ha
ρ_{dp}	cost of the loss of fertilizer and remedial work for environmental pollution (per unit volume) of deep percolation, \$/m^3
ρ_y	unit cost of production, \$/kg
ρ_w	unit cost of water, \$/m^3
$\overline{\Delta q}$	mean deviation of emitter flow from the mean value

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11. MAINTENANCE

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11.1. EMITTER OPERATION

11.1.1. Evaluation of Emitter Clogging

Emitter clogging continues to be a major problem in microirrigation systems. For high-valued annual crops and for perennial crops, where the longevity of the system is especially important, emitter clogging can cause large economic losses. Even though information is available on the factors causing clogging, control measures are not always successful. Problems can be minimized by appropriate design, installation, and operational practices. Reclamation procedures to correct clogging increase maintenance costs, and unfortunately, may not be permanent. Clogging problems often discourage the operators, and consequently cause the abandonment of the system and the return to a less efficient irrigation application method.

Emitter clogging is directly related to the quality of the irrigation water, which includes factors such as suspended particle load, chemical composition, and microbial type and population. Insect and root activities within and around the tubing can cause similar problems. Consequently, these factors dictate the type of water treatment or cultural practices necessary for clogging prevention. Clogging problems are often site-specific and solutions are not always available or economically feasible (Bucks et al., 1979; Nakayama, 1986; Nakayama and Bucks, 1991).

11.1.1.1. Source of water

No single foolproof quantitative method is available for estimating clogging potential. However, by analyzing the water for some specific constituents, possible problems can be anticipated and control measures can be formulated. Water quality evaluation is especially advisable before a new microirrigation system is installed. Most tests can be made in the laboratory. However, some analyses must be made at the sampling sites because rapid chemical and biological changes can occur after the source water is introduced into the microirrigation system. Water quality can also change throughout the year so that samples should be taken at various times over the irrigation period. The water analysis data listed in Tab. 11.1 can be classified into the physical, chemical, and biological factors that play major roles in the clogging process. These are further rated in terms of an arbitrary clogging hazard ranging from minor to severe. Clogging problems are diminished with lower concentrations of solids, salts, and bacteria in the water. Additionally, clogging is aggravated by water temperature changes. For example, the solubility of some chemical compounds decreases with an increase in temperature, whereas microbial activities often increase.

Table 11.1. Water quality criteria used for indicating emitter clogging hazards. After Bucks and Nakayama (1980).

Type of problem	Minor	Moderate	Severe
Physical			
Suspended solids[a]	50	50-100	>100
Chemical			
pH	7.0	7.0-7.5	> 8.0
Dissolved solids[a]	500	500-2000	> 2000
Manganese[a]	0.1	0.1-1.5	> 1.5
Total iron[a]	0.2	0.2-1.5	> 1.5
Hydrogen sulfide[a]	0.2	0.2-2.0	>50000
Biological			
Bacterial population[b]	10000	10000-50000	>50000

[a] Maximum measured concentration from a representative number of water samples using standard procedures for analysis (mg/L).
[b] Maximum number of bacteria per mL can be obtained from portable field samplers and laboratory analysis. Bacterial populations do reflect the presence of increased algae and microbial nutrients.

Regardless of the water source, microirrigation systems require some type of filtration to remove the bulk of the suspended materials. However, complete removal of all suspended particles is impractical. Calcium or magnesium carbonates can precipitate in filters, pipelines, and emitters when the water sources have pH values greater than 7.2, high temperatures and hardness. Temperature, soluble organic matter, and pH are factors that influence bacterial growth and slime development. Although slime bacteria grow best at temperatures between 20 and 30° C, they can still develop at lower temperatures. High bacterial counts generally reflect the presence of readily available nutrients that can adequately support the growth of algae and bacterial populations.

Fertilizer injected into the microirrigation lines may also contribute to clogging. Field surveys in Florida indicate considerable variation in fertilizer solubility in different water sources (Ford, 1977a). For example, sulfide-laden waters can react with dissolved iron and manganese to form precipitates that can cause emitter clogging. To ascertain a potential precipitation problem, a simple test can be performed as follows:

1) Add sufficient drops of a liquid fertilizer to a sample of the water source in a transparent container so that the final concentration is equivalent to the concentration of the diluted fertilizer mixture that would be flowing through the irrigation line.
2) Cover and store the mixture in the dark for 12 h.
3) Determine whether any precipitate is formed in the bottle by directing a light beam at the bottom of the container. If there is no apparent precipitation, the fertilizer should be safe to use in the specified water.

11.1.1.2. Surface water

Surface water sources should be tested for soluble salts such as iron complexes, suspended solids, and pH. Filter-clogging algae can also be identified using the illustrations shown in the American Public Health Association book, "Standard Methods for the Examination of Water and Waste Water, 20th Edition, 1998. A general indication of the suspended particulate load can be obtained by shining a beam of light through a clear transparent container with the water sample. A thick white cloud in the light beam suggests considerable suspended material, but does not indicate anything concerning the size of the particles. The amount of suspended solids in the water can be determined gravimetrically following standard laboratory procedures.

Turbidity of the water is a useful measurement when fine particles and other suspended materials are present in the water and is usually made in the laboratory. This test can be combined with laboratory filtration that gives an indication of clogging potential and at the same time permits microscopic examination of the residue. In this procedure, a vacuum filter system is used with a glass filter holder having a 25-mm cellulose-ester type filter paper with 0.45 μm size pores. If 50 mL of the water sample can pass through the filter under suction without serious clogging and discoloration of the filter, the water can be considered free of sludge and suspended solids. The filter paper can also be stained with 2% Prussian blue in 1% of hydrochloric acid to detect the ferric or oxidized form of iron (Fe^{3+}) and with 10% carbol fuchsin to indicate the presence of organic slimes. To characterize the types of organisms, the paper is pre-treated with a special immersion oil with a refractive index of 1.5 and the deposit examined under the microscope at 50 to 100 times magnification.

An additional test suitable for surface waters involves the use of flocculating agents to precipitate the fine suspended particles, which can pass through most filter systems. Three hundred mL of surface water is treated with 1 mL of 24% aluminum sulfate and 1 mL of 9% sodium hydroxide. When precipitates form at the bottom of the bottle, suspended solids are present in the water and can contribute to emitter clogging.

Total iron should be measured at the site as soon as possible after sampling because the dissolved iron can precipitate before the water sample can be taken to the laboratory for analysis. Water sampled in the field can be tested for iron with portable kits containing the necessary test chemicals. Sulfide and iron problems are rare in surface waters so that measurement of these ions is usually unnecessary.

Controlling the pH of the water is a key factor in both chemical and biocidal treatments. For example, chlorination for bacterial control is relatively ineffective above pH 7.5. Thus, acid treatment is necessary to lower the pH to optimize the biocidal action of chlorine. The complexes that iron forms with tannins or humates are more stable at pH 6.5 than at lower pH values.

Iron may be found in emitters when tannins are detected in quantities greater than 2 mg/L in the surface water. Tannin-like compounds, phenolics, and humic acids react with iron to form soluble complexes in water originating from lakes and streams. Tannin-like compounds can also be detected with portable test kits. Soluble organic compounds such as tannins cannot be removed by filtration. Organic compounds introduced into the irrigation system serve as nutrients for bacteria and contribute to slime formation.

11.1.1.3. Groundwater

Water from shallow wells 6 to 15 m deep frequently causes clogging problems, especially when the wells are open to contamination from the surface. Tests should be made for total iron, hydrogen sulfide, pH, suspended solids, and soluble salts. Actinomycetes are often present in emitters utilizing shallow well water and, *Vitreoscilla*, a filamentous bacterium, is also found in profuse quantities in open shallow wells. The slime-like materials formed by such organisms can clog emitters by their voluminous mass and gelatinous property. *Thiothrix* sulfur bacteria are a problem when hydrogen sulfide is present. *Pseudomonas* and *Enterobacter* type slime bacteria that can also oxidize the soluble ferrous iron are found in waters from many shallow wells.

The deeper wells in Florida are sometimes of artesian origin and may contain 1.0 mg/L or more hydrogen sulfide (H_2S). Problems with hydrogen sulfide can also occur in other locations throughout the world, but it may not be as common. Testing for hydrogen sulfide, total iron, soluble salts, pH, and estimating the tendency for calcium carbonate precipitation are recommended for water originating from deep wells (Ford and Tucker, 1975; Nakayama et al., 1978; Pitts et al., 1990).

11.1.1.4. Wastewater

Wastewater derived from municipal treatment facilities is becoming an important source of microirrigation water. (See also Ch. 9, Application of Biological Effluent). Wastewater use continues to increase and in certain localities may become the only source of water for landscape and recreational applications. In addition to the water quality problems of wastewater, various health restrictions have been placed on its use, especially for the irrigation of edible crops. The chemical composition of wastewater mirrors that of the source water, but typically its salinity and nutrient contents tend to increase as a result of use. Other chemicals may appear in the wastewater due to chemical treatments. Problems have occurred with wastewater that has been improperly treated, but those that have undergone adequate tertiary treatment generally have been successfully used in microirrigation.

11.1.2. Water Quality

11.1.2.1. Physical aspects

Physical clogging may be caused by factors (Tab. 11.2) such as suspended inorganic particles (sand, silt, clay, precipitates or plastic), organic materials (plant fragments, insects, animal residues, fish, snails, etc.), and microbiological debris (algae, diatoms, larvae, etc.).

Table 11.2. Physical, chemical, and biological contributors to clogging of microirrigations systems. After Bucks and Nakayama (1980).

Physical (suspended solids)	Chemical (precipitates)	Biological (bacterial activities)
Inorganic particles:	Calcium or magnesium carbonate	Filaments
Sand		
Silt		Slimes
Clay	Calcium sulfate	
Plastic		Microbial deposits:
	Heavy metal	Iron ochre
Organic particles:	hydroxides, carbonates,	Sulfur ochre
Aquatic organisms	silicates, and sulfates	Manganese ochre
(phytoplankton/algae)		
Zooplankton	Oil and other lubricants	
Snail		
Fish	Fertilizers:	
Non-aquatic organisms	Phosphate	
Insect larva	Aqueous ammonia	
Ant	Iron, copper, zinc,	
Spider	manganese	

Sand and silt particles may be carried into the irrigation water supply from open-water canals or from wells where the water is pumped directly into the microirrigation system. Such particles when introduced into the supply lines during installation or repair can cause problems unless they are flushed out from the system before any emitters are placed on the line. Physical clogging *per se* can be controlled with proper filtration and periodic flushing of laterals. However, particulate matter that combines with bacterial slimes can create a type of clogging that cannot be controlled by filtration alone. Small particulate matter inside emitters can become cemented together with bacterial slimes of the genera *Pseudomonas* and *Enterobacter*. The combined mass clogs emitters even though the individual particles are small enough to pass through the emitter. Particulate-slime type of clogging is a major problem in many areas. Periodic superchlorination treatments at 1000 mg/L active chlorine seems to be able to control the problem, but at this high concentration precaution must be taken to avoid direct contact of the solution with plants.

11.1.2.2. Chemical aspects

Salinity is an important water quality factor in irrigated agriculture. It does not contribute to emitter clogging unless the ions in solution interact with each other to form precipitates or promote slime growth. Chemical precipitates are formed following reactions of dissolved cationic constituents such as Ca, Mg, Mn or Fe with anionic ions such as sulfates, phosphates, silicates, and hydroxide (Tab. 11.3).

Table 11.3. Major chemical constituents in water associated with clogging problems.

Cation (+)		Anion (-)		Anion precipitating compounds
Insoluble scale forming		CO_3	carbonate	Ca, Mg
Ca	calcium	HCO_3	bicarbonate	Ca, Mg
Mg	magnesium	PO_4	phosphate	Ca, Mg, Fe
Fe	iron	OH	hydroxide	Ca, Mg
Mn	manganese	SO_4	sulfate	Ca, Mg, Fe, Mn
Soluble compounds				
Na	sodium	NO_3	nitrate	
K	potassium	Cl	chloride	

Precipitates can also form by the reaction of soluble cations with organic materials such as humates, sugars, amino acids and degraded organic plant and bacterial matter, which are an integral part of any surface water.

Precipitation of calcium carbonate is prevalent with waters rich in calcium and bicarbonates and clogging occurs when such precipitates accumulate in the narrow passages of the emitter. Waters can be analyzed in the laboratory for calcium, carbonates, and bicarbonates using a simple qualitative test to estimate the potential for $CaCO_3$ precipitation. A clean transparent container is filled with the water sample and ammonium hydroxide is added to raise the pH between 9.2 and 9.5. After 12 h, the sample is shaken to stir suspended solids that settled to the bottom. After shaking, the bottom of the bottle is observed in a dark room by directing a light beam at the bottom of the container. The appearance of an opaque coating of white-to-reddish sparkling particles is indicative of $CaCO_3$ precipitation; the thicker the deposit, the more severe the potential for clogging with calcium carbonate. There is an exception to the interpretation. Water containing hydrogen sulfide, and with calcium carbonate concentrations greater than 40 mg/L, will show precipitation with the ammonia test. However, in the irrigation laterals, hydrogen sulfide is acidic and can prevent the precipitation of $CaCO_3$. No $CaCO_3$ precipitation has been found in microirrigation systems using sulfide-laden water even though the calcium content may be 300 mg/L. In controlled laboratory tests, 3 mg/L hydrogen sulfide in flowing water completely dissolved thin coatings of $CaCO_3$ (Ford, 1979b). The solubility of $CaCO_3$ is related to temperature and decreases with increasing temperature (Hills et al., 1989). Thus, at elevated temperatures, precipitation of $CaCO_3$ is likely to occur. Once a precipitate is formed, lowering the temperature will not cause the precipitate to redissolve.

Iron deposits (ochre) have also created problems with microirrigation systems and severe clogging has been reported primarily in the southeastern United States (Ford, 1979a; Pitts and Capece, 1997). The soluble, reduced form of iron (ferrous ion or Fe^{2+}) is known to be present in well water from many locations. Ochre sludge that occurs at Fe^{2+} concentrations above 0.4 mg/L is usually associated with the oxidation of Fe^{2+} and the precipitation of insoluble Fe^{3+} by iron bacteria such as *Gallionella, Leptothrix, Toxothrix, Crenothrix,* and *Sphaerotilus* plus certain nonfilamentous aerobic slime bacteria of the genus *Pseudomonas* and *Enterobacter*.

The scale forming reactions in irrigation systems result from the chemical response to the changing conditions of the irrigation water. The formation of phosphate-related precipitates depends on several factors (Boman, 1990). For example, depending on pH, temperature, concentration of species in solution, time, etc., Ca and PO_4 can form several different combinations. Three forms of calcium phosphate (hypo-, meta-, and pyrophosphate) are insoluble. The naturally occurring brushite ($CaHPO_4.2H_2O$) and whitlockite ($Ca_3(PO_4)_2$) have solubilities of 0.3 kg per m^3 and 0.02 kg per m^3, respectively. Mono-orthophosphate and pyrophosphate pentahydrate have significantly higher solubilities. The solubility of all of the preceding compounds decrease with increasing pH. Phosphates not only precipitate rapidly, but the compounds they form are very stable. Reactions with Ca, Mg and Fe are of special concern because these elements are widely found in many irrigation waters. These react with phosphate to produce insoluble phosphate compounds that are not available to the plants.

Flows in microirrigation systems can be as high as several thousands of liters per minute. As a result, large amounts of dissolved chemicals are continually being introduced and distributed throughout the irrigation system. For example, a system with a 3000 L/min flowrate with water containing 1500 mg/L total dissolved solids (TDS) will have 270 kg of additional dissolved solids entering the system each hour. Correlating laboratory reports of water quality to real-life precipitate potential for irrigation systems with high flowrates is very difficult. However, information on the theoretical potential for precipitate formation for various combinations of cations and anions can be useful to determine whether a potential for clogging problems may exist. Although there are usually several possible combinations that can occur, only a single cation concentration is presented for each compound (Tab. 11.4).

11.1.2.3. Biological aspects

Biological clogging is a serious problem in microirrigation systems containing organic sediments plus iron or hydrogen sulfide. Most water sources contain carbonates and bicarbonates, which can serve as inorganic energy sources for certain slime forming autotrophic bacteria.

Several types of slime-forming organisms can deposit onto the tubing walls and contribute to clogging, particularly in the presence of Fe^{2+} and H_2S. When algae in surface waters are introduced into the system, they provide organic carbon food for the slime organisms that accumulate in the tubing. The combination of fertilizer and warming of the black lateral tubing exposed to sunlight may further enhance microbial growth.

Table 11.4. Calculated precipitate formation rates and characteristic colors for various cation and anion combinations. After Boman and Ontermaa (1994).

Cation	CO_3	PO_4	SO_4	OH	SiO_3/SiO_4	Oxide
<u>Ca (100 mg/L)</u>						
Precipitate (kg/m^3)[A]	0.312	0.264	0.336	0.180	0.288	0.144
Precipitate formula	$CaCO_3$	$Ca_3(PO4)_2$	$CaSO_4$	$Ca(OH)_2$	$CaO\text{-}SiO_2$	CaO
Anion needed (mg/L)[B]	210	158	160	85	190	140
Color of precipitate	colorless, white	colorless, white	colorless	colorless	colorless	white
<u>Mg (100 mg/L)</u>						
Precipitate (kg/m^3)	0.443	0.360	1.007	0.240	0.096	0.168
Precipitate formula	$MgCO_3$	$Mg_3(PO_4)_2$	$MgSO_4.7H_20$	$Mg(OH)_2$	Mg_2SiO_4	MgO
Anion needed (mg/L)	346	260	396	140	190	66
Color of precipitate	colorless, white	colorless, white	colorless	colorless	white	colorless
<u>Fe (1.0 mg/L)</u>						
Precipitate (kg/m^3)	0.002	0.004	0.002	0.001	0.001	0.001
Precipitate formula	$FeCO_3$	$FePO_4.2H_20$	$FeSO_4$	$Fe(OH)_2$	Fe_2Si0_4	Fe_2O_3
Anion needed (mg/L)	1.5	1.7	1.7	0.6	0.8	0.4
Color of precipitate	gray amorphous pink	white-black yellow-white black-green	yellow white	green white	colorless red-brown	black
<u>Mn (0.1 mg/L)</u>						
Precipitate (kg/m^3)	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001
Precipitate formula	$MnCO_3$	$Mn_3(PO_4)_2$	$MnSO_4$	$Mn(OH)_2$	Mn_2Si0_4	Mn_2O_3
Anion needed (mg/L)	0.2	0.1	0.2	0.06	0.08	0.04
Color of precipitate	rose, red light brown	rose, red gray	pink, rose olive	white-pink brown-black	red dark red	black

[A] Calculated amount of precipitate that can potentially be deposited in an irrigation system assuming a sufficient supply of anions is present. The calculations are based on a cation concentration of: 100 mg/L for Ca, 100 mg/L for Mg, 1.0 mg/L for Fe, and 0.1 mg/L for Mn.

[B] The minimum anion concentration that is required for the reaction to proceed completely.

Algal, actinomycete, and fungal organisms are present in all surface water sources. Quantifying algal population is of little value because of the drastic fluctuations in populations throughout the year. While filamentous algae can clog emitters, their most damaging feature is the formation of a gelatinous matrix in the tubing and emitters that serves as a base for bacterial slime growth. Surface water may also contain naturally occurring complexing agents such as tannins, phenolics, and humic acids that form complexes with the ferrous iron. Such complexing agents can be found in canal waters, which can sequester up to 2.0 mg/L of Fe^{2+}. Iron bacteria in the microirrigation lines can precipitate the iron that is part of the soluble iron complexes. Bacteria can also utilize and precipitate ferrous iron that is complexed with polyphosphates and other chelating materials used as iron amendments.

11.1.3. Causes

11.1.3.1. Physical, chemical, and biological factors

The physical, chemical, and biological factors contributing to emitter clogging are summarized in Tab. 11.2. These three factors are closely interrelated, and controlling one factor may also alleviate problems caused by the others. For example, by reducing microbial slime, the tendency of suspended particles to stick, agglomerate, and build up in microirrigation lines and emitters are also reduced. In addition, small aquatic organisms such as snail eggs and larva, that are not readily observed and analyzed, can develop into large colonies in the lateral tubings and results in a combined physical and biological problem.

Clogging problems in the southwestern United States are caused primarily by high concentrations of suspended solids and water hardness, whereas problems in the southeastern United States include insects and a combination of chemical and biological sources in association with calcium, iron, and sulfide compounds. In Hawaii, major clogging problems are associated primarily with biological growth and accumulation of slimes and filaments. In the lower Colorado River of Arizona, the predominant causes of emitter clogging and flow reduction are physical factors, followed by the combined effects of biological and chemical factors as listed in Tab. 11.5. Overall, microbial clogging is the most difficult to control and requires a greater expenditure of resources than those caused by physical clogging.

11.1.3.2. Microorganisms

Many types of bacteria are of concern in microirrigation systems. They can discolor the water, cause odors, and form precipitates and slime. They reproduce rapidly to produce capsular structures, extracellular excretions, and secondary nutrients that can be used by other organisms. Bacterial clogging develops rapidly when mineral food sources are available in addition to suspended particles where the bacteria can attach. Microscopic observation has revealed that bacteria attach to the tube surface either by physical trapping by the microspore or by secondary chemical attraction. This chemical adhesion occurs when an organic or inorganic compound formed in the water bonds to the wall of the tubing and the bacteria attach to it.

Table 11.5. Causes of clogging or flow reduction and relative percent occurrence in microirrigation emitters at Yuma, Arizona. After Gilbert et al. (1981)[a].

Causes of clogging	Occurrence (%) Individual	Total
Physical factors		
Sand grain	17	
Plastic particles	26	
Sediment	2	
Body parts of insects and animals	3	
Deformed septa[b]	7	55
Biological factors		
Microbial slime	11	
Plant roots and algal mats	3	14
Chemical factors		
Carbonate precipitates	2	
Iron-manganese precipitates	0	2
Combined factors[c]		
Physical/biological	8	
Physical/chemical	2	
Chemical/biological	6	
Physical/biological/chemical	2	18
Nondetectable (probably physical)		11

[a] Results are representative of eight emitter systems and four water treatments (C, D, E, and F, Tab. 11.10), which were operated for more than 4 years. There were 1220 emitters installed in these water treatments, and 119 with reduced flow or clogged conditions (50% of designed flow) were dissected and microscopically examined for causes of flow reductions.

[b] Silicone rubber disks were deformed by chlorine treated water and acid treatments (D and E, Tab. 11.10), which restricted flow.

[c] The observations indicated that the most likely initial cause of flow reduction was a physical factor, followed by the development of biological and chemical factors. The major physical factors involved were sand grains and plastic particles.

Detailed biological analyses of clogged emitters have shown that the most common bacteria are *Pseudomonas, Flavobacterium, Vibro, Brevibacterium, Microccus,* and *Bacillus*. The presence of *Bacillus* is prevalent on filters, but these can be greatly reduced by chemical conditioning of the water. No strictly anaerobic bacteria, such as *Clostridium* sp., are detected when the water is treated with chlorine and acid. Pigmented bacteria, *Flavobacterium lutescens* and *Cytophaga hutchinsonii* may cause the yellow coloration of the slime deposits in biologically clogged emitters, and their growth may be supported by *Pseudomonas stutzeri*, a non-pigmented bacterium. Iron bacteria, *Sphaerotilus* spp., are typically absent in water sampled from Arizona.

In the southeastern United States, bacterial clogging is associated with three types of slimes: (1) iron, (2) sulfur, and (3) nonspecific filaments and nonfilamentous slimes. Ochre (filamentous iron deposits) occurs when ferrous iron in the water is precipitated as ferric iron by the activity of filamentous bacteria such as *Gallionella, Leptothrix, Toxothrix, Crenothrix,* and *Sphaerotilus* plus nonfilamentous aerobic slimes such as *Pseudomonas* and *Enterobacter*. The primary clogging agents are the sticky bacterial slimes that adhere to the suspended solids and not necessarily the precipitated ferric iron itself. Aerobic sulfur slimes are formed by the transformation of hydrogen sulfide to elemental sulfur by the filamentous bacteria *Thiothrix* and to a lesser extent *Beggiatoa* sp. *Thiothrix* requires only traces of oxygen for its development, and its optimum pH range is between 6.7 and 7.2. Hydrogen sulfide in solution can inhibit ochre and other non-sulfur slime clogging problems. Miscellaneous bacteria such as filamentous *Vitreoscilla,* and nonfilamentous *Pseudomonas* and *Enterobacter* can also clog emitters by their sheer mass.

Iron reactions with organic complexing agents are also important in ochre formation. Certain Fe-organic complexes can stick to glass and plastic materials such as the grooves of emitters, and walls of microirrigation tubing, even when bacteria are killed with chlorine. The tenacious adhering properties of complexed Fe can be seen by the reddish-brown stains formed on rocks when the phenolics dissolved in well water complexes with Fe. This discoloration can be prevented by treating water with chlorine (0.5 mg/L NaOC1) or hydrogen peroxide (5 mg/L H_2O_2). Treatments for 30 min each hour can prevent Fe deposits on the rock only when the oxidizing biocides are being injected. Apparently, the oxidants can separate ferric iron from the complex so that Fe^{3+} cannot stick to the rock.

<u>Algae.</u> Algae are unicellular or multicellular, autotrophic, and photosynthetic protists. As with other organisms, algae require nutrients to reproduce. Their principal nutrients are carbon dioxide, nitrogen, and phosphorus. In addition, trace elements, such as iron, copper, and molybdenum, are also important. The four broad classes of algae:

Green *(Chlorophyta).* The green algae are principally freshwater species and can be unicellular or multicellular. A distinctive feature of this group is that the chlorophyll and other pigments are contained in chloroplasts, membrane-surrounded structures, which are the sites of photosynthesis. Common green algae are those of the Chlorella group.

Motile-Green *(Volvocales Euglenophyta).* Colonial in nature, these algae are bright green, unicellular, flagellated, and colonial in nature. Euglena is a member of this group of algae, as is *Mastigophora* containing chlorophyll.

Yellow-Green or Golden-Brown *(Chrysophyta).* Most forms of the Chrysophyta are unicellular. They are primarily freshwater inhabitants and their characteristic color is due to yellowish brown pigments that conceal the chlorophyll. Of this group of algae, the most important are the diatoms, which are found in both fresh and salt waters. Diatoms have shells composed mainly of silica and deposits of these shells are known as diatomaceous earth.

Blue-Green *(Cyanophyta).* The blue-green algae have simple form and are similar to bacteria in several respects. They are unicellular, usually enclosed in a sheath, and have no flagella. They differ from other algae in that their chlorophyll is not contained in chloroplasts, but is diffused throughout the cell.

Green algae can grow only in the presence of light, and thus, will not grow in buried pipelines or in black polyethylene laterals or emitters. However, enough light can enter through exposed white PVC pipes or fittings to permit growth in some parts of the microirrigation system. Whenever practical, exposed PVC pipe and fitting should be painted to reduce light penetration and algal growth. Chlorination is the recommended treatment to kill algae growing within the irrigation system.

In summary, algae contribute to the maintenance problems of microirrigation systems in several ways. Floating and suspended algae can get caught by intake screens and filters and reduce water flow. Dead algae that remain in filters and distribution lines can be used as a readily available carbon source by bacteria. Algae that pass through filters travel through the system and attach to surfaces near emitter orifices where light is available. As the algae grow, they restrict emitter discharges and eventually clog the emitter. Extensive algae growth has been observed that completely covers and clogs emitters and microsprinklers.

Algal clogging of emitters normally occurs from growth in the emitter orifice or bridging in the base of the emitters where solid particles can collect. Algae are photosynthetic organisms that may exist as single cells, as loosely organized groups of cells (colonies), as sheet-like structures, or as intricately branched filaments. Algae are most commonly found in surface water and not typically expected to be present in groundwater due to their light requirement. Algae occur in the most severe habitats on earth. Some species grow on snow in perpetually freezing temperatures; others thrive in hot springs at temperatures of 70° C or more; a few survive in extremely saline bodies of water; others withstand the pressure and low light intensity conditions 100 m and deeper below the surface of lakes or oceans.

Algae can grow profusely in reservoirs and can become very dense, particularly if the water contains plant nutrients, especially nitrogen and/or phosphorus. Algae can be a great nuisance in surface waters because, when conditions are right, they will rapidly reproduce and cover water bodies with large floating colonies called blooms.

Algae have been found in significant amounts in irrigation water from shallow wells in Florida. This is likely due to the large-sized macropores and the very shallow depths where sunlight may be available.

Iron bacteria. An emitter clogging problem occurring in certain areas of Florida is caused by iron bacteria (Ford and Tucker, 1975). Iron bacteria frequently thrive in iron-bearing water. It is unclear whether the iron bacteria exist in groundwater before well construction and multiply as the amount of iron increases due to pumping, or whether the bacteria are introduced into the aquifer from the subsoil during well construction. Well drillers should use great care to avoid the introduction of iron bacteria into the aquifer during the well drilling process. All drilling fluid should be mixed with chlorinated water at 10 mg/L free chlorine residual.

Some problem-causing microbes are iron bacteria that change soluble iron (Fe^{3+}) into the insoluble ferric hydroxide ($Fe(OH)_3$) form. The bacteria create a slime that form red, yellow or tan colored aggregates called ochre. The species *Sphaerotilus* generates sheath formations and deposits the iron around itself causing thick, slimy carpet woven tubes crusted with iron deposits. These formations (globs) can then be severed from the walls of the microirrigation tubing due to changes in pressure, temperature, flows, etc., and collect on the emitters to cause clogging.

Another iron microbe, *Gallionella,* forms stalks or ribbons of iron, which are deposited around the organism by secretions. This deposit can rapidly trap suspended particles, and thus increase the food source, resulting in an exponential growth of the colony.

Emitter clogging caused by iron oxidizing bacteria is especially difficult to control. Even very small iron concentrations (less than 0.5 mg/L) are sufficient to provide bacterial growth, which generally appears reddish. These bacteria oxidize iron from the irrigation water as an energy source. Precipitation of the iron and rapid growth of the bacteria create voluminous material that can completely clog a microirrigation system in a matter of a few weeks.

Bacteria have long been recognized to have an important role in the oxidation of ferrous iron in groundwater systems. Only recently, however, has it been known that bacteria reduce ferric iron in the soil to the ferrous state, which can then dissolve and become part of the groundwater. Because ferric iron reduction by bacteria takes place where O_2 is limited with little chance for re-oxidation, accumulation of high concentrations of ferrous iron in groundwater is possible. Iron-reducing bacteria occur most frequently between the aerobic and anaerobic zones of an aquifer system. Thus, it may be possible during well construction to isolate these high iron zones to minimize the iron problem.

Sulfur bacteria. Some Florida microirrigation systems have ceased to function properly because of filter and emitter clogging caused by sulfur bacteria (Ford, 1976). *Thiothrix nivea* is usually found in high concentrations in warm mineral springs and contributes to this problem. This bacterium oxidizes hydrogen sulfide to sulfur and can clog small openings within a short period. *Beggiatoa,* another sulfur bacterium, is also often found in microirrigation systems. Continuous chlorine or copper treatment can control sulfur bacterial problems.

Other groups of bacteria that can cause problems are those that fix sulfur or sulfur derivatives. A beneficial bacterium in this group is *Thiobacillus,* which is tolerant to pH levels below 1.0. These bacteria utilize elemental sulfur (S) in their metabolic processes and convert it into sulfuric acid. This bacterium is one reason that powdered sulfur can be applied to the soil to decrease soil pH. *Desulfovibrio sulfuricans* also tolerate low pH, but they change sulfate (SO_4) and other sulfur compounds to hydrogen sulfide (H_2S), an acidic gas. The bacterial formation is a whitish slime with a strong odor of rotten egg typical of H_2S. When conditions have been right, some irrigation systems have been impaired within two weeks due to this bacterium. Therefore, when foul odor is evident in an irrigation system, continuous and careful observation of the system combined with a well-planned preventive maintenance are advisable in order to avoid exponential population growth.

11.1.3.3. Macroorganisms

Clogging of microsprinklers in a Florida citrus grove was noted to be inversely related to the orifice dimension of the emitters (Boman, 1995). Clogging occurred when irrigation water from a pond was used where the water was chemically conditioned, and filtered through a sand media filter. Emitter clogging was caused by algae (46%), ants and spiders, (34%), snails (16%), and solid particles (4%) such as sand and bits of PVC. About 20% of the 0.76 mm orifice emitters required cleaning or replacement during each quarter compared with about 14% for the 1.02 mm, 7% for the 1.27 mm, and 5% for the 1.52 mm orifice emitters.

Other pests can damage or clog emitters or system components and increase maintenance costs. Some cause leakage problems and others cause clogging. Coyotes and burrowing animals have been observed to damage microirrigation tubing. Similarly, rats and mice have chewed holes in microirrigation tubing (Stansly and Pitts, 1990). *Tortricidae* (Lepidoptera) larvae and pupae of *Chrysoperla externa* (Hagan) have caused emitter clogging (Childers et al., 1992). Emitter clogging by spiders and ants is a problem in many surface microirrigation and microsprinkler systems. Additional problems include damage to spaghetti tubing and destruction of diaphragms in pressure compensating emitters.

Larvae. The larvae of *Selenisa sueroides* (Guenee) have damaged spaghetti tubing of microirrigation systems in south Florida citrus groves (Brushwein et al., 1989). Larvae of *S. sueroides* used the spaghetti tubing on microsprinkler assemblies as an alternate host to native plant species with hollow stems. The *S. sueroides* caterpillars chewed holes in the spaghetti tubing in order to enter and pupate. The deterioration appeared to be selective as *S. sueroides* damaged stake assemblies constructed with black tubing to a larger extent than with colored spaghetti tubing (Boman and Bullock, 1994). In addition, tubing composition could also affect the severity of damage, with a higher incidence of damage on polyethylene tubing compared with vinyl spaghetti tubing, and even less damage on assemblies made with colored tubing.

Problems caused by the *S. sueroides* caterpillars can be controlled by methods other than pesticide treatment of the emitters (Boman et al., 1995a). Elimination of known host plants in early autumn through herbicide application and mowing is probably more cost effective than pesticide treatment. When infestations of *S. sueroides* caterpillars persist after mid-September, spray applications of liquid Teflon® to the emitter assemblies provide some protection from *S. sueroides* larvae.

Ants. Ants frequently cause clogging of emitters leading to nonuniform water application. In addition to causing clogging, ants can also physically damage certain types of emitters causing increased flowrates. For example, red imported fire ants (*Solenopsis invicta*, Buren) chewed and damaged the silicone diaphragms that control flow of micropulsators (Boman et al., 1995b). Ant activities decreased the diaphragm mass (partial to complete removal) and increased the orifice diameters. Extensive damage occurred within a 16-month period and more than 9000 m of microirrigation tubing with internal compensating emitters had to be replaced (Boman, 2000).

Plant roots. Problems with plant roots affecting water flow in subsurface microirrigation systems have been observed. This is a case of "the root biting the hand that feeds it." Roots can penetrate into cracks and grow within the tubing or the emitter and restrict water flow. Control of root activity has been done by chemical injection or impregnation of the tubing, emitter, or filter with Trifluralin (Ruskin and Ferguson, 1998). Massive root growth has been observed to physically pinch flexible tubing, and thus restrict water flow.

11.2. WATER TREATMENT

Microirrigation water quality ideally should be similar to municipal water where the source water has been treated to remove suspended particles, color, odor, and pathogenic bacteria. However, municipal water is not practical for use in crop production. Instead, onsite treatment of water is made to a level acceptable for proper performance of the microirrigation system. The pioneers of microirrigation surely did not envision the need for elaborate water treatment, but because emitter operation is the key to the success of the whole system, this subject has become the focal point of system design, operation, and maintenance.

11.2.1. Filtration

With the exception of municipal water sources, irrigation water usually requires some sort of filtration treatment. Particles present in the water range in size from the submicron virus to the larger sand-size fractions as listed in Tab. 11.6.

Table 11.6. Classification of screens and particle sizes.

Screen mesh number	Equivalent diameter (μm)	Particle designation	Equivalent diameter (μm)
16	1180	Coarse sand	>1000
20	850	Medium sand	250-500
30	600	Very fine sand	50-250
40	425	Silt	2-50
100	150	Clay	<2
140	106	Bacteria	0.4-2
170	90	Virus	<0.4
200	75		
270	53		
400	38		

The silt-size particles are visible to the eye, but not the smaller clay-size particles. The relative sizes of the particles are illustrated in Fig. 11.1. The size of soft, organic particles is difficult to pinpoint accurately because these suspensions behave differently from solid particles especially in flow situations. The amount of suspension present in irrigation water ranges from a few mg/L to greater than 1000 mg/L. Turbidity as an indication of suspended load can be observed in the 50 mg/L range and higher depending upon the particle size.

In practice, the suspended solid concentration in surface irrigation water is much greater than 10 mg/L and in reality represents a tremendous amount of solids that passes through pipelines and especially the emitters. When the suspended materials are left in the pipelines, they can eventually become cemented together by microbial byproducts and chemical reactions to form larger particles. As a consequence, significant changes can occur in the flow and pressure characteristics of the supply lines and emitters. Complete removal of the suspended materials from water used for microirrigation is impractical. For industrial applications where high pressure and flow conditions prevail, the general rule is that the particles of least one-half the diameter of the pore opening and larger should be removed. However, field experience with microirrigation systems with low pressure and flow has shown that the particle sizes should be in the order of one-tenth the emitter pathway and orifice opening. Because filter removal of the finer particles becomes cost prohibitive, water treatment is aimed primarily at removing the larger particle sizes and allowing the final suspended load to be in the range that the emitters and delivery system can tolerate for long operational periods. Removal of suspended particles from the microirrigation system also extends its useful life.

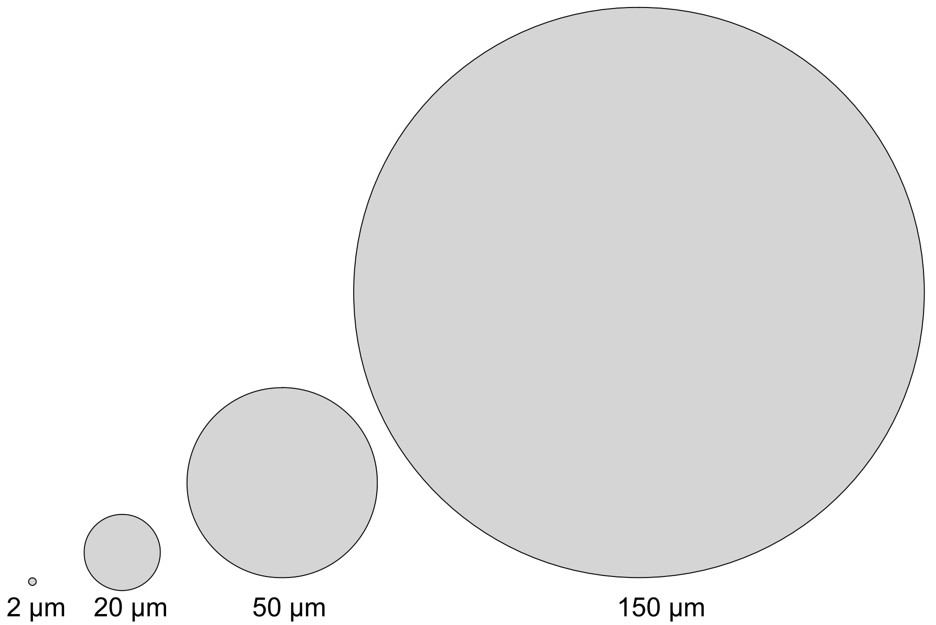

Figure 11.1. Relationship of different particle sizes.

Filtration equipment used for removing the suspended solids in microirrigation systems is based on technology developed for industrial, municipal, and domestic water treatment operations. Transfer of such technology with additional modifications and refinements has been successful. These involve adaptation of automatic cleaning process and weather-protection for the equipment to withstand extremes in the outdoor working environment. The use of filters has become important and the filter types are classified descriptively as screen, media, disk, cyclonic, and settling basins (Fig 11.2).

11.2.1.1. Screen filters

Screen filters are the most frequently used type in microirrigation systems for removing particles. The method of operation varies with the manufacturer's design and relates to the way that water entry, circulation, and exit are handled. Some models (Fig. 11.2) operate with water coming from the inside of the screen and exiting from the periphery, whereas others are designed with water flowing in the opposite direction. When properly sized and maintained, screen filters do an adequate job of removing suspended particles from the water.

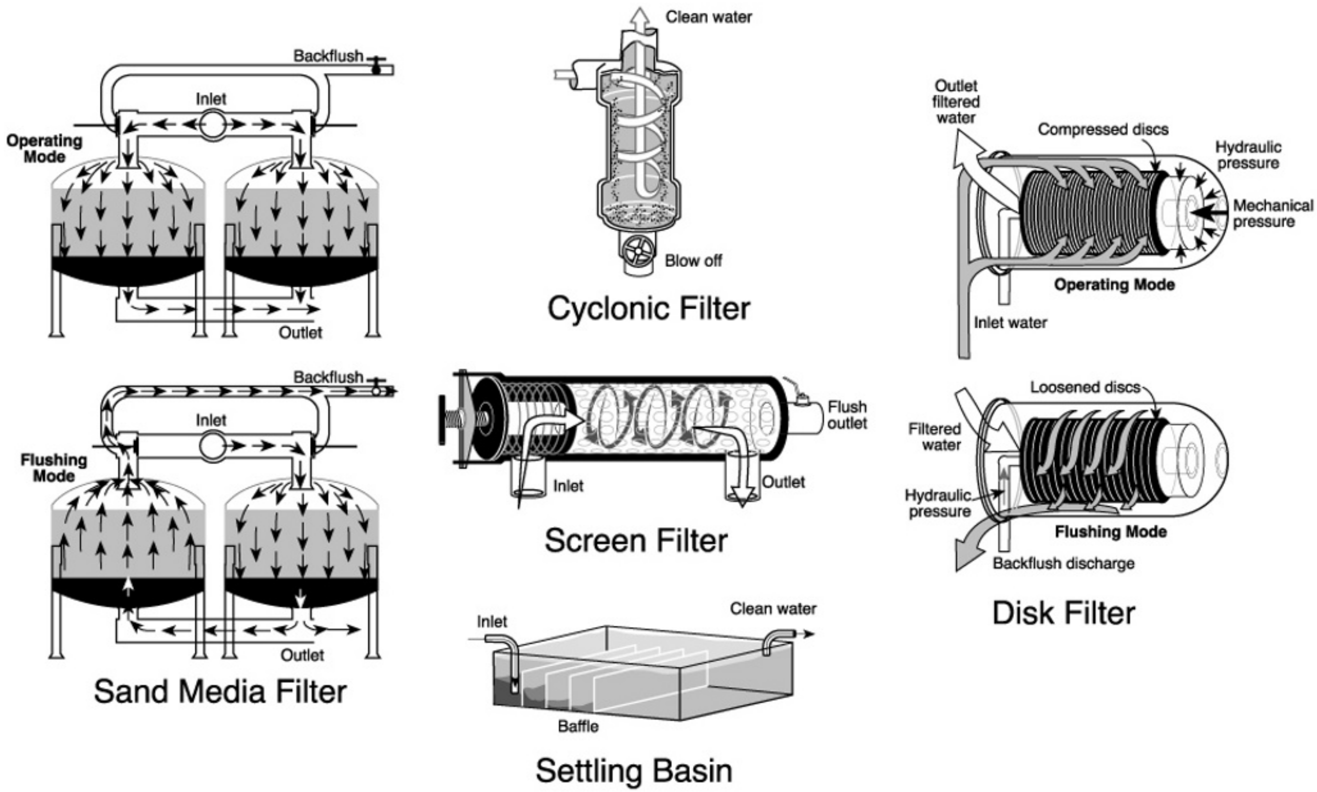

Figure 11.2. Schematic description of various sediment removing devices. Courtesy of Kansas State University, adapted from Nakayama and Bucks (1986).

Some screen filters have been designed using the cross flow principal to improve load capacity where the particle buildup on the screen is washed away by the flowing liquid. This operation provides a self-cleaning, backwashing capability without the need to dismantle the equipment for cleaning. The mesh sizes in the 140 to 200 ranges are used primarily to remove very fine sand particles. In actual operation, successively finer particles are removed because of the buildup of materials on the screen opening leading to an effective diameter smaller than the initial value. High amounts of algal debris are very difficult to handle with screen filters. The soft algal material tends to intertwine between the screen mesh and removal is difficult when the packing becomes dense.

Screens are usually constructed from corrosion resistant stainless steel and plastic materials. A good support for the screening component, which may be soft-textured, cloth-like material or stiff metal wire mesh, is needed to prevent deformation caused by pressure differentials. Screens must be inspected routinely for physical integrity. A minor tear or mesh hole enlargement can drastically affect the particle removing ability of the screen because water and particle flows are disproportionately greater through the enlarged opening than the normal screen opening. Pressure gauges at the inlet and exit sides of the filter give an indication about the operational condition of the screen. The appearance of pressure differences between the gauges indicates that the screen is beginning to clog. In contrast, when no pressure change occurs over a long period, the screens or seals may be broken. For self-cleaning screen systems, pressure changes are less noticeable than the manual cleaning types.

A slight modification of the rigid screen is the “bag” type filter with soft, flexible sides that conform to the surrounding basket when in operation. This type is usually made of materials that can be cleaned a few times before they must be discarded. Cartridge filters with rigid sides operate in a similar manner with inserts that can be washed a few times before disposal. Cartridge filters and Y-strainers are installed primarily in home garden, nurseries, and landscapes where they do not encounter high sediment loading.

Non-pressurized, gravity screen filters are installed in an irrigation canal before the pump intake or delivery system. These are designed to remove large organic debris such as leaves and weeds. In some cases, smaller screen openings have been used to remove gravel, sand, and silt where the suspended load is extremely high. Screening devices have been constructed to operate like a looping conveyor belt to make the screens self-cleaning. Water jets are also directed at an appropriate angle to the screen to wash away particles that become entrapped in the mesh openings.

Self-cleaning screens have been available for many years, but saw limited use for agricultural irrigation until improved designs were developed. These improved filters have a rotating mechanism inside them that can “scrub" the contaminants off the surface of the screen when it starts to accumulate debris. Several different designs for these types of filters are available. Some filters are based on a rotating cleaning (flushing) feature with a hydraulically driven mechanism, whereas others depend on an electric motor to rotate the cleaning mechanism. Self-cleaning screen filters require only a small installation site, and use little water for the backwash operation. They have automatic flushing that is triggered by a differential pressure switch. The complete cycle takes only 10 to 15 s, with a backwash volume typically only 75 to 200 L. These filters have been used successfully with surface water containing high organic loads.

11.2.1.2. Disk filters

Disk filters have more surface area than screen filters of similar sizes and like screen filters must be cleaned periodically (Burt et al., 1998). The filtration element in disk filters consists of a number of plastic or plastic-coated metal disks that are placed side-by-side on a telescopic circular shaft inside the housing (Fig 11.2). When these disks are stacked tightly together, they form a cylindrical filtering body, which resembles a deep tubular screen. Water flows through the disks from the outside inwards along the radii of the disks. Particles suspended in the water are trapped in the grooves of the disks, and clean water is collected in the center of the disks. The top groove of each disk is at an opposing angle to the bottom grove of the previous disk.

The disk elements can be manually or automatically cleaned. During manual cleaning, the housing is removed, the telescopic shaft is expanded, and the compressed disks separated for easy cleaning. The filter is normally cleaned by rinsing with a hose. The telescopic shaft prevents the individual disks from falling off the shaft during rinsing. On automatic flushing systems, the backflush is triggered by a preset pressure differential. This pressure differential opens the exhaust valve and water flows backwards through the disks, removing trapped particles from the grooves. The grooves of each disk are randomly positioned relative to the adjacent disks, so a matrix of various screens is formed. Water passing through the cylinder will encounter 12 to 32 groove intersections, depending upon the size of the disk mesh. The extent of filtration depends upon the number of grooves in the individual grooved rings. Typical filters are equivalent to 40, 80, 120, 140, and 200 mesh screens.

Disk filters are a good choice for small flowrates because they have a larger filtration capacity than screen filters, and because media filters are more expensive for low flowrates. The small disk units are often composed of a single filter element that must be disassembled and cleaned manually. Larger units are available in batteries of parallel cylinders. Automatic backwashing may require a higher pressure (275 to 345 kPa) than is available from the irrigation pump, so a special booster pump to supply pressurized backwash water may be needed. Typical differential pressures at the time of backflush are 40 to 55 kPa. During backflush, the disks are separated. In the case of automatic flushing, multi-jet nozzles provide tangential spray on the loosened disks. As the disks spin from the spray, the retained debris is flushed outward. The volume of water used for backflushing is typically less than that used for media tank filtration. Disk filters are generally not recommended for removal of large sand loads, as sand tends to become lodged between the disks during backflushing. Problems are also reported when they are used with stringy algae.

The rules for pre-treatment and adjustment of frequency, duration, flowrate, and dwell time are similar to those found for media filters. Typical disk filters are made almost entirely of plastic, so corrosion is not a major concern. Periodic lubrication is required on some of the filter parts.

11.2.1.3. Media filters

Pressure-type, high-flow sand or mix-bed media filters are the more popular ones used to clarify irrigation water for microirrigation systems (Fig 11.2). Gravity operating sand media filters have low flowrates, and thus, require large surface area to produce the equivalent volume of filtered water as pressurized filters. Almost the full depth of the sand is used in the pressurized filters compared with gravity filters, where surface action is the primary filtration mechanism. In either case, the filtration process actually becomes more efficient with passage of time because successively smaller particles can be filtered out as the flow passages become smaller. Unfortunately, the filtering operation cannot proceed indefinitely because the resistance to water flow increases and the flowrates are drastically reduced. Sand media filtration appears to be a simple process, yet many complex relations have been formulated to explain the filtration and flow characteristics in the sand bed.

Filter capacity is designated in terms of flow volume per unit time per unit of bed area. Larger banks of media filtration units, as well as other types of filtration systems, can be placed in a parallel arrangement (Fig. 11.3) to accommodate the design flow of the system while staying within the manufacturer's recommendations for filtration for a single unit. Flowrates encountered in microirrigation systems range from 80 to 2,000 L/min-m^2 with finer filtration occurring at the lower rates. Part of the filter body is packed with silica sand or equivalent crushed material that is inert to water and chemicals. In some parts of the world, beach sand originating from coral material is available, but it should not be used because it is composed of calcium carbonate. The manufacturer's recommendation concerning the amount, type, and size of fill material to use must be followed because the physical dimension of the media container has been optimized for a specific volume of filtering agent, pressure, and flowrate. Conceivably, sand-size particles carried in by the raw water can change the depth of the bed and this factor must be noted to avoid detrimental changes to filter performance.

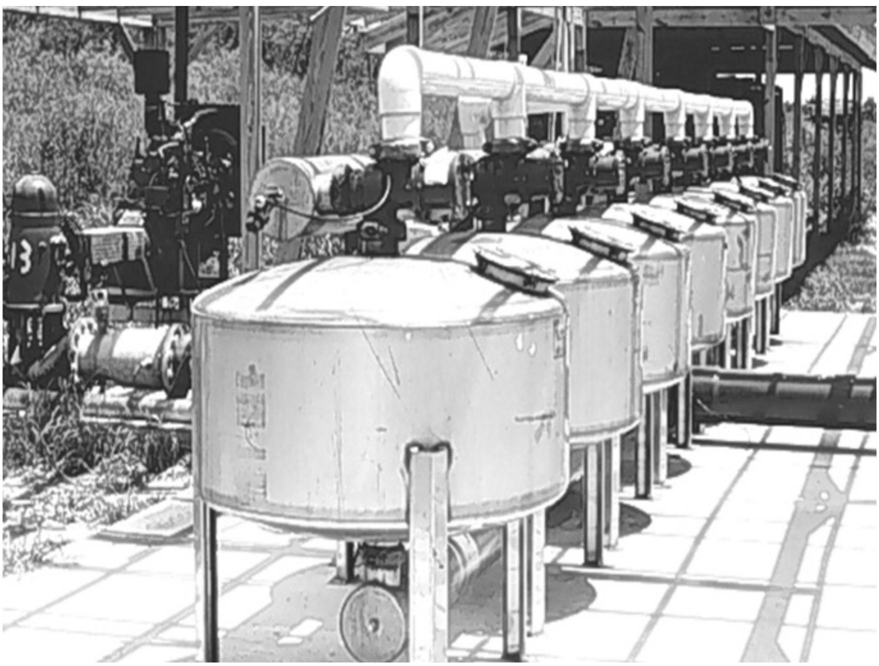

Figure 11.3. Parallel multiple arrangement of sand media filter units.

The sand sizes usually used in the filters range from No. 11 (0.79 mm), 16 (0.66 mm) and 20 (0.46 mm) that give filtration of particles in the 75, 50, and 40 μm ranges, respectively. The major classifications of other sand sizes are listed in Tab. 11.6. Actually, the sand particles are not perfect spheres or single dimensioned, but have irregular edges with a range of sizes, so that filtration for a given particle size depends upon a variety of physical factors that make up the filter medium.

No universal guide has been developed that would help to predict accurately when filter cleaning or backwashing is necessary. Predicting the time of filter duration, *T*, is strictly empirical, and a useful relation has been developed as follows:

$$T = f\,[\,(A^2 p^4\, H S L) / (V^{1.5} c)\,] \tag{11.1}$$

where c is the concentration of suspended particles in the water (g/m^3), A is the area of filter bed (m^2), p is the porosity, H is the terminal head loss (kPa), S is the surge or changes occurring in the flowrate through the sand filter (m^3/s), L is the depth of penetration (m), and V is the filtration rate (m^3/s). Operators soon find by experience the time interval needed between cleaning. Decision on when to backwash usually is related to the pressure differential developed between the inlet and outlet sections of the filter system, in the order of 69 kPa and less. "Rat holing" involves the formation of large, interconnected pores or tunnels in the sand media and decreases filter efficiency. When this happens, pressure differential is slow to develop and pressure differential cannot be relied upon as a guide for backwashing. In most instances, media filters have been able to operate properly from 1 to 12 h or even longer without backwashing. The selection of the filter operation period between backwashing is based primarily on convenience and cost.

Backwashing is a critical part of media filter operation and performance. The reverse flow velocity must be adequate to cause the separation and suspension of sand material into individual particles. Media filter design must allow for the expansion of the bed. Otherwise, the sand would be lost with the backwash water. Increasing the backwash flowrate beyond the suspension or fluidized rate serves no useful purpose unless some deeply trapped particles are present. Even then, water is wasted unless provision is made to reuse the water in other parts of the field. In the fluidized state, where particle-to-particle contact in motion is maximum, sand particles interact to rub off the loosely adhered materials. The initial backwash water is extremely turbid, followed by a gradual clearing. Backwash operation should take from 2 to 5 min. Inspection of the backwash water by passing it through a transparent plastic pipe that can withstand the operating line pressure is a simple method for checking the efficiency of the cleaning operation. Periodic inspection of the filter bed right after backwashing should be made to determine whether the sand particles are loosely packed as in the original condition. Additional sand may be required when sand is washed away, or a complete change may be needed when backwashing cannot remove the organic or other materials adhering to the sand grains.

The first increment of water entering the lines immediately after backwashing may be of similar quality as the untreated water when raw water is used for backwashing. To avoid this, dual media filter systems are usually installed, where the filtered water from one tank is used to backwash others. Another alternative is to install a bypass or dump valve arrangement to get rid of the first increment of water after backwashing. Again, a transparent pipe to monitor the quality of the filtered water entering the main distribution line is useful. In addition, screen filters should be installed downstream from the media to prevent accidental introduction of sand into the lines.

Caking or cementation of the media can result in complete clogging of the bed, or alternately, the formation of large, continuous pores called "rat holes" that decrease filter performance. In such cases, filtration is minimal and backwashing serves no beneficial purpose. This situation can be brought about through microbial aggregation of the sand granules where backwashing fails to disperse and remove the aggregating materials properly. The filter beds are an extremely good environment for microbial activity because organic nutrients are readily available. Cementing of the sand with suspended silt and clay particles can also occur by chemical reactions caused by calcium carbonate precipitation. A particularly good example of this condition has been observed when water from a well with high concentrations of dissolved carbon dioxide is passed through the sand filters. When the ambient pressure is decreased from that of the originating water, carbon dioxide is released into the atmosphere and calcium carbonate precipitates because of the resultant increase in pH.

11.2.1.4. Settling basins

Sedimentation or settling basins (Fig. 11.2) are used for clarifying waters, especially where the suspended loads of the water are extremely high and would otherwise quickly overload the filter system. Municipal water treatment systems using settling basins have been described in detail (Urquhart, 1959). Settling basins can also aid in removing soluble sulfides and heavy metals such as iron and manganese that create special emitter clogging problems. The reduced forms of manganese and iron when allowed to oxidized to the insoluble compounds in the basins can precipitate and can be filtered out before they can get into the microirrigation lines. The basins need not be elaborate structures as long as they can be adequately cleaned and maintained. Land availability usually limits the installation of the basins.

The settling behavior of suspended particles can be described by Stokes' equation as follows:

$$V = \mathrm{g}\ (d_S - d_W)\ D^2 / 18\mu \qquad (11.2)$$

where V is the velocity of the particle (cm/s), g is the gravitational acceleration constant (cm/s^2), d_s and d_w are the densities of the particle and water (g/cm^3), respectively, D is the diameter of the particle (cm), and μ is the liquid viscosity (g/cm-s).

An idealized settling basin is illustrated in Fig. 11.4. A particle with a settling velocity *(v_o)* at height *(H_o)* when it follows the path V will be removed once it touches the basin bottom. Other suspended particles entering the basin with heights less than h_o will follow similar parallel paths as V and will also be removed. Suspended particles with settling velocities $v_i < v_o$ will follow another path v_i and will be removed when their entrance elevation is less than h_i, and will be carried out by the main stream if the entrance height is greater than h_i.

The net time for settling is $t = L/V$ and the critical settling velocity is $V_o = h_o/t_o$, but because $V = Q/h_oW$, where W is the width and the product W•L is the area of the basin, these factors can be equated to

$$Vo = h_o w/L = Q/W{\bullet}L = Q/A \qquad (11.3)$$

Thus, the ratio *Q/A*, the overflow rate or surface loading, defines the minimum particle sedimentation velocity for complete removal of materials passing through the settling zone.

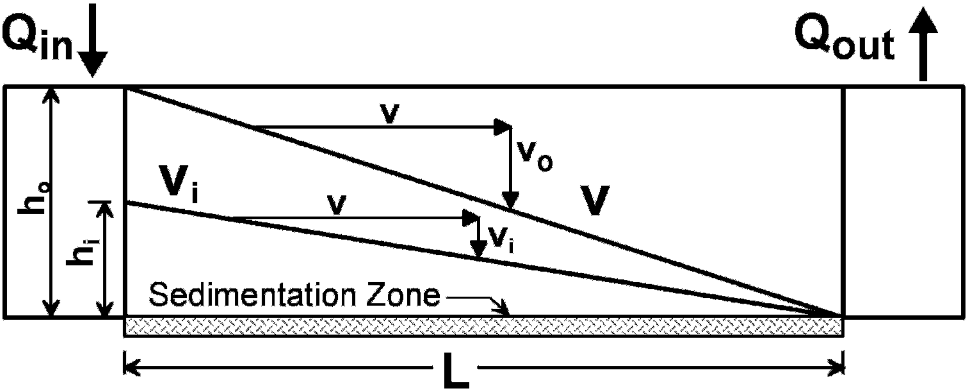

Figure 11.4. Schematic of sedimentation behavior in a settling basin. After Fair and Geyer, 1958.

Water velocities in the sediment basin cannot exceed a critical value; otherwise scouring of the settled particles will occur and the deposited materials will be carried out with the flow. This critical velocity V_c can be related to the various parameters by

$$V_c = [\,(8k/f)\bullet g\bullet(d_p - d_w)D]^{1/2} \tag{11.4}$$

where k ranges from 0.04 for single particles to 0.06 for sticky materials, f is a friction factor equal to 0.03, g is the gravitational constant, d_p and d_w are the densities of the particle and water, respectively, and D is the diameter of the particle. To avoid scouring velocities, the ratio of the basin depth and/or surface area, A_s, to the cross sectional area, A_c, must be kept below a threshold value as

$$L/h = A_s/A_c = V_c/V_s \bullet K \tag{11.5}$$

where $K = 1$ for an ideal basin.

By using similar approaches for other particle sizes, a practical limit can be estimated for basin dimensions and overflow velocity. Experience based on municipal sedimentation basins preceding sand filter systems indicates an average overflow velocity of 25 cm/s with minimum and maximum ranging by a factor of three. However, the velocity within the basin is not uniform throughout the cross sectional area of the basin (i.e., velocity is zero at the bottom and wall, and progressively larger closer to the water surface).

The preceding is applicable for an ideal situation. However, uncontrollable environmental factors such as wind and wave action, convection currents caused by temperature gradients, biological activities, and variable inlet velocities and liquid densities alter the flow pattern in the basin and affect the initial estimate of basin design.

Sedimentation ponds suffer from other shortcomings, the major ones being algal growth and organic matter decomposition. Control is limited to the application of algicide at low concentrations to avoid damage to plants that receive the treated water. Wind-blown dust and debris also detrimentally affect the aesthetic condition of the basin and create management problems.

11.2.1.5. Cyclonic filters or centrifugal separators

Cyclonic filters are in-line equipment that is used to remove suspended materials with specific gravities greater than water. Particle size need not be categorized because any dense particle can be potentially removed. Their operational principle is entirely different from the screen or media filters, but because the end result is similar, they are sometimes considered as filters. Normally, organic materials that are less dense than water are not removed unless they are bonded to the heavier particles. By directing liquid mixture tangentially at the inlet section of the chamber, kinetic energy is converted to centrifugal force. This is equivalent to increasing the gravitational factor of Stokes' equation that causes particle separation to occur during the period that a given volume of water moves from the inlet to outlet ports. Various types of internal construction are used to aid in optimizing the flow geometry. Centrifugal force directs solids to the outer edge or perimeter and the particles then drop to the less turbulent part of the chamber to be purged from the separator. The rest of the liquid flow, with the particles removed, is directed radially inward due to the lower pressure and up through the outlet port. A pressure drop occurs across the separator even though the water is not passed through tiny pores as in the case of other types of filter systems.

11.2.1.6. Filter design and operation

The design capacity of any type of filter installation should closely match the actual flow of the microirrigation system. Filters are most efficient at their rated capacity. When filtration capacity is too small, frequent backwashing or cleaning is required for media and screen filters and sediment basins. Also, when the flowrate is too small, undesirable flow patterns can occur especially in the cyclonic filters that decrease their efficiency. On the other hand, filtration overcapacity also leads to waste in material and equipment performance.

11.2.2. Chemical Treatment

Physical, chemical, and biological factors are responsible for the clogging of emitters. Physical problems can be alleviated by water filtration. The remaining two factors require other types of water treatment typically involving the addition of pH-modifying and bactericidal chemicals. Selecting the amount and type of chemicals for water treatment requires an understanding of the composition of the water and the reactions that the chemicals undergo when they are added to the water.

11.2.2.1. Chemical precipitation

Clogging caused by the formation of insoluble salts is often the result of chemical reactions at the orifice and internal parts of emitters. One of the primary chemical constituents responsible for clogging is calcium carbonate formed from soluble calcium and carbonates present in the irrigation water. Removal of the dissolved salts with ion exchange columns or reverse osmosis equipment is impractical. The other alternative is to prevent the precipitates from forming by controlling solution pH. Before this is done, however, the water analysis should be evaluated to determine whether carbonate precipitation would occur. The classical Langelier Saturation Index *(LSI)* concept provides a systematic approach for determining the tendency for $CaCO_3$ formation (Langelier, 1936). It is based on relating a calculated pH (pH_c) to the measured pH (pH_m) of the water. The calculated pH_c is obtained from the Ca^{2+}, HCO_3^-, and total salt concentrations of the water. This concept has been applied to evaluate $CaCO_3$ precipitation tendency in irrigation water (Bower et al., 1965).

The following simplified derivation of *LSI* involves the definitions of the solubility product of $CaCO_3$, K_S, and the dissociation constant K_d of HCO_3^-

$$Ca^{2+} + CO_3^{2-} = CaCO_3 \text{ (solid)} \tag{11.6}$$

$$K_s = (Ca^{2+})(CO_3^{2-}) \tag{11.7}$$

$$HCO_3^- = H^+ + CO_3^{2-} \tag{11.8}$$

$$K_d = (H^+)(CO_3^{2-})/(HCO_3^-) \tag{11.9}$$

Division of K_s by K_d gives

$$K_s/K_d = (Ca^{2+})(HCO_3^-)/(H^+) \tag{11.10}$$

The logarithm of the various parts of the preceding equation yields:

$$\log K_s - \log K_d = \log (Ca^{2+}) + \log (HCO_3^-) - \log (H^+) \tag{11.11}$$

The negative log of the hydrogen ion activity is defined as pH, and under equilibrium condition is a distinct and identifiable value. For simplification, the solution is assumed closed or unexposed to atmospheric carbon dioxide. Langelier proposed that by calculating the pH of the solution using Eq. 11.11, and comparing this calculated pH_c with the measured pH_m of the test solution, the difference between these calculated and measured pH values would give an indication of the precipitation potential of the Ca and bicarbonates. When $pH_m - pH_c = 0$, the constituents are in equilibrium, when $pH_m - pH_c < 0$, no precipitation will occur, and when $pH_m - pH_c > 0$ then the precipitation of $CaCO_3$ is very likely to occur. By redefining Eq. 11.11 in terms of negative logarithms with "p" representing such a translation, the equation becomes

$$pH_c = (pK_d - pK_s) + p[Ca] + p[HCO_3] + p(ACF) \tag{11.12}$$

In the original derivation, total alkalinity ($= HCO_3^- + 2CO_3^{2-} + OH^- - H^+$) was used, but under the conditions encountered, HCO_3^- is the dominant species so that this concentration is usually used. The term ACF is the activity coefficient factor and includes the activity coefficients for Ca^{2+} and HCO_3^-. This is necessary to correct for the non-ideality of the solution because the dissociation and solubility product constants defined by Eqs. 11.7 and 11.9 are derived in terms of an ideal solution, where the activity coefficients are unity.

Both K_d and K_c values are temperature dependent and the relation to express this dependency is given by:

$$pK_d - pK_s = 2.586 - 2.621 \times 10^{-2}t + 1.01 \times 10^{-4}t^2 \qquad (11.13)$$

where t is the solution temperature in degree Celsius.

Because the calcium carbonate solubility product and the carbonate dissociation constants are temperature dependent, the calculated Langelier saturation index is also temperature related. The index can change from negative to positive values over the temperature range encountered by the microirrigation tubing and emitters under field conditions. An example of temperature effects on *LSI* is presented in Tab. 11.7 for a specified water quality. Over the temperature range of 10 to 50° C, the calculated *LSIs* change from negative to positive values indicating an increase in potential for $CaCO_3$ precipitation as the temperature increases. Once precipitates are formed, whether caused by temperature or other mechanisms, redissolution by reversing the condition does not take place at the same rate, but rather at a much slower rate.

Table 11.7 Effect of temperature on Langelier Saturation Index *(LSI).*

Variable	Temperature, °C				
	10	20	30	40	50
LSI	-0.2	0.0	0.2	0.4	0.6

Solution composition: Ca = 38 mg/L; alkalinity = 268 mg/L; pH = 7.7; TDS = 600 mg/L

The ACF factor is also temperature dependent, but the difference in this factor for the temperature range of 0 to 50° C is only in the order of 0.02, and thus, the temperature factor for ACF can be ignored for most practical situations. However, ACF is related to solution concentration and can be related to the equation:

$$p(ACF) = 7.790 \times 10^{-2} + 2.160 \times 10^{-2}\,TDS - 5.477 \times 10^{-4}\,TDS^2 + 5.323 \times 10^{-6}\,TDS^3 \qquad (11.14)$$

where TDS is the total dissolved ion concentration in me/L.

11.2.2.2. Acid treatment

Two important aspects of water treatment and precipitation potential can be derived from the various equations presented relating to $CaCO_3$ precipitation. First, adjusting the solution pH or pH_m by acid addition will force the saturation index to become negative so that precipitation can be prevented. With irrigation waters close to a *LSI* equilibrium value of zero, adjustment of 0.5 pH unit is usually sufficient to obtain a negative *LSI.*

A spontaneous change in pH can occur especially for water from wells that contain large concentrations of dissolved CO_2 brought about by a high hydrostatic pressure in the aquifer. A decrease in total pressure when the well water is exposed to atmospheric pressure causes the release of solution CO_2. This loss of dissolved CO_2 causes the solution pH to increase and $CaCO_3$ to precipitate if it was dissolved in the groundwater.

The Langelier saturation index value, while easily applied, cannot be used to determine the quantity of acid needed to adjust the pH of the irrigation water to the level necessary to prevent carbonate precipitation. This quantity can only be determined by acid titration of the water. The procedure involves adding known increments of a standard acid to the test water and measuring the pH changes occurring in the mixture. An example of such a titration curve is shown in Fig. 11.5.

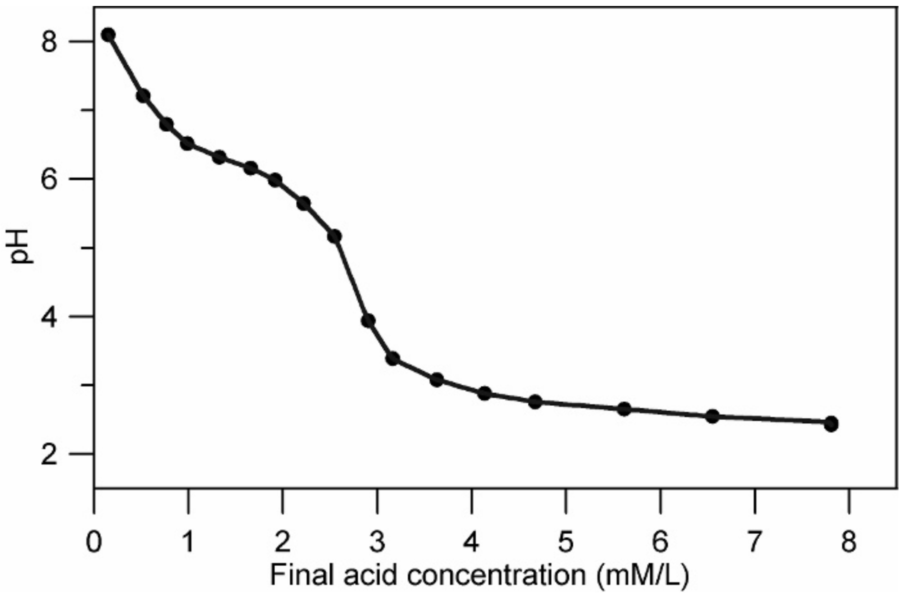

Figure. 11.5. Typical acid titration curve for irrigation water.

A rapid decrease in pH occurs with the first increment of acid addition followed by a gradual change. The effect of acidified fertilizer on pH can be tested in a similar manner. In microirrigation water treatment, the objective is to maintain the pH of the water in the 6 to 7 range. Waters vary in their response to acid because of their buffering capacity. For most waters with an initial pH 8 range, the pH will decrease approximately one unit with the addition of 0.5 me/L acid. In general, 1 me/L acid addition would lead to a pH ranging between 6.0 and 6.5. With continuous dilute acid treatment, carbonate precipitation can be prevented. Furthermore, if minor precipitation has already started prior to acid treatment, the carbonate precipitate can be dissolved assuming that the acidified water can make contact with the precipitated material. Iron and manganese sulfide precipitates will not dissolve at the acid concentrations used for carbonate control. Treatment with excessive acid is uneconomical and may cause other problems such as the corrosion of metallic fittings and erosion of some types of plastic materials.

The question is frequently raised about the effect of chemical treatment on the salinity of the water. A 1 me/L sulfuric acid addition is equivalent to 49 mg/L of dissolved solid concentration, and depending on whether the irrigation water is 350 or 1500 mg/L of dissolved solids, the acid addition would have some to very little effect on total salinity. The sulfate of sulfuric acid is a constituent of gypsum ($CaSO_4$) used to improve soil structure, but the acid addition in water treatment is too small to be effective in soil structural improvement.

Besides calcium carbonate precipitation, sulfide precipitation problems can occur and are usually related to a specific locale. In the United States, carbonate problems occur primarily in the West and Southwest, whereas sulfide problems predominate in the East and Southeast. Exceptions to this generalization are present, notably with the Biscayne aquifer in Florida (Pitts et al., 1996a). The chief sulfide precipitates formed are manganese and iron.

$$Mn^{2+} + S^{2-} = MnS \text{ (ppt)} \tag{11.15}$$

$$Fe^{2+} + S^{2-} = FeS \text{ (ppt)} \tag{11.16}$$

The precipitated MnS and FeS are black in color. With exposure of the sulfides to oxygen, the hydroxy oxides of these metals are formed and are characterized as “ochre.” The iron and manganese sulfide precipitates have also created problems in drainage systems by clogging pipes much larger than those used in microirrigation (Ford, 1987). The sulfides are found under reduced conditions caused by bacterial reduction of sulfate (SO_4^{2-}) when no oxygen supply is available, and similarly could be present at pond bottoms where oxygen content is limited. Hydrogen sulfide (H_2S), with the typical “rotten egg” odor indicates the presence of sulfide. Portable test kits are available to quantify the sulfide concentration. Once formed, the MnS and FeS precipitates are difficult to remove chemically.

11.2.2.3. Chlorination

Biologically-caused clogging is a special problem in microirrigation when surface water is contaminated with bacteria. Water pumped directly from wells into the microirrigation lines generally presents less biological problems than surface waters because microbial contamination is less. An exception is well water containing iron-reducing bacteria. Bacterial activity can corrode the metal casing and screens resulting in soluble materials, which eventually precipitate in the emitters and lines when exposed to oxygen.

The chemistry and application principles of chlorination for microirrigation water are similar to those used in industrial and municipal potable water and wastewater treatment facilities. The principles are also applicable to home swimming pool maintenance. An understanding of chlorine chemistry is helpful for avoiding potential problems that may be encountered when using this chemical (White, 1972). The various forms of chlorine and the reactions commonly applicable to microirrigation waters are listed in Tab. 11.8.

When chlorine gas is injected into water, it reacts to form hypochlorous acid (HOCl), hydrogen (H^+), and chloride (Cl^-), ions (Eq. 11.17A, Tab. 11.8). The HOCl can further dissociate to form the hypochlorous anion (OCl^-) (Eq. 11.17B). Note in this reaction that the hydrogen ions formed will lower the pH. The extent of pH lowering will depend upon the amount of chlorine gas added and the buffering capacity of the water.

Table 11.8 Basic forms and reactions of chlorine and its salts.

$Cl_2 + H_2O = H^+ + Cl^- + HOCl$	(11.17 A)
$HOCl = H^+ + OCl^-$	(11.17 B)
$NaOCl + H_2O = Na^+ + OH^- + HOCl$	(11.17 C)
$Ca(OCl)_2 + 2H_2O = Ca^{2+} + 2OH^- + 2HOCl$	(11.17 D)
$HOCl + NH_3 = NH_2Cl + H_2O$	(11.17 E)
$HOCl + NH_2Cl = NHCl_2 + H_2O$	(11.17 F)
$HOCl + NHCl_2 = NCl_3 + H_2O$	(11.17 G)
$HOCl + 2Fe^{2+} + H^+ = 2Fe^{3+} + Cl^- + H_2O$	(11.17 H)
$Cl_2 + 2Fe(HCO_3)_2 + Ca(HCO_3)_2 = 2Fe(OH)_3 + CaCl_2 + 6CO_2$	(11.17 I)
$HOCl + H_2S = S°\downarrow + H_2O + H^+ + Cl^-$	(11.17 J)
$Cl_2 + H_2S = S°\downarrow + 2H^+ + 2Cl^-$	(11.17 K)

Sodium hypochlorite (NaOCl) (Eq. 11.17C) and calcium hypochlorite ($Ca(OCl)_2$) (Eq. 11.17D) are other sources of HOCl. Sodium hypochlorite is available in liquid form, more commonly called laundry bleach. Calcium hypochlorite is available in solid form, which must be dissolved in water. Note, in both sodium and calcium hypochlorite compounds, their hydrolysis in water produces hydroxyl ions (OH^-) that will raise the pH of the water.

Hypochlorous acid can react with ammonia (NH_3), or ammonium ion (NH_4^+), and amine group (NH_2). The amine is an integral part of organic matter. Eqs. 11.17E through 11.17G of Tab. 11.8 depict such reactions with the formation of monochloramine (NH_2Cl), dichloramine ($NHCl_2$), and trichloramine (NCl_3). The chloramines are perceptible to taste and smell and are in the order of sensitivity, $NCl_3 > NHCl_2 > NH_2Cl > HOCl$ in the concentration range of 0.02, 0.8, 5.0, 20.0 mg/L, respectively. The off-taste and odor in swimming pool and drinking waters are due to the chloramine and not necessarily the chlorine gas (Cl_2). Hypochlorous acid can oxidize soluble ferrous ion (Fe^{2+}) to the ferric ion (Fe^{3+}), and in this case, insoluble ferric hydroxide ($Fe(OH)_3$) can be readily formed (Eqs. 11.17H and 11.17I). Similar reactions occur with the manganous ion (Mn^{2+}). Reaction can also take place between chlorine and hydrogen sulfide forming elemental sulfur (S°) (Eqs.11.17J and 11.17K). Because the chlorine is used to react with the sulfide ion, allowance must be made for the extra chlorine that is needed to permit enough residual for controlling the microorganisms.

Hypochlorous acid plays the dominant role in controlling bacteria. The amount of HOCl present in solution is pH dependent (Fig. 11.6), with more of the active form occurring at the lower pH as described by Eq. 11.17B. Note that at extremely low pH or high acidity, the gaseous Cl_2 form will dominate (Eq. 11.17B). This is the reason for recommending that acids and hypochlorite sources should be stored separately. Any accidental mixing of these chemicals will result in the release of chlorine gas and also large amounts of heat that can cause combustion.

Accurate pH control is strongly emphasized in swimming pool chlorination, and from knowledge of the reaction of chlorine, we can see why alkaline solutions must be added to pools that are chlorine gas treated, whereas acid solutions must be added to the hypochlorite treated water. Sulfur dioxide (SO_2), from the burning of sulfur, instead of sulfuric acid has been used directly as an acid source for microirrigation systems. This acidification technique is not practical when chlorination is being added because the sulfurous acid (H_2SO_3) formed by the reaction of SO_2 with water can also react with the hypochlorous compound and cause the inactivation of the chlorine source. This reaction process can be represented by

$$SO_2 + H_2O = H_2SO_3, \text{ and} \tag{11.18}$$

$$H_2SO_3 + HOCl = H_2SO_4 + HCl \tag{11.19}$$

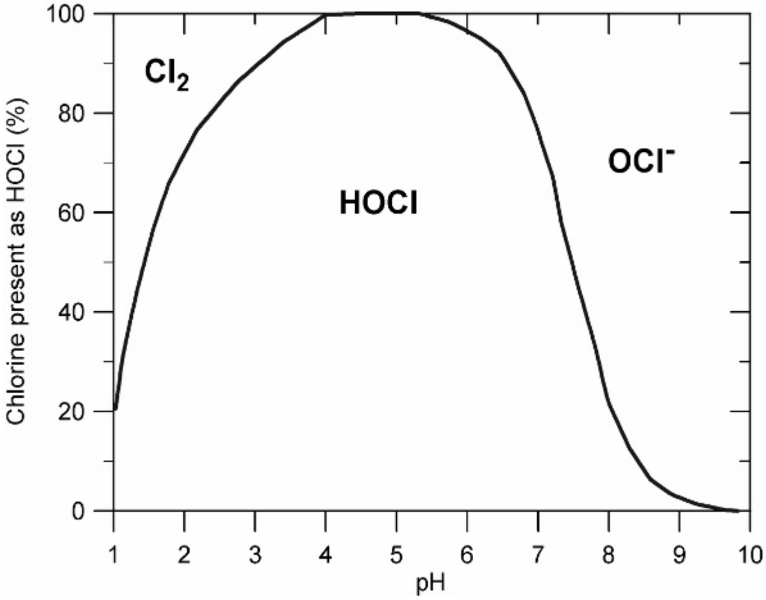

Figure 11.6. Relative amounts of hypochlorous acid (HOCl) present in solution as a function of pH.

Actually, sulfur dioxide has been used as a dechlorinating agent in municipal and industrial treatment facilities when an undesirably high concentration of chlorine is present in the water.

The effectiveness of chlorination is tested by measuring the concentration of HOCl. Portable units suitable for field use are available where the test-water is treated with an indicator crystal or solution and the resultant color compared with a color chart, disk or standard reference solution. Swimming pool-type test kits, based on the orthotolodine indicator, give the total combined residual chlorine and include the various chloramines plus the hypochlorous acid forms.

Test kits are available with the N, N-diethyl-p-phenylene diamine (DPD) indicator reagent that is specific for determining the "free residual" or available chlorine, which is the primary bactericidal agent. DPD in conjunction with pH-buffers and potassium iodide can be used to determine the individual chloramine compounds. More precise measurements of free available chlorine can be obtained by amperometric titration in the laboratory. A reducing agent is used as the titrant for the HOCl. An abrupt change in current can be observed when the endpoint is reached.

Most pathogenic bacteria and viruses are inactivated at free residual chlorine concentration of 1 mg/L with sufficient contact time on the order of 10 to 30 min. Municipal treatment facilities must not only control bacteria, but also taste and odor so that levels higher than 1 mg/L are sometimes used. Free residual chlorine is less than 1 mg/L by the time the water is distributed to the household. Studies made in municipal systems have shown that the transmission capacity of poorly performing pipelines could be improved and maintained by chlorination. The build-up of bacterial slime is controlled by the chlorine treatment and such observations have been used in microirrigation systems.

Obtaining a specified free residual chlorine concentration in microirrigation water is usually achieved by trial and error. To obtain a 1 mg/L final chlorine equivalent concentration, a slightly higher injection rate of chlorine concentration is required than that based on calculation. The reason for this is that most waters have an inherent chlorine demand. Chlorine can react with suspended organic matter, soil particles, or other dissolved constituents besides bacteria. For example, when hydrogen sulfide is present, 2 mg/L of chlorine are required to react with 1 mg/L of the sulfide (Eqs. 11.17J and 11.17K); when ferrous iron is present, 0.6 mg/L of chlorine is needed to react with 1 mg/L Fe (Eq. 11.17H). In fact, this chlorination method has been used as a possible means of solving the iron clogging problem. Chlorination would oxidize the soluble ferrous iron to the ferric form that would eventually form insoluble ferric hydroxide. The ferric hydroxide can be removed from the water using the filtration system. The usual practice is to chlorinate the water just before the filter, but a close proximity to the filter may not allow adequate time for complete chemical reaction to take place and for the smaller-sized $Fe(OH)_3$ precipitate to agglomerate to larger sizes that can then be removed by the filter.

The different types of chlorine sources are listed in Tab. 11.9. Relative costs can be estimated by evaluating the quantity of the specific chemical needed to attain a given chlorine concentration and the cost of the chemical. Initial cost of the injection system and availability of the chemical must also be considered in the selection of a chlorination system. Operators with systems that require large water volumes have selected gas chlorination because it is the most economical, whereas those with smaller needs have chosen liquid hypochlorite solutions because of its convenience.

Table 11.9. Chlorine equivalents of commercial sources and quantity needed to treat 1000 m^3 water to obtain 1 mg/L Cl_2.

Chemical	Quantity equivalent to 1 kg of Cl_2	Quantity to treat 1000 m^3 to 1 mg/L Cl_2
Chlorine gas	1.00 kg	1.00 kg
Calcium hypochlorite		
65-70% available chlorine	1.50 kg	1.50 kg
Sodium hypochlorite		
15% available chlorine	5.59 L	5.59 L
10% available chlorine	8.32 L	8.32 L
5% available chlorine	16.67 L	16.67 L

11.2.2.4. Chemical injection

Chemical injection for water treatment is an important operating component for maintaining the entire microirrigation system. Controlled amounts of known chemical concentrations must be introduced into the main water stream to maintain the desired concentration for achieving the proper results. Fortunately, existing technology provides the operator with a choice from a variety of injection equipment that can do an adequate job of applying chemicals. Chemical injection equipment and operation are described in Chapter 8.

Chemical injection procedures require special considerations not necessarily related to the actual injection process. Bulk chemicals must be stored separately when they are incompatible. Storage should be in secured facilities, and storage tanks and fittings must be compatible with the chemical solution. Safety showers or ample water supply, protective clothing, respirators, and related devices must be nearby and in working condition for use in case of accidental chemical spillage and contact by personnel. Primary stock dilutions, when needed, should always be made by the addition of the chemical to the bulk water to avoid possible heating and splattering of concentrated solutions. Backflow prevention devices must be installed at the inlet side to prevent chemicals from getting back into and contaminating the water supply lines (Smajstrla et al., 1988; ASAE, 2002). This is particularly important with domestic water supply connections where the water is used for human and animal consumption. Local ordinances usually require such backflow prevention equipment. The injection pump should be interlocked with the primary water flow to insure that the chemicals will not be injected into the system when water is not flowing. Also, the chemical supply containers should be protected from water flowing back into them to avoid an overflow of the chemical solution from the storage tanks. Chemicals should be injected separately, unless there is a good reason for combined injection with knowledge that any reactions occurring between the injected materials will not harm the system, particularly the emitters.

Water treatment is an unavoidable additional expense that the microirrigation operator must contend with to attain proper system performance. Prevention of clogging is much cheaper than the replacement or reclamation of emitters. Properly working emitters lead to uniform water and fertilizer application, which automatically improves operation efficiency.

11.3. MAINTENANCE OPERATION

11.3.1. Approach

Effective and efficient microirrigation operation requires properly designed and maintained irrigation systems. Performance generally decreases with long-term use (Boman and Parsons, 1993). Microirrigation systems for perennial crops are generally designed to discharge water at low flowrates with each irrigation event requiring several hours of operation. As a result, variations in discharge rates that are small in magnitude may result in significant nonuniformity of water applications (Nakayama et al., 1979; Nakayama and Bucks, 1981). Damage and clogging by insects can greatly affect both the uniformity and efficiency of microirrigation systems. Therefore, insect control is an important maintenance aspect for microirrigation system operators.

Durability of the components and ease of maintenance are both important considerations with regard to long-term operation of microirrigation systems. Insects can clog emitters and impair microirrigation components to an extent that they render the system inoperable. Therefore, careful attention should be directed to the maintenance aspects during the design phase of a microirrigation system. When possible, large-orifice diameter emitters should be used because they are less prone to clogging than those with smaller orifices. Emission devices without diaphragms should be considered because they are not as affected by ant damage. Once the system is installed, weed and insect control must be part of the overall maintenance program for microirrigation systems.

Many field studies have shown that emitter clogging can be the major cause of emitter discharge variation within a microirrigation system (Pitts et al., 1996b). Other conditions such as emitter construction, water temperature, and emitter aging can also cause flow variations. System operation with respect to time of day or year, water temperature, fluctuation in water quality, and chemical addition, other than for water treatment, can all affect emitter clogging and discharge variability. Preventative maintenance continues to be the best solution for reducing or eliminating emitter clogging.

Preventative maintenance practices include water filtration, field inspection, pipeline flushing, and chemical water treatment. Water filtration and field inspection are absolutely essential. Flushing laterals and pipelines can help to minimize sediment buildup, and in conjunction with chemical water treatment can improve the long-term performance of a microirrigation system.

11.3.1.1. Chemical water treatment research

The following discussion is limited to experimental results from research in Arizona and Florida where most of the investigations were conducted. The Arizona study, using Colorado River water, compares the effectiveness of various water treatments for preventing emitter clogging (Tab. 11.10) in terms of the number of emitters operating at less than 50% of an initial designed flowrate at the end of the experiment. Screen filtration alone was inadequate, as the overall emitter failure was 68%. In contrast, a combination of sand media and screen filtration (Treatment C) reduced the incidence of clogging to 23%, and chemically conditioning the water (Treatments D, E, and F) reduced it even further. Emitters functioned best with continuous sulfuric acid (Treatment F), where only 8% clogging occurred. These results indicate that the most efficient treatment for prevention of emitter clogging in the conditions encountered was the continuous acidification for pH control to prevent carbonate formation and precipitation. However, such treatment will only be effective when coupled with media and screen filtration. A combination of continuous (1 mg/L) or intermittent (10 mg/L) chlorine and sulfuric acid treatments also were effective in reducing emitter clogging.

Evaluation of water treatments for slime control requires some knowledge of the interactions between treatments and slimes. Special bacterial growth chambers have been used successfully to grow emitter-clogging slime bacteria (Ford, 1977b; 1978). The growth chambers consisted of 5-cm diameter, corrugated polyethylene tubes 6 m long. Bacteria were allowed to grow on the walls of the tubing, glass slide, strips of Neoprene, and stainless steel screens inserted into the lines. Various materials such as ferrous iron, bacterial energy sources, complexing agents, biocides, and acids to control pH were injected into the system. The glass slides were monitored for the formation of any deposits. Bacterial slimes formed within 10 h and bacterial iron deposits within 24 h. Results using such methods indicated that chemically oxidized iron was more porous and, therefore, less of a clogging agent than biologically induced ochre. The easiest organisms to grow were *Thiothrix* and *Beggiatoa* sulfur bacteria at pH 7.2. Slimes were visible in the chambers within 2 days after treating continuously with 3 mg/L hydrogen sulfide. Biocides were rated for their minimum concentrations of the active ingredient that completely inhibited *Thiothrix* for 7 days. Ratings for seven biocides against *Thiothrix* are listed in Tab. 11.11.

Table 11.10. Effect of water treatment on clogging for the Colorado River water at Yuma, Arizona. After Gilbert et al. (1981) [a].

Water Trt.	Filtration	Chemical	No. emitters clogged	Clogged emitters (%)
A	Screen (50 mesh)	None	205	68
B	Screen (50 mesh)	Intermittent chlorine[c] (10 mg/L) and acid[d] (lower pH to 7)	205	68
C	Sand (Silica No. 20) + Screen (20 mesh)	None	68	23
D	Same as Trt. C	Same as Trt. B	53	18
E	Same as Trt. C	Continuous chlorine (1 mg/L) and acid (lower pH to 7)	41	14
F	Same as Trt. C	Continuous acid (lower pH to 7)	25	8
		Total =	597	33

[a] Pooled observations from 300 emitters for each of eight different designs with a total of 1800 emitters.
[b] Clogged and partially clogged emitters had discharge rates of less than 50% of initial design.
[c] Free residual chlorine.
[d] Sulfuric acid.

Experiments in Florida indicate that ferrous iron concentration as low as 0.2 mg/L can contribute to iron deposition, and that chlorination successfully controlled ochre when iron was less than 3.5 mg/L and the pH was below 6.5. One method for iron control is to inject chlorine near the bottom of the well, and remove the precipitated iron in a sand media filter or settling basins. Long-term operation using water with high concentrations of iron, manganese, or hydrogen sulfide along with bacteria (Tab. 11.1) may not be suitable for microirrigation.

11.3.1.2. Preventive maintenance practices

<u>Water filtration</u>. A discussion on the various types of filters has been presented in a preceding section. The selection of filter type, size, and capacity depends upon water quality and emitter design. Recommendations by emitter manufacturers on the degree of filtration required should be followed. However, where no recommendations are available, the general practice is to filter

to one-tenth the diameter of the emitter's smallest opening. When suspended solids become severe, (Tab. 11.1 and 11.2) two or more filters types in series may be needed. As a general rule, filtration units should be designed with at least 20% extra capacity. Pump systems should also be increased accordingly to provide some reserve operating pressure and capacity for backwashing of filters and flushing of microirrigation lines.

Table 11.11. Slimicide screening in a monitored bacterial growth chamber after 7 days continuous treatment for control of *Thiothrix* slime development in Florida. After Ford (1977b)[a].

Slimicide treatment	Rate of application (mg/l)[b]	Slime detected (no. of days)	Undesirable side effects
Sodium hypochlorite	16.0	3	sulfur formed
Sodium hypochlorite	35.0[c]	none	none
Acrolein	0.5	none	none
Quaternary ammonium A	1.0	none	brown stain
Quaternary ammonium B	2.0	none	black sludge
Quaternary ammonium C	2.0	none	black sludge
Xylene	5.0	2	*Thiothrix* slime
Isopropanol	245.0	3	*Thiothrix* slime

[a] Hydrogen sulfide injected at 4 mg/l in all chambers.
[b] Expressed as amount of active ingredient.
[c] One mg/L free residual chlorine (34 mg/L sodium hypochlorite was destroyed by 4 mg/L hydrogen sulfide).

Screen filters made of stainless steel, plastic, or synthetic cloth and enclosed in a special housing are the simplest. Aquatic algae in the water tend to cause screen blockage and can reduce filter capacity. Manufacturers provide screen sizes ranging from the finer 100 or 200 mesh (150 or 75 μm) to a coarser 30 mesh (600 μm). Screen filters, as well as other filtering systems, must be routinely cleaned and inspected to insure satisfactory operation of any microirrigation system.

Media filters consist of fine gravel and sand of selected sizes placed in a pressurized tank. Because media filters are not easily clogged by algae, they can remove relatively large quantities of suspended solids before backwashing is needed. However, they can provide conditions favorable for increased bacterial growth. Media filters that are presently used will retain particle size in the range of about 25 to 100 μm. Media filters can be followed by a secondary filter or a rinse-away valve to prevent possible contaminants from going beyond the sand filter during the backwashing process.

Disk filters are based on a different design and operating principle than media or screen filters. Disk filters are preferred where the flowrate is low and requires a larger filtration capacity than screen filters. They are not used where large sand loads or stringy type algae are present.

Sand separators, hydrocyclones, or centrifugal filters remove suspended particles that have a specific gravity greater than water and diameters larger than 75 μm, but these filters are ineffective for removing most organic solids. A sand separator can effectively remove large amounts of sand particles and can be used as an effective pretreatment for other types of filters.

Settling basins, ponds, or reservoirs can remove large quantities of sand and silt. With adequate aeration, Fe^{2+} and H_2S can be oxidized in the storage basins. Unless the reservoirs have a protective covering, the water is subject to windblown contamination and algae growth that must be controlled. Thus, these structures are normally used only for the pretreatment of surface water sources, although they can be used to remove iron in groundwater.

Chemical water treatment. Sulfuric and hydrochloric acid are commonly used acids to reduce chemical precipitation. Phosphoric acid can also be used as a water treatment and fertilizer source. Chlorination and chelated copper are chemical treatments used to control microbial activity. Sodium hypochlorite (liquid), calcium hypochlorite (solid or powder), and chlorine gas are the different sources of active chlorine. All of these chemicals must be used with extreme caution. When chlorination is utilized, test kits designed to measure free residual chlorine, which is the excess of active chlorine over the amount required to kill bacteria, should be used. The orthotolidine indicator commonly used for swimming pools should not be used, because the chemical only gives the total not the free residual chlorine concentrations. Research indicates that very high applications of chlorine are necessary to injure citrus roots (Ford, 1977b). Plant damage is not expected to occur at chlorine application rates normally used to control microorganisms that are encountered in microirrigation systems.

Another problem in using chemicals for controlling slime involves the need to obtain an Environmental Protection Agency registration for the biocide. Only those compounds with proper clearance for a specific problem can be used in the United States. Numerous potential biocides are being screened for use against various types of slime bacteria that can clog emitters. The interactions and side effects are complicated.

Some other alternative chemicals to control bacteria and algae are acrolein, copper salts, hydrogen peroxide, iodine, and quaternary ammonium salts. Acrolein requires special handling and does not destroy certain iron complexes in the laboratory.

Copper salts have been widely used to control algae in settling basins, ponds, and reservoirs. Hydrogen peroxide can be a good bactericide for iron problems, but there is no satisfactory method to monitor concentrations. It is generally poor for sulfur and other slimes that do not contain iron. Iodine is an excellent bactericide, although it complexes with iron and is toxic to plants. Quaternary ammonium salts also kill bacteria and even snails, but they are expensive.

Chemicals for water treatments (acids, algicides, bactericides) can be safely injected through microirrigation systems. Several types of pumps are available for injecting the water-soluble chemical for water treatment. The final chemical concentrations for water treatments are generally low, between 0.5 and 10 mg/L. The concentration should be determined routinely after the solution has passed the primary filter and before it enters the main line. For maintenance purposes, tests should be done routinely at the end of the last lateral line to ensure that the treatment solution at the proper concentration has been distributed throughout the system.

Acids and chlorine compounds should be stored separately, preferably in epoxy-coated plastic or high density polyethylene storage tanks. Acid can react with hypochlorite to produce chlorine gas and heat—a hazardous situation. Sodium and calcium hypochlorites will react with emulsifiers, fertilizers, herbicides, and insecticides, and destroy their effectiveness. Bulk chemicals and diluted chemical solutions should be stored in a secure place. For preparing dilutions, concentrated acid or other chemicals should be added to the water and not vice versa. A readily available water source should be provided near the chemical tank and injector for washing off any chemicals that may contact the skin. Protective goggles, face shields, and clothing should also be worn when making the chemical dilutions. State and local regulations and codes must be followed in regards to type of backflow-prevention device used to ensure against contamination of the irrigation well or potable water supply (ASAE, 2002). Where gas chlorinators are used, safety devices should be installed and routinely inspected to prevent the buildup of excessive pressure or contamination in the chlorine supply bottles.

11.3.1.3. Flushing

Flushing of microirrigation systems is needed to remove particles that accumulate in the lines before they build up to sizes and amounts that cause clogging problems (Smajstrla and Boman, 1998). Filtration systems do not remove all suspended materials from the water. Because of the high cost of removing very small particles, agricultural filters are usually designed to remove only particles larger than about 10% of the emitter orifice diameter. Therefore, filters do not normally remove clay and silt size particles. Although these particles are small enough to be discharged through the emitters, they can cause clogging problems when large quantities are present. They may travel through the filters as individual particles, but then flocculate or become attached to organic residues and eventually become large enough to clog emitters.

Organic growths in pipelines, especially bacteria, are difficult to eliminate completely, and they provide the 'glue' that sticks small particles together. Many types of algae are too small to be filtered, and thus can readily enter pipelines. Even if they are killed by chlorination or other chemical treatment, they can cause small particles to stick together. As the algae die, the cells rupture and the organic residue becomes an adhesive for small particles or groups of cells.

Most debris accumulation in distribution lines begins as small particles, which then join together to cause clogging problems. These small particles are light enough to be suspended and readily transported by the flowing water when the velocity is high. However, the velocity of water flow in a microirrigation system decreases as water is discharged along the length of the pipelines, especially along the lateral lines. At the very end of laterals, the water flow is reduced to only the flowrate of the last emitters. The debris accumulates at this point because the water velocity is no longer fast enough to carry particulate matter. As a result, even small particles settle to the bottom of the laterals. Emitter clogging from this cause normally is evident at the ends of laterals.

Individual lateral and those combined as manifolds should be designed so they can be flushed properly. In most instances, accumulation of loose debris in pipelines can be removed by flushing. To be effective, flushing must be done often enough to remove debris before it accumulates in large amounts to clog emitters. Also, flushing velocities must be sufficient to dislodge and transport the accumulated debris. Flowrates needed to flush out debris for different line sizes are listed in Tab. 11.12.

Irrigation lines are flushed by opening the ends of the lines during operation and allowing water to discharge freely to transport the particulate matter along. The discharge water must have sufficient velocity so that the particulate matter will be suspended and removed from the system with the flush water. Lines must be equipped with valves or other means of allowing the pipeline to be opened quickly. Often, polyethylene laterals are simply folded over and clamped or tied, which makes flushing lines simply a matter of removing the clamp and straightening the tubing. Automated valves are sometimes preferred when frequent flushes are needed.

Table 11.12 Minimum flowrate (L/min) required to flush microirrigation lateral and manifold lines at a lineal velocity of 0.3 m/s.

Nominal pipe/tubing size (mm)	Flow required for 0.3 m/sec (L/min)	Nominal pipe/tubing size (mm)	Flow required for 0.3 m/sec (L/min)
13	3.2	76	91.6
19	6.1	102	151
25	10.2	152	328
38	16.9	203	556
51	27.0	254	864
64	42.2	305	1216
76	61.8	----	-----

Note: Polyethylene tubing assumed for sizes below 51 mm. Class 200 PVC pipe assumed for sizes of 51-mm and larger.

When flushing lines, it is important to observe the type and amount of debris that is being discharged. A clean white-colored bucket or other suitable container can be used to collect the flushed material. A cheesecloth or similar filter placed over the end of the pipe can also be used to trap the flushed sediment. When large quantities of material are discharged, the flushing cycle should be increased. When only a small amount is flushed, the cycle can be decreased. Collecting and inspecting the flushed material regularly is important because water quality may change during the irrigation season, which may affect the required flushing frequency. When systems are not in operation for weeks or months at a time, a good practice is to start the system and flush the lines every 4 to 6 weeks, even when irrigation is not required. Emitter clogging can be prevented when fertigation is practiced by flushing the lateral lines prior to shutting off the microirrigation operation.

Flushing operations should continue until the collected water appears sufficiently clean or until no improvement in clarity is observed. This observation normally only requires a short time and usually only a minute or two is sufficient. Observing the type and amount of material flushed may also suggest other changes in management practices. For example, the presence of organic growths could indicate the need for chlorination or other chemical applications. The presence of large particles may indicate filter failure. The presence of chemical precipitates that have been deposited and then flaked off of the pipe walls might suggest a need to inject acid or change fertilizer injection procedures.

To achieve proper flushing, the discharge water velocity must be high enough to dislodge and transport particulate matter from the pipelines. Typically, a minimum velocity of 0.3 m/sec in the line is recommended. However, a velocity of 0.6 m/sec may be needed where larger particle sizes need to be discharged. This often occurs in microsprinkler systems where coarser filters are used compared with those used in microirrigation operation. High flushing velocities will aid particle removal and shorten the flushing time needed.

Microirrigation systems must be properly designed so that adequate flushing velocities can be obtained. At times, all laterals cannot be flushed at the same time because sufficient flow velocity may not be available. In such cases, only a portion of the flush valves should be opened. The main manifold should be flushed first and then followed by the laterals served by the manifold.

Flowrates can be determined in the field by collecting the flush water in a graduated cylinder and measuring the time required to collect a given volume of water. When the measured flushing velocity is not adequate, the discharge rate per lateral must be increased by closing some of the flush valves, and flushing fewer laterals at once. The number of laterals that can be flushed at the same time depends on many factors. The easiest way to determine this is to measure flow for each irrigation zone by a combination of opening and closing flush valves until the required minimum flowrate is obtained.

11.3.1.4. Reclamation

Reclamation of partially clogged emitters has been successful in several cases. Slime deposits have been removed with high levels of chlorination (1000 mg/L), but extreme care is required to prevent plant injury. Emitters with slime have been cleaned by using 250 mg/L of sodium hypochlorite for at least 12 h without causing injury to citrus trees (Myers et al., 1976). A 2% hydrochloric acid treatment used for 15 min removed ochre and slimes from operational emitters. Unfortunately, the soil pH was lowered from 6 to 5. In Arizona, (Nakayama et al., 1977), flushable emitters clogged with biological slime were reclaimed by treating the system for about 24 h with 100 mg/L of chlorine and adding sulfuric acid to lower the pH to 2. The discharge rate was increased from a low of 50% to the original design of 90 to 95%. After the reclamation treatment, a continuous 1 mg/L chlorine (NaOCl) at a pH of 7 helped to maintain the system operational for the three remaining years of the investigation.

11.4. GUIDELINE AND PRACTICES

Reliable operation of microirrigation systems depends upon preventive maintenance. A preventive maintenance program should include water filtration, field inspection, pipeline flushing, and chemical water treatment. A suitable combination of type, size, and capacity filter unit is required. Appropriate procedures should be followed for the field inspection and flushing of microirrigation systems. Chemical water treatment should be properly selected for maintaining emitter performance. Because water quality is of primary importance in the design and operation of the system, adequate water analysis should be made and evaluated on the basis of past experience such as the water classification scheme presented to evaluate the clogging potential of the microirrigation water source.

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12. SURFACE DRIP IRRIGATION

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12.1. INTRODUCTION

Surface drip irrigation is widely used to irrigate perennial crops (trees and vines) and annual row crops. However, because the design and management of irrigation systems for these types of crops are different, this chapter will address the two cropping systems separately.

12.2. SURFACE DRIP IRRIGATION OF PERMANENT CROPS

12.2.1. Introduction

The design of surface drip irrigation systems for trees and vines is similar. Polyethylene drip tubing with on-line drip emitters is very common, but built-in or fused-in drip emitters are also used. Thin-walled collapsible emitting hoses, commonly referred to as drip tapes in the United States, are frequently used to irrigate annual crops, but seldom used to irrigate permanent crops because these driplines do not have the longevity required. Filters, control and valve systems, injection systems, underground pipelines, and other components of drip irrigation systems are similar for both orchards and vineyards (Fig. 12.1). They will be discussed here together and key differences will be noted when necessary.

12.2.2. Advantages and Disadvantages of Surface Drip Irrigation for Permanent Crops

Advantages of surface drip irrigation of trees and vines include the following:

- Improved water management - Surface drip irrigation has lower evaporative losses than surface, sprinkler, or microsprinkler irrigation because surface drip systems wet a smaller surface area. Reduced evaporative losses and surface drip systems' high irrigation uniformity (Schwankl et al., 1996) often results in high irrigation application efficiencies. A reduction in such losses is beneficial in a young orchard or vineyard where large surface areas are exposed to sunlight and wind.

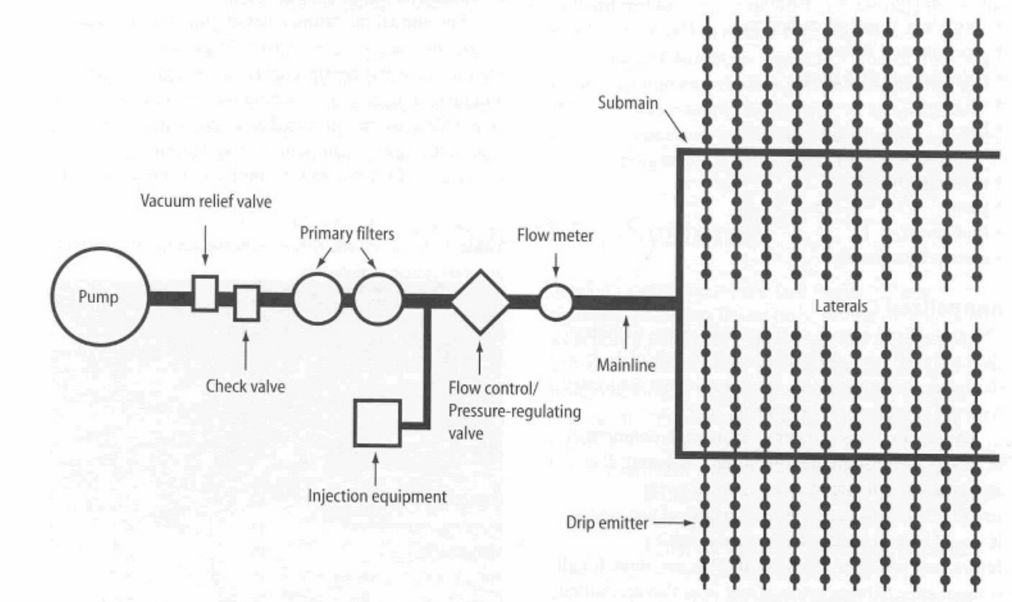

Figure 12.1. Typical components of a surface drip irrigation system.

- Potential energy savings - Energy requirements and costs may be less for low-pressure drip irrigation systems than for high-pressure systems such as impact sprinklers. However, surface drip systems may require more energy than efficiently operated, low-pressure surface irrigation systems.
- Improved crop establishment - A surface drip irrigation system is ideal for establishing orchards and vineyards. Strategic placement of emitters can target water to the limited root zone of the young plants, and the root zone can be refilled as needed with frequent, small irrigations. The water demands of young trees and vines are less than for mature orchards or vineyards, but sufficient water penetration is needed to encourage root development of the young plants. This can be accomplished with drip irrigation (Roth and Gardner, 1985; Andreu et al., 1997).
- Fertigation - Fertilizer application through the irrigation system can be done conveniently and efficiently through a surface drip irrigation system. The nutrients are delivered to the volume of soil with the greatest root concentration, improving fertilizer application efficiency and optimizing growing conditions (Nielsen et al., 1998).
- Improved weed control - Weed control is frequently easier with surface drip irrigation than with full coverage irrigation systems or microsprinklers. This is especially effective in arid regions with limited rainfall during the growing season. Weed growth in the tree or vine row can often be controlled with herbicide strip sprays.
- Yield and quality enhancement - Crop yield and quality can often be improved because surface drip irrigation wets a limited surface area, making it possible to irrigate right up to the time of harvest or even between pickings in a multiple harvest tree crop.

- Lower costs - Surface drip irrigation systems are often less expensive than sprinkler or microsprinkler systems (Schwankl et al., 2000). Drip irrigation systems are often designed with smaller water flow rates than sprinkler or microsprinkler systems. Smaller flow rates result in lower irrigation system capital costs due to reduced size of pumps, mainlines, submains, and filters.
- Reduced insect problems - Several microirrigation system managers and manufacturers report that surface drip systems are less likely to be plugged by insects than microsprinklers. This is probably due to the smaller discharge openings in drip emitters relative to microsprinklers.

Disadvantages of surface drip irrigation systems include the following, although many problems can be mitigated through good system management.

- High cost - The investment cost of surface drip irrigation systems is quite high, approximately $US 2500/ha (Schwankl et al., 2000). They are significantly less expensive than solid-set sprinkler systems, and slightly less expensive than microsprinkler systems, but still require a significant investment.
- Limited wetting of crop root zone - It can be difficult to achieve sufficient wetted soil volume with drip irrigation systems (Schwankl et al., 1999). There is no definitive recommendation regarding the amount of of surface area of an orchard or vineyard floor that should be wetted, although one-third to one-half of the area has been suggested (USDA-NRCS, 1984). The wetted area seems to be less important in vineyards, where many successful drip irrigation systems wet no more than one-third of the vineyard surface.
- Cover crop limitations - Use of surface drip irrigation may exclude the use of cover crops during periods of low rainfall.
- Persistence maintenance requirements - Drip emitters usually have slightly smaller flow passageways than microsprinklers and are more easily clogged by particulate matter. Flow velocities are also low in drip emitter passageways, thus adding to the clogging hazard. Manufacturers often recommend a greater degree of filtration for drip emitters than for microsprinklers.
- Potential for herbicide breakdown problems - Due to frequent soil wetting, pre-emergent herbicides may break down rapidly, thereby potentially requiring more frequent herbicide applications (Edstrom and Schwankl, 1998).
- Potential for excess deep percolation - Deep percolation losses can occur under drip irrigation because the total crop water demand is applied to a relatively small volume of soil. For soils with high infiltration and permeability rates, the downward movement of water may dominate lateral water movement. Good irrigation scheduling should be practiced to avoid deep percolation water losses under these conditions (Andreu et al., 1997).
- Difficulties in visual inspection - It is often difficult to detect clogging problems through simple visual inspection of a drip irrigation system. This is particularly true in orchards where the drip irrigation lateral lines are on the ground and the drip emitters are difficult to see. Visual inspection is easier in vineyards when the drip irrigation system is attached above ground on a trellis. However, in both orchards and vineyards, it is

difficult to determine when partial clogging of drip emitters is occurring unless emitter discharge rates are measured (Povoa and Hills, 1994).

- Cleaning difficulties - It is not possible to clean most drip emitters manually when they are clogged. Even for those few drip emitters that can be opened, hand cleaning is often impractical due to the large number of emitters in orchards and vineyards. In contrast, growers can clean clogged microsprinklers.
- Low application rate - The design application rate of most surface drip irrigation systems for orchards is low, requiring long irrigation durations to meet tree water requirements. The low application rate reduces the cost of the drip irrigation system, but during peak evapotranspiration periods, daily irrigations are often required to meet tree water requirements. When the drip irrigation system is under-designed, daily irrigations of long duration leave little management flexibility when problems with the irrigation system occur (e.g., pump repair or replacement).
- Minimal frost protection capabilities
- Application problems - Care must be taken in vineyard surface drip irrigation systems to ensure that drip emitters apply water near the vines. Because the drip irrigation system is frequently suspended on a trellis, the emitter discharge may not "drip off" at the emitter, but rather move along the drip tubing and drip off at a tubing low point. This is a problem with young vineyards where the newly planted vines have not developed an extensive root system.

12.2.3. Suitability

12.2.3.1. Suitable tree and vine crops

Surface drip irrigation is suitable for nearly all tree and vine crops and can often improve crop quality and yield. This can be attributed to the improved soil water availability for growth and the ability of the irrigator to match crop water demands efficiently.

12.2.3.2. Geographical considerations

Surface drip irrigation for tree and vine crops is suitable worldwide. Two factors should be considered in determining whether drip irrigation is appropriate. First, is it economical? Initial capital costs of drip irrigation systems are quite high (Schwankl et al., 2000). However, these costs may be offset by improvement in crop yield or quality, or savings in irrigation water costs due to improved irrigation efficiency. Economic benefits of alternative irrigation systems are often difficult to compare and quantify. Second, are the technology, labor, and hardware support readily available? Drip irrigation systems are more complicated than traditional systems, requiring skilled labor to manage and maintain them. Proper maintenance of these drip systems is required to address clogging problems. It is also important to have replacement components readily available for emergency repairs. System downtime while awaiting parts, even for a few days, can have extremely negative consequences for the crop, especially during peak water demand periods.

12.2.3.3. Water supply and quality

To make the best use of a drip irrigation system, a reliable on-demand water supply system should be available. This water supply can either be a well/groundwater source or a surface water (natural or man-made) source. Many of the advantages of microirrigation are lost when irrigation cannot be performed on a frequent basis to maintain soil water for optimum growth conditions.

Water quality is important because drip emitters can become clogged when the water contains organic material (e.g., algae or bacterial slimes), particulate matter such as sand particles, or dissolved constituents that could precipitate. Most of these clogging hazards can be mitigated by good filtration and chemical treatment.

Saline waters may be hazardous to plant growth and production. Microirrigation and salinity issues are addressed in detail in Chapter 4, but often drip irrigation can work well even with high salinity water (Shalhavet, 1994; Oron et al., 1999).

12.2.3.4. Maintenance and longevity

Maintenance of microirrigation systems is discussed in detail in Chapter 11. In addition to appropriate filtration and chemical water treatment, flushing of drip irrigation systems must be done on a regular basis. Clay and silt particles that are too small to be caught on microirrigation filters move into the pipelines and lateral lines where they tend to accumulate until flushed out.

Flush valves, appropriately sized, should be installed on the drip irrigation system mainlines and submains. Flushing should begin with the pipeline and proceed to the lateral lines. The lateral lines are flushed by manually opening the ends of only a few lateral lines at a time until water flow is clear. The initial flush water may appear dirty, but it should clear within a minute or two. When it takes substantially longer for the water to clear, flushing should be done more frequently and filters should be checked for proper operation.

Self-flushing caps are available for the ends of lateral lines. These caps have a spring-loaded check valve, which is normally open, but closes as the pressure increases in the drip irrigation system. These valves allow a flushing period at the beginning and the end of the irrigation event. They have worked successfully for many growers, but add cost to the drip irrigation system. Additionally these flush valves must be checked periodically for leakage because they may not fully close.

A very important maintenance task is inspection. Conscientious growers often inspect the drip irrigation system each time it is operated, or on a regular schedule, looking for leaks or other obvious problems. Inspections for clogging problems require a more intensive and detailed evaluation of the drip irrigation system.

With good maintenance, most drip irrigation system components should last 15 to 20 years (Jensen, 1983; Schwankl et al., 2000). Ultraviolet inhibitors blended with the plastic of the drip tubing and emitters enable these components to last at least 15 years. Drip systems do require routine repair and replacement. Components are susceptible to damage by animals and workers. Complete replacement cost of drip tubing and emitters is approximately 20% of the total system capital cost.

12.2.3.5. Irrigation uniformity

A major advantage of drip irrigation systems is that a high degree of irrigation uniformity can be achieved, ensuring that all portions of the orchard or vineyard receive nearly the same amount of irrigation water. The field measurement frequently used to quantify irrigation application uniformity is the field-measured emission uniformity *(EU_f)*, defined as:

$$EU_f = 100 \bullet \left(\frac{q_{lq}}{q_{avg}} \right) \tag{12.1}$$

where EU_f is in percent, q_{lq} is the average discharge rate of the lowest 25% (lower quartile) of field-data emitter discharge readings (L/h), and q_{avg} the average of all the field-data emitter discharge rates (L/h).

For drip emitters without pressure compensation capabilities (discharge rate varies with pressure differences within the drip irrigation system), pressure differences must be kept within allowable limits to achieve high irrigation uniformity. Pressure differences within a drip irrigation system are due to: (1) friction losses in mainlines, submains, and drip lateral lines, and (2) elevation changes within the orchard or vineyard. Designing microirrigation systems to account for pipeline friction losses is thoroughly discussed in Chapter 5. Elevation differences in a vineyard or orchard cause pressure changes at a rate of approximately 9.6 kPa for each meter of elevation change. Lifting water 1 m in elevation requires 9.6 kPa of pressure, but water running water downhill 1 m in elevation will gain 9.6 kPa of pressure.

Pressure-compensating drip emitters maintain constant discharge rates across a wide range of pressures, ensuring good irrigation uniformity. Pressure-compensating (PC) emitters, however, are more expensive than non-PC drip emitters.

12.2.4. Surface Drip Design and Application

12.2.4.1. Drip emitters

Selection of a drip emitter for vineyards and orchards is often based on the expected pressure difference within the irrigation system. When pressure differences are expected to be significant, a pressure-compensating (PC) drip emitter is often chosen. Otherwise, regular emitters are used.

One source of pressure differences within an irrigation system is pipeline and lateral line friction losses. Friction losses increase energy costs that will exist throughout the life of the drip irrigation system. Friction losses can be minimized in the design phase by using larger pipe or lateral lines. However, larger pipe and/or drip tubing will increase system costs.

Significant system pressure differences, resulting from pipeline friction losses, can cause irrigation non-uniformity in which portions of the vineyard or orchard receive more water than others. PC emitters can be used in such a situation to improve the irrigation uniformity. Their higher cost may be recovered by allowing use of smaller pipelines and/or drip tubing in the drip irrigation system. Use of PC emitters may also permit longer drip lateral lines with a resultant decrease in submains.

A second source of irrigation system pressure differences is the topographical changes that occur in an orchard or vineyard, changes that can be difficult to account for. Drip irrigation system design must accommodate vineyard or orchard layouts, which often consider row orientation to the sun, equipment access constraints, configuration of the land parcel, movement of warm/cold air for frost protection, etc.

Drip emitter selection is based on the required emitter discharge rate. Emitters are usually available with nominal discharge rates of 2 L/h, 4 L/h, or 8 L/h. The following factors influence the choice of emitter discharge rates.

- Soil characteristics - Infiltration and the soil water redistribution rates are important factors in choosing an emitter discharge rate. Runoff should not occur under drip irrigation. An emitter with a high discharge rate may have a tendency to cause runoff. Care should be taken in choosing the appropriate discharge rate of emitters installed where the slopes are steep.
- Crop water demands - Drip irrigation systems must be designed to meet peak water demands and emitter discharge rates must be matched with an acceptable maximum daily irrigation run time.
- Susceptibility to clogging - The flow passageways in low discharge emitters are often smaller than those with high discharge rates, and thus have a greater potential for clogging. For example, manufacturers frequently recommend increased filtration (a higher filter mesh number) for use with 2 L/h drip emitters than with 4 or 8 L/h emitters.

12.2.4.1.1. Physical description of drip emitters

The majority of non-pressure-compensating (non-PC) emitters on the market today are turbulent flow, tortuous-path emitters (Fig. 12.2). Turbulent-flow emitters have larger flow passageways for reducing the risk of clogging while still being less sensitive to pressure changes. Other styles of non-PC emitters include continuous flushing emitters (Fig. 12.3) and spiral, or long-path emitters. The continuous flushing emitter is generally used where poor quality water is a problem. It has a series of silicon diaphragms, each with an orifice in them. Long-path emitters use pressure losses along their passageway to dissipate energy, but they are more sensitive to system pressure differences than turbulent flow emitters. Many of the long-path, vortex, and orifice emitters previously available are no longer on the market, having been replaced with more reliable turbulent-flow, tortuous-path emitters.

Pressure–compensating (PC) emitters have a nearly constant discharge rate across a range of irrigation system pressures (Fig. 12.4). There is usually some minimum threshold pressure head of approximately 7 m below which the PC emitter will no longer compensate for pressure changes. PC emitters also frequently have a flexible orifice, and thus may be better able to flush water contaminants out of the emitter.

Figure 12.2. Schematic of a turbulent-flow, tortuous-path drip emitter. Courtesy of Bowsmith, Inc.

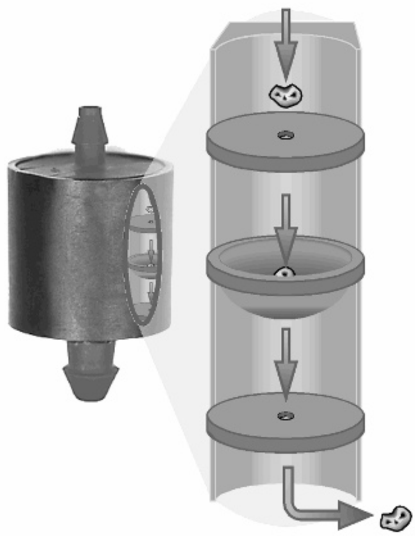

Figure 12.3. Schematic of a continuous flushing drip emitter. Courtesy of Bowsmith, Inc.

12.2.4.1.2. Emitter hydraulic characteristics

The discharge characteristics of a drip emitter can be described by:

$$Q = kP^x \tag{12.2}$$

where Q is the emitter discharge rate (L/h), P is the emitter operating pressure (kPa), k is a constant varying by drip emitter model and units used, and x is an emitter discharge exponent that also varies with the emitter model (Jensen, 1983; Nakayama and Bucks, 1986).

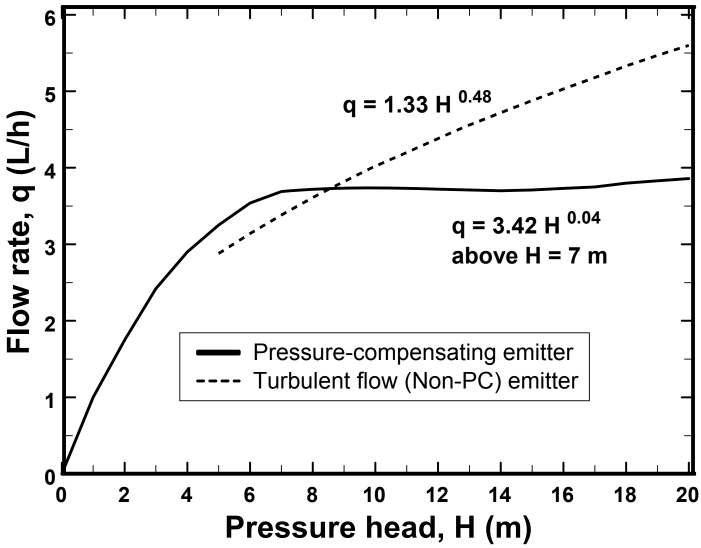

Figure 12.4. Flow rate (L/h) versus pressure head (m) relationship for a typical non-PC turbulent-flow drip emitter and for a PC drip emitter.

The lower the value of the emitter discharge exponent (x), the less sensitive is the emitter discharge rate to changes in pressure. It is desirable for an emitter's discharge rate to be less sensitive to pressure changes that occur within a drip irrigation system. The turbulent flow-tortuous path emitters have an x-value of approximately 0.5. A PC drip emitter will have an emitter discharge exponent *(x)* of approximately zero, indicating that the emitter discharge will remain nearly constant even though the pressure changes.

12.2.4.1.3. Coefficient of manufacturing variation

Drip emitter discharge rates will vary slightly from one emitter to another even when the emitters are made by the same company, due to variability in the emitter manufacturing process. This manufacturing variability will contribute to the non-uniformity of emitter discharge within a drip irrigation system. The measure of manufacturing variability is the coefficient of variation *(CV)*,

$$CV = s / q_{avg} \tag{12.3}$$

where s is the standard deviation of the discharge rates of a sampled set of emitters and q_{avg} is the average discharge rate of the sampled set of emitters. Table 12.1 (ASAE EP405.1, 2000) shows the interpretation of the CV values. Many of the drip emitters currently available have CV values of 0.05 or less.

Table 12.1. Criteria for microirrigation component manufacturing variability (CV) values. Adapted from ASAE EP405.1 (2000).

Coefficient of variation, *CV*	Interpretation
0.05 or less	Excellent
0.05 – 0.10	Average
0.10-0.15	Marginal
0.15 or more	Unacceptable

12.2.4.2. Lateral line drip tubing

The polyethylene drip tubing in which emitters are installed is available in diameters ranging from 4 mm to 27 mm, providing flexibility in designing drip irrigation systems. With non-PC drip emitters, frictional pressure losses along a drip lateral line are usually minimized to maintain high application uniformity. For a particular emitter discharge rate and emitter spacing, frictional pressure losses are related to the lateral line length and the drip tubing inside diameter (Fig. 12.5). For a given flow rate, larger tubing will have less frictional pressure loss than smaller tubing. This reduced pressure loss may be used to maintain high irrigation uniformity or it may allow lateral lines to be longer. Larger diameter tubing is more expensive, but it may reduce the number of submains required in the drip irrigation system, and thereby reduce drip irrigation system capital costs. For example, a larger 20-mm diameter tubing, instead of 16 mm, allows longer lateral lines to be used while still maintaining acceptable irrigation application uniformity.

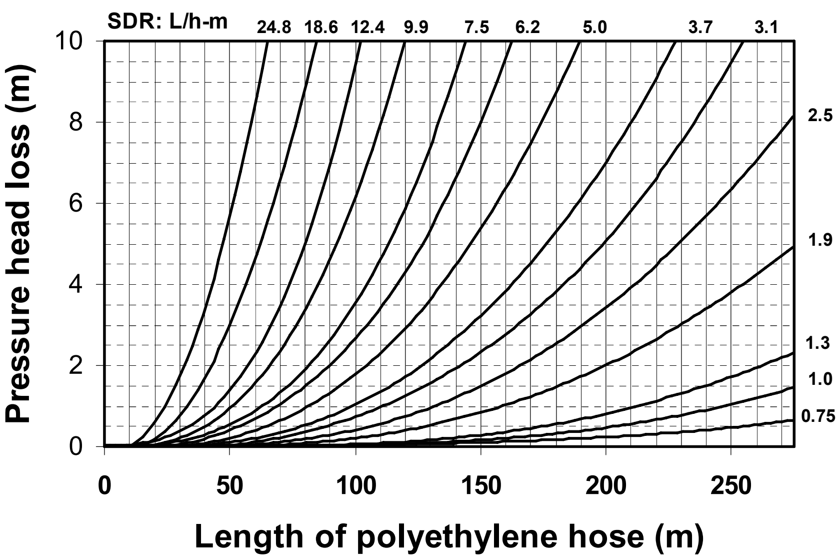

Figure 12.5. Pressure head loss as related to lateral line length for 16 mm ID polyethylene drip tubing. After Boswell (1984).

12.2.4.2.1. Lateral line spacing

For both orchard and vineyards, lateral line spacing is determined by the row spacing of the trees or vines. Row spacing is usually determined by equipment and harvest requirements, recommended planting spacing for crop vigor, and soil conditions. Usually, vineyard surface drip irrigation system have one dripline per vine row, but orchards may have two driplines per tree row (Bieloria, 1985). In orchards, the dual laterals are usually placed slightly away from each side of the tree row (less than 1 m) to provide a larger wetted soil volume. This arrangement also keeps the tree crown dry minimizing the potential for disease. However, the driplines should not be placed at locations that might interfere with or be damaged by cultural operations.

12.2.4.2.2. Lateral length

The objective of lateral line design is to maintain high irrigation application uniformity. The primary factors that should be considered include:

- Discharge rate of the selected drip emitter.
- The relationship between discharge rate and pressure of the selected drip emitter.
- Topography of the proposed land parcel.
- Configuration of the land parcel and the layout of the orchard or vineyard.
- Proposed operating pressure of the drip irrigation system.
- Spacing of emitters along the drip lateral.
- Size (ID) of the drip lateral line.

12.2.4.3. Emitter spacing

Emitter spacing is different for vineyard and orchard drip irrigation systems. For vineyards, one or two plug-in drip emitters are used per vine, usually located within 0.5 m of the vine. Placing emitter(s) close to the vine is important during establishment of the vineyard. The number of drip emitters per vine and the discharge rate of the emitters (usually 2 L/h or 4 L/h) are determined by the water demand of the vine and the soil conditions. The higher application rate system (e.g., two 4 L/h drip emitters/vine) is usually installed on systems designed for vines that are grown under high water use conditions. Drip irrigation systems on soils with poor lateral water redistribution will likely have two 2 L/h drip emitters per vine instead of a single 4 L/h emitter.

For orchards, peak water demand period and the maximum acceptable daily operating time are two factors that determine the emitter spacing. In addition, soil and wetted soil volume considerations will determine emitter spacing. Surface drip irrigation systems should be designed to meet peak water demands with 12 to 15 h of operation. This type of design allows the system to operate longer when needed in order to catch up on irrigation after a system is shutdown for repairs or cultural operations.

Emitter spacing is also influenced by soil conditions and wetted soil volume conditions. As discussed earlier, it is desirable to wet at least 40% of the orchard floor with the drip irrigation system. To accomplish this, emitters should be spaced so that the wetted volume of one emitter overlaps with the adjacent emitter along the drip lateral.

12.2.4.4. Design emission uniformity

An estimate of the design emission uniformity (EU) can be made from the following equation (ASAE, 2000):

$$EU = 100\left[1.0 - \frac{1.27\,CV}{\sqrt{n}}\right]\frac{q_{min}}{q_{avg}} \tag{12.4}$$

where EU is the design emission uniformity, n is the number of drip emitters per plant or 1 whichever is greater, CV is the manufacturer's coefficient of variation, q_{min} is the minimum emitter discharge rate (L/h) for the minimum pressure in the system, and q_{avg} is the average or design emitter discharge rate (L/h) for the system.

The design emission uniformity *(EU)* and design emitter discharge rate (q_{avg}) must be selected together with a drip emitter model. The drip emitter will have an associated manufacturer coefficient of variation (CV) and a unique discharge rate to pressure relationship. The minimum allowable discharge rate for a proposed design can be determined by rearranging Eq. 12.4 to solve for q_{min} as presented in Example 12.1.

Example 12.1.

A surface drip irrigation system is needed for a 16 ha (400 m on a side) level orchard. Trees will be planted on a 7 m row spacing and 5 m between trees in the row. The drip irrigation system should achieve at least 85% design emission uniformity (EU). Emitter spacing will be 1.0 m (5 emitters/tree).

Two emitter types will be evaluated. One, a non-pressure compensating emitter (Fig. 12.4), has a CV of 0.03 and the design emitter discharge rate (q_{avg}) is chosen as 4.0 L/h. The CV of the PC emitter (Fig. 12.4) is 0.04 and the design emitter discharge rate (q_{avg}) is chosen as 3.7 L/h.

<u>*Minimum emitter discharge and pressure determinations*</u>
For the non-PC emitter, and rearranging Eq. 12.4:

$$q_{min} = \frac{85 \bullet 4.0}{100\left[1.0 - \frac{1.27(0.03)}{\sqrt{5}}\right]}$$

q_{min} *= 3.5 L/h.*

From Fig. 12.4, a q_{avg} of 4.0 L/h corresponds to a pressure head of 10 m, whereas a q_{min} of 3.5 L/h corresponds to a pressure head of 7.4 m.

For the PC emitter, and rearranging Eq. 12.4:

$$q_{min} = \frac{85 \bullet 3.7}{100\left[1.0 - \frac{1.27(0.04)}{\sqrt{5}}\right]}$$

q_{min} *= 3.2 L/h.*

From Fig. 12.4, the discharge rate of the PC drip emitter remains nearly constant at 3.7 L/h as long as a pressure head of approximately 7.0 m (threshold pressure) is maintained. It is, therefore, relatively easy to maintain the minimum emitter discharge rate, q_{min}*, at 3.2 L/h or greater.*

<u>Lateral line design</u>
A layout of drip lateral lines and pipelines must be selected to fit the 16 ha square parcel while maintaining the desired emission uniformity of 85% or greater. Fig. 12.5 is a lateral line design aid for 16 mm ID drip hose. The chart is based on using a Specific Discharge Rate (SDR) concept where the SDR is the emitter discharge rate (L/h-m of dripline).

For the non-PC emitter:
An allowable pressure head loss in the drip irrigation system to maintain an EU of 85% is 2.6 m (i.e., 10 m – 7.4 m = 2.6 m). Two possible lateral line configurations are lateral lines 67 m long (Fig. 12.6) and 100 m (Fig. 12.7). The SDR for the non-PC emitter would be 4.0 L/h-m (i.e., 4.0 L/h / 1.0 m). The pressure head losses for these lateral lengths (Fig. 12.5) are summarized in Tab. 12.2

Table 12.2. Summary of pressure loss calculations for various driplines used in Example 12.1.

Type of emitter	*Dripline length (m)*	*Pressure head loss (m)*
Non –PC	*67*	*0.4*
Non –PC	*100*	*1.2*
PC	*67*	*0.3*
PC	*100*	*1.0*
PC	*200*	*7.2*

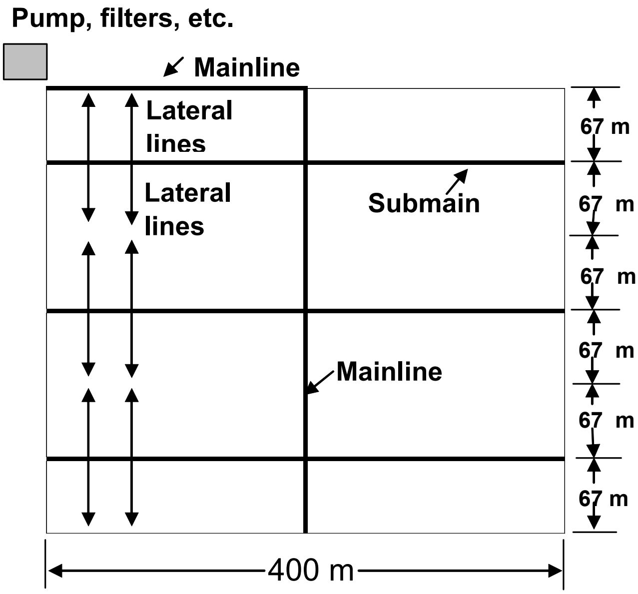

Figure 12.6. Sample surface drip lateral line layout for 67 m lateral length in Example 12.1.

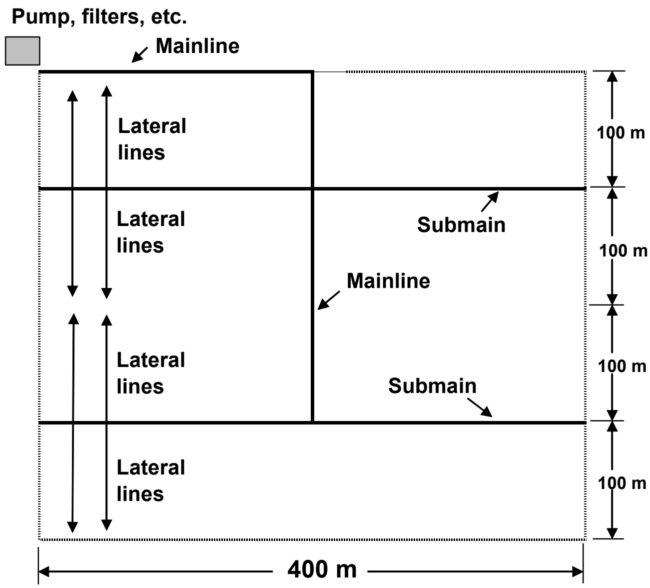

Figure 12.7. Sample surface drip lateral line layout for 100 m lateral length in Example 12.1.

For the PC emitter:
In this case, the SDR would be 3.7 L/h-m (i.e., 3.7 L/h / 1.0 m). Three possible lateral lengths will be investigated, a 67 m lateral length (Fig. 12.6), a 100 m lateral line (Fig. 12.7), and a 200 m lateral line length (Fig. 12.8). Table 12.2 summarizes the pressure head losses for these lateral line configurations.

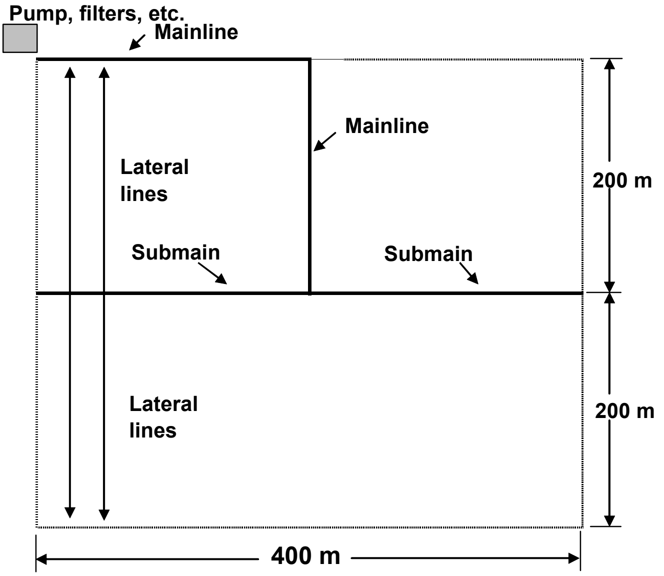

Figure 12.8. Sample surface drip lateral line layout for 200 m lateral length in Example 12.1.

<u>Selection of lateral line length</u>
Non-PC emitter:
The total allowable pressure head loss in the drip delivery system to maintain an EU of 85% is 2.6 m. The 67 m lateral line would have 0.4 m of pressure head loss along it whereas the 100 m lateral line would have 1.2 m of pressure head loss. The remaining allowable pressure head loss in the pipeline system would be 2.2 m (i.e., 2.6 m – 0.4 m) for the 67 m lateral line configuration, and 1.4 m (i.e., 2.6 m – 1.2 m) for the 100 m lateral line design. Either of these lateral line lengths would work adequately although the 100 m lateral length system may require slightly larger pipeline sizes than the 67 m lateral length system in order to remain within the pressure loss limits. The 100 m lateral length system would require one less submain, a considerable cost savings, along with fewer fittings and connections. The final selection of the lateral length would be based on the cost of the system, particularly on the cost of the mainlines and submains.

PC emitter:
Because of the pressure-compensating characteristics of the PC emitter, the emitter discharge remains constant at 3.7 L/h as long as the pressure head remains above 7 m. The lateral line could, therefore be quite long, reducing the number of required submains.

Because pipelines (usually made from PVC) are expensive, the reduction in pipeline cost may compensate for any increased cost of the PC emitters compared with the non-PC emitters.

*Energy costs should also be considered when selecting the lateral lengths with PC emitters. Lateral line friction losses must be accounted for in the determination of the pumping head in order to remain above the PC emitter's threshold pressure level. Thus, for the 200 m lateral line length vs. the 100 m lateral line length, 6.2 m (7.2 m – 1.0 m) of additional pumping pressure head must be present in the 200 m lateral length system (Tab. 12.2)***.**

Again, the final decision on lateral line length is economic. The fewer pipeline requirements of the longer lateral line systems (e.g., 2 submains for the 100 m lateral line system vs. 1 submain for the 200 m lateral line system) should be balanced against the pumping head / energy cost differences.

12.2.4.5. Installation issues

When considering the installation of a surface drip irrigation system, an owner must decide whether to use his own employees or to contract the work. Installation by contractors can be quite expensive, so many choose to do much of the installation themselves. Unfortunately many owners incorrectly assume that using their personnel for installation has no additional cost. Many owners decide to let a professional install the pump, filters, valves, and other equipment at the control head of the system, and then use their own employees to install the rest of the drip irrigation system. Additionally, some owners will have the pipelines installed by a contractor.

Timing and logistics are also important factors in planning the installation of a drip irrigation system. It is difficult to install underground mainlines and submains after the orchard or vineyard is planted. Thus, as a prerequisite, pipelines should be installed prior to planting. When this is done, tree or vine placement should be carefully laid out so that the risers connecting the underground pipelines to the surface drip irrigation system are placed properly. The risers must be in the tree or vine row and not too close to the plant. Placing the riser too close to a tree can result in the roots pinching off or breaking the riser as the tree matures.

12.2.5. Management, Evaluation, and Maintenance of Surface Drip Irrigation Systems

12.2.5.1. Water requirements

Crop water needs of trees and vines are dependent both on the local weather conditions and on the plant species. Irrigation scheduling has been discussed in Chapter 3, but it should be emphasized here that the water requirements are the same, no matter what kind of irrigation system is used. It may be possible to apply less irrigation water with a surface drip irrigation system than with another system type, but this is only because the system has high potential irrigation efficiency.

It is important to determine the plant water requirements before designing a surface drip irrigation system and while operating it after installation. The drip irrigation system should supply the peak water demands of a mature orchard or vineyard along with any water lost to irrigation inefficiency. Several good resources are available to assist in determining irrigation water requirements for trees and vines (Univ. of California, 1989; Allen et al., 1998; Hanson et al., 1999).

12.2.5.2. Crop response

In addition to the high irrigation efficiency possible with drip irrigation, improved crop response of trees and vines has been reported. Azzena et al. (1988) observed better growth and yield of orange trees grown with drip irrigation than microsprinklers. Also in oranges, Kumar and Bojappa (1994) reported higher yield and quality with drip irrigation than surface irrigation. The improved response of trees to drip irrigation is likely attributable to the improved soil water conditions for growth. Evans et al. (1990) noted that daily surface-irrigated sweet cherries had similar growth and yield to drip-irrigated cherries, but indicated the need for careful management of such frequent irrigations with a surface irrigation system.

Studies on vine response to drip irrigation are limited. Srinivas et al. (1999) reported significantly higher yield and growth for drip-irrigated vines than for basin-irrigated vines. In contrast, Araujo et al. (1995b) found no difference in growth or yield between drip-irrigated and furrow-irrigated Thompson seedless grapes. However, they did note that drip irrigation provided a potential for manipulating grape quality.

12.2.5.3. Drip irrigation system application rate

The application rate of a drip irrigation system is dependent on the discharge rate of the drip emitter(s) and the number of drip emitters per tree or vine. For a surface drip irrigation system, the application rate is frequently expressed in terms of L/h per tree or vine. Because the daily plant water requirements are frequently given in mm/day, unit conversion is required. Conversion from mm/day to L/day of plant water use is given by:

$$Q_c = A \bullet ET_c \tag{12.5}$$

where Q_c is the plant daily water use (L/day), A is the plant growing area (m^2), and ET_c is the plant daily water use (mm/day). For example, an orchard with trees planted on a 5 m by 7 m spacing and a daily tree water use of 6 mm requires 210 L/day of water (i.e., 5 m x 7 m x 6 mm/day = 210 L/day).

By assuming that there is a single lateral line/tree row, an emitter spacing of 1 m (5 emitters/tree), and an emitter discharge of 4 L/h, the drip irrigation system should be operated for at least 10.5 h/day [i.e., 210 L/day / (5 emitters x 4 L/h-emitter) = 10.5 h/day].

12.2.5.4. Irrigation efficiency

Irrigation efficiency is a measure of how much of the applied irrigation water is beneficially used. The predominant beneficial use of water is meeting the evapotranspiration demands of the plant. Although the terms irrigation efficiency and application uniformity are not directly related, it is difficult to achieve high irrigation efficiency when the system has poor application uniformity

(Hanson, 1995). Even for drip irrigation systems with high uniformity, the correct amount of water must be applied to achieve high irrigation efficiency. Thus, achieving excellent irrigation efficiency requires a highly uniform drip irrigation system that is well managed to apply the correct amount of water.

For the preceding example, irrigation inefficiency requires that the applied irrigation be greater than the 210 L/day needed to replace evapotranspiration. The better the drip irrigation system uniformity, the more efficiently a drip irrigation system can be managed.

12.2.5.5. Irrigation frequency

One of the major advantages of microirrigation is its ability to maintain the soil water at an optimal level for growth. Water stress can be detrimental for plant growth and production, and similarly excessive soil water is also undesirable. The problems with soil aeration and root diseases that flourish under very wet soil conditions (Utkhede and Smith, 1996) suggest irrigation frequencies that allow for soil drying between irrigations. This must be balanced against the application rate of the drip system as well as the soil characteristics of the orchard or vineyard.

From the previous example where irrigation period was determined to be 10.5 h (plus some additional time to account for irrigation inefficiencies), irrigations must be done either daily (10.5-plus h) or every-other-day (21-plus h). One day for the soil to dry between irrigations may be beneficial, but runoff may become a problem over the 21-plus h irrigation. It is also possible that deep percolation of irrigation water could become a problem during the longer irrigation event. Experience gained by operating the drip irrigation system and analyzing its performance should provide guidance in selecting the appropriate irrigation frequency and duration. It may be possible to delay irrigation during portions of the growing season when trees use less water.

12.2.5.6. Special management issues

A surface drip irrigation system is well-suited for establishing orchards and vineyards. Irrigations can be targeted to the limited root zone of the young plant, so that little water is lost to irrigating areas where roots are absent. In such areas, much of the applied water would be lost to evaporation (Araujo et al., 1995a). Thus, a surface drip irrigation system can be very efficient during the orchard or vineyard establishment period.

Even though the water use of a young plant is small, its root zone is also limited so that frequent irrigations are needed to maintain optimal soil-water environment for growth. Surface drip irrigation systems are ideally suited for such situations.

Most vineyards are established with the same drip irrigation system that will be used to irrigate the mature vineyard. For example, when the system is designed for two drip emitters per vine, the emitters should be installed together instead of separately. However, the usual practice in orchards is to establish the trees with fewer emitters per tree and increase the number as the trees mature. This is done to improve water application efficiency by avoiding watering soil areas where roots are absent. It is important to be efficient with water applications, but young tree root development should not be constrained by a limited wetted soil volume. All the drip emitters are usually in place by the second, and certainly by the third growing season.

12.2.6. Evaluation of Surface Drip Irrigation Systems

Evaluation of microirrigation systems has been covered in detail in Chapter 10, but a discussion of informal, day-to-day methods of evaluating the performance of a surface drip irrigation system is necessary. One of the best ways to monitor the performance of a surface drip irrigation system is to install flowmeters on the drip irrigation system and monitor them on a regular basis.

There are two locations in a surface drip irrigation system where flowmeters can be particularly valuable. First, a flowmeter is useful at the pumping/control head of the drip irrigation system, to monitor the total flow into the entire drip irrigation system. Monitoring water applied during an irrigation event provides a measure of the average amount of water applied. This is useful for irrigation scheduling purposes. In addition, comparing system application rates of sequential irrigation events can provide an indication of clogging or leaks. When indications of clogging are observed, flowrate comparisons must be made with the drip irrigation system operating at the same pressure.

In addition, flowmeters installed at the beginning of the drip laterals can be very useful to measure flow into individual lateral lines. These small flowmeters, with throat sections of 20 to 25 mm are inexpensive and easily installed into the surface drip tubing. They are also sensitive enough to detect clogging problems before they become detectable with the large flowmeter at the drip irrigation system head. Because of their low cost, numerous meters can be installed throughout the system. Weekly monitoring of these lateral line flowmeters will provide information on the amount of water applied and give early indication of emitter clogging.

Flushing of the irrigation system is an important maintenance task, but it can also be an important evaluation tool. During flushing of the lateral lines, the flushwater should be examined for any type of contaminants. A good way of doing this is to run the flush water through a piece of cheesecloth or similar type of material. Appearance of larger sand particles may indicate a failure in the filtration system, whereas evidence of slimes or organic matter in the flush water indicates that water treatment with a biocide may be necessary.

A long flushing period that is required before the flushwater becomes clear may be indicating a problem occurring within the filtration system. Unusual flowrate reductions during flushing could indicate restricted flow upstream, possibly caused by root pinching of a riser line (connection between the underground pipeline and the surface drip lateral) or by a break in the lateral.

12.3 SURFACE DRIP IRRIGATION FOR ROW CROPS

12.3.1. Advantages and Disadvantages of Surface Drip Irrigation for Row Crops

Surface drip irrigation is sometimes used for annual crops instead of subsurface drip irrigation for the following reasons:

- <u>Cultivation alternatives</u> - Extensive cultivation is possible between crops because the dripline is removed prior to harvest. Cultivation practices must be modified when using subsurface drip irrigation to prevent damage to the dripline.

- Reduced system damage - Damage to driplines during harvest is reduced because the dripline is removed prior to harvest. Some types of crops such as cool weather vegetables may require irrigation near harvest time, resulting in wet soil at the time of harvest. Experience has shown that considerable damage can occur to subsurface driplines under these conditions.
- Stand establishment - Surface drip systems can be used for stand establishment under some conditions.
- Salinity - Seedbed soil salinity might be better controlled by surface drip irrigation than by subsurface drip irrigation.
- Reuse of driplines - The driplines can be recovered and used elsewhere.
- Better leaching capabilities - Leaching can occur from the soil surface downward with surface drip irrigation, but no leaching occurs above driplines of subsurface drip irrigation.
- Repairs - It is easier to repair or replace damaged dripline.
- Underground pests - Damage is less from burrowing rodents and insects.
- Visual inspection - Potential clogging problems can be seen and quickly remedied during the early stages of plant growth.
- Avoidance of unique subsurface drip irrigation (SDI) problems - Problems associated with SDI systems are eliminated, such as dripline crimping, root intrusion, and soil ingestion.

Disadvantages of surface drip irrigation compared with subsurface drip irrigation include:

- Dripline installation and removal issues - Installation and removal costs are needed for each crop. Driplines must be removed prior to harvest to prevent damage or interference with harvesting equipment. This may prevent the use of surface drip irrigation for some crops such as processing tomato where the weight of the fruit pressing down on the dripline may prevent its extraction without damage.
- Damage to driplines - Surface-installed driplines are more susceptible to damage during cultural operations and from animal pests compared with SDI.
- Length limitations - Lateral lengths may be limited because of the need to extract driplines.
- Clogging potential - Temperature variation and accumulation of salts at the emitters can cause clogging problems.

12.3.2. Suitability

Microirrigation in general is suitable for situations involving higher cash value crops, marginal soil conditions, marginal water quality, and steep or undulating field slopes. Specifically, surface drip irrigation can be considered for the following conditions:

- Cultivation requirements - Cultivation may be needed between crops to reduce or prevent soil degradation, disease, or insect problems. Cultivation may damage subsurface drip systems depending on the depth of the driplines.

- Soil restrictions - Driplines cannot be buried because of rocks, hard pans, or other restrictive layers.
- Field rotation issues - The drip irrigation system must be moved from field to field. This is the case in the Highlands area of Jordan where several years of surface drip irrigation at a given location severely degrade soil hydraulic properties, and where rocks prevent cultivation.
- Uncertainty **-** Uncertainty exists about the long-term use of a leased field.

12.3.3. Drip Materials

Drip irrigation of row crops normally uses collapsible, thin-walled emitting hose, commonly referred to as drip tape by the drip irrigation industry, instead of drip tubing (hard hose) normally used for tree crops and vineyards. The thin-walled dripline with periodically spaced emitters inflates upon pressurization. In contrast, drip tubing (hard hose) has thicker walls and retains its round cross-section. Thin-walled dripline with inside diameters typically ranging from 10 to 35 mm and emitter spacings ranging from about 50 mm to 1 m is made by a number of manufacturers (Tab. 12.3). The 16-mm and 22-mm diameter driplines are frequently used for most commercial agricultural production, whereas the 10-mm diameter dripline is used in home gardens. However, use of 19 and 22-mm diameter dripline for surface drip irrigation is increasing. The 35-mm diameter dripline is generally used for subsurface drip irrigation.

The combination of emitter spacing and emitter discharge rate determines the dripline discharge rate (L/h-100 m). Discharge rates of driplines are generally classified as low-flow, medium-flow, high-flow, and very-high-flow. Low-flow dripline is the most widely used, thus maximizing lateral length.

Several types of emitters are used with thin-walled driplines. Most manufacturers use strip emitters as shown in Fig. 12.9. These emitters, made of the dripline material, consist of a long narrow design with an inflow section, a turbulent flow section, and an outlet. Another emitter type is the molded plastic emitter welded to the inside of the dripline (Fig. 12.10), and a third type, used in drip tubing (hard hose), is an in-line molded plastic emitter (Fig. 12.11).

The hydraulic characteristics of drip emitters are described by the emitter discharge coefficient and the emitter discharge exponent (see Eq.12.2). The value of k depends on the dimensions of the emitter flow passage and the units used for P and q. The exponent is an indicator of the sensitivity of the emitter discharge rate to changes in pressure. Larger values of x indicate more sensitivity to pressure changes. Exponents of most driplines range from 0.40 to 0.60 (Tab.12.4). The coefficient of manufacturing variation *(CV)* describes the variability in emitter discharge rates due to the manufacturing process (Eq. 12.3) and is a measure of the manufacturing quality of the material with smaller values of CV being better. Most thin-walled driplines have a CV of 0.05 or less (Tab. 12.4), which is considered to be excellent (Tab. 12.1).

Table 12.3. Characteristics of some collapsible thin-walled emitting hoses (drip tapes) used in the USA.

Manufacturer and (dripline name)	Diameter (mm)	Wall thickness (mil)	Emitter spacing (mm)	Emitter flowrate (L/h)
T-Systems International (T-Tape)	10, 16, 22, 35	4, 6, 8, 10, 15	102, 203, 305, 406, 456, 610	0.53, 0.76, 1.02, 1.29, 1.51
Netafim (Streamline, Typhoon)	16, 22, 25	6, 8, 10, 13, 15	203, 305, 406, 610, 762	0.61, 0.79, 1.25
Roberts Irrigation Products (RO-DRIP)	16, 19, 22	5, 6, 8, 10, 13, 15	102, 203, 305, 406, 610	0.41, 0.91, 1.29
ToroAg (Aqua-Traxx)	16, 22	4, 6, 8, 10, 12, 15	102, 203, 305, 406, 610	0.49, 0.76, 1.02
Chapin Watermatics (Twin-Wall)	16, 22	4, 6, 8, 10, 15, 20, 25	51, 102, 203, 229, 305, 406, 610	0.57-2.27
Queen-Gil	12.5, 16.5, 20.5	6, 8, 2, 16	100, 200, 300, Variable	0.2, 0.4, 0.8, 1.0, 1.2, 1.6, 1.8, 2.7
Eurodrip	16, 22		Customized	1.2, 1.55, 2.45
Drip Tape Manufacturers and Engineers, Inc. (Tiger Tape)	16, 22	5, 6, 7-8, 10, 15	108, 216, 317, 438	0.57, 0.79, 1.06

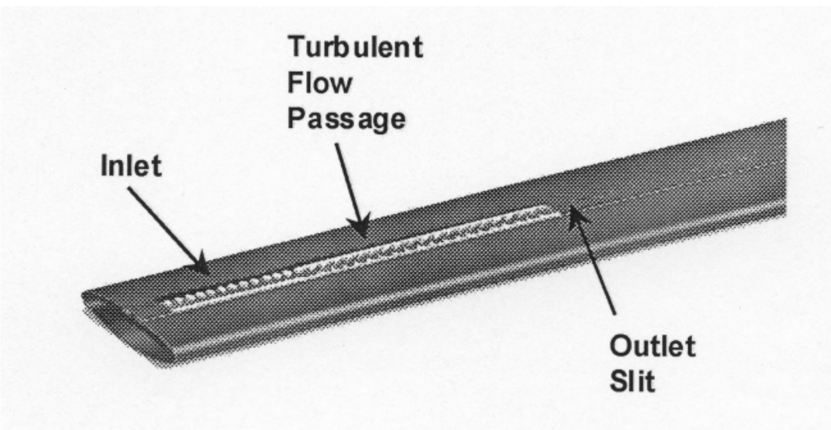

Figure 12.9. Strip emitter used in thin-walled dripline (drip tape). Courtesy of T-Systems International, Inc.

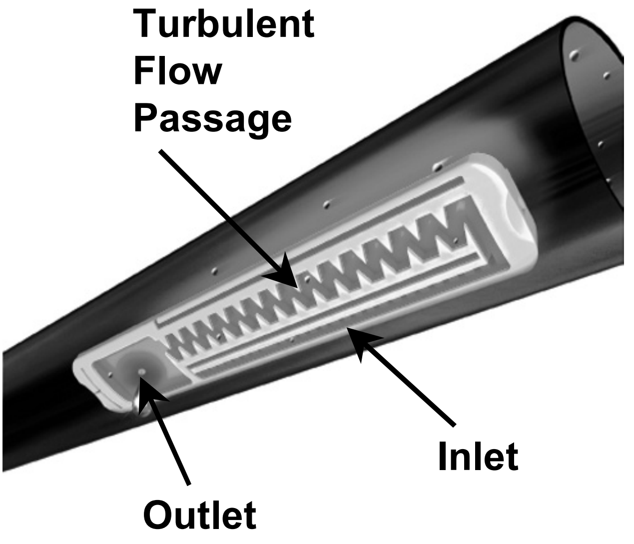

Figure 12.10. Molded plastic emitter used in drip tape. Courtesy of Netafim Irrigation Products, Inc.

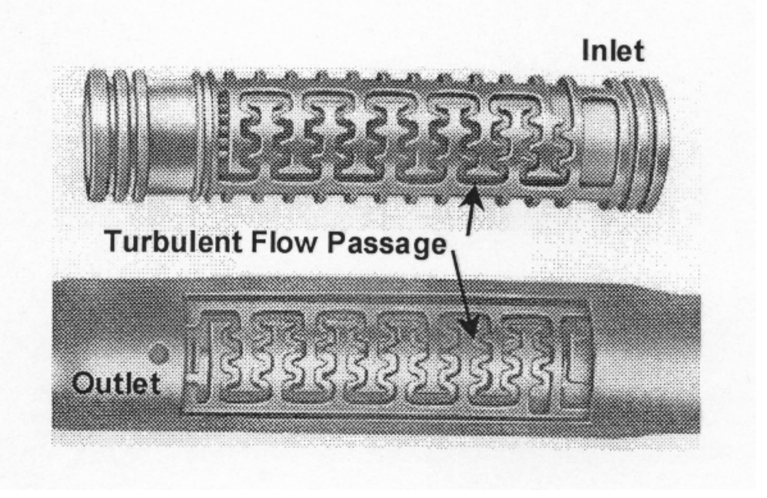

Figure 12.11. In-line emitter used in drip tubing. Courtesy of Toro-Ag, Geoflow, Inc.

Table 12.4. Performance characteristics as represented by manufacturer's coefficient of variation, *CV* and emitter discharge exponent, *x* for some typical collapsible thin-walled emitting hoses (drip tapes) used in the United States.

Manufacturer and (dripline name)	*CV*	*x*
T-Systems International (T-Tape)	0.03[a]	0.50-0.52[a]
Netafim (Streamline, Typhoon)	0.03[b]	0.44-0.48[b]
Roberts Irrigation Products (RO-DRIP)	0.03[b]	0.52, 0.57[b]
ToroAg (Aqua-Traxx)	0.02-0.04[b]	0.50, 0.54[b]
Chapin Watermatics (Twin-Wall)	0.01-0.03[a]	0.51-0.58[a]
Queen-Gil	<0.05[b]	0.56[b]
Eurodrip	0.01-0.02[a]	0.53-0.60[a]
Drip Tape Manufacturers and Engineers, Inc. (Tiger) Tape)	0.049[b]	0.52[b]

a Obtained from CATI Publication 990102, *Irrigation equipment performance report – Drip emitters and microsprinklers*, Center for Irrigation Technology, California State University, Fresno, California.

b Supplied by manufacturer.

12.3.4. Driplines

Uniformity of emitter discharge rates within an irrigation system is described by indices such as the field emission uniformity, EU_f (Eq. 12.1), and the discharge ratio. EU_f is defined as the average emitter discharge rate of the lowest one-fourth of the measured rates divided by the average discharge rate of all of the measured values. The discharge ratio is defined as the ratio of the minimum discharge rate to the maximum discharge rate.

EU_f accounts for the uniformity along the dripline plus that along mainline, submains, and manifolds. Numerous evaluations of microirrigation systems have shown that initial values of EU_f should be at least 80%. Achieving that level of uniformity, however, means that the design emission uniformity, EU, (see Eq. 12.4) of a dripline must be at least 90%. The EU of a dripline depends on its length and its discharge rate, which in turn depends on emitter spacing and emitter discharge rate. Using design software for driplines (T-Systems International, Inc., Roberts Irrigation Products, Inc., and Nelson Irrigation), the maximum dripline lengths for EU of 90% were determined for various slopes, dripline discharge rates, and dripline diameters (Tab. 12.5).

Table 12.5. Approximate dripline lengths needed to achieve a design emission uniformity, *EU,* of 90% assuming an inlet pressure of 80 kPa. The maximum lengths are the range of values obtained from the different computer models.

Dripline diameter (mm)	Dripline discharge rate (L/h-100 m)	Slope (%)	Maximum lateral length (m)
16	163 – 186	0	229 – 259
		0.1 downhill	236 – 267
		0.1 uphill	213 – 221
		0.5 downhill	274 – 305
		0.5 uphill	152 – 183
	298 – 327	0	152 – 183
		0.1 downhill	168 – 183
		0.1 uphill	152 – 160
		0.5 downhill	183 – 198
		0.5 uphill	122 – 137
	500	0	122 – 130
		0.1 downhill	130
		0.1 uphill	122
		0.5 downhill	137
		0.5 uphill	107
22	163 – 186	0	366 – 427
		0.1 downhill	396 – 488
		0.1 uphill	335 – 396
		0.5 downhill	488 – 549
		0.5 uphill	244 – 274
	298 - 327	0	290 – 305
		0.1 downhill	305 – 335
		0.1 uphill	274
		0.5 downhill	366
		0.5 uphill	198 – 229

12.3.5. Manifolds

Surface drip irrigation systems frequently use collapsible tubing for manifolds that are removed prior to harvest. These materials may be installed on the ground surface or buried. Use of these materials allows cultural operations during the irrigation season without damaging the manifolds. The fittings used to connect driplines to the manifold should be installed along the fold or crease of the collapsible material.

12.3.6. Emitter and Dripline Spacing

Several studies have investigated the effect of dripline and emitter spacing in surface drip irrigation systems on crop yield. Plaut et al. (1988) found no trend in cotton yield for different ratios of dripline spacing to row spacing with emitter spacing of 0.4 m, and emitter discharge rate of 1.4 L/h. Ayars et al. (1985) used dripline spacings of 1.5 m and 2.5 m for cotton irrigation in a clay loam and found no yield differences for an emitter spacing of 1 m and emitter discharge rate of 2 L/h. Similar results were also obtained with an emitter spacing of 0.5 m and emitter discharge rates of 2 L/h to 4 L/h (Plaut et al., 1985; Howell et al., 1987; Russo, 1987; Bar-Yosef et al., 1989; Meiri et al., 1992).

Collapsible thin-walled emitting hose (drip tape) is used for surface drip irrigation of row crops in many areas. Emitter spacings and emitter discharge rates are usually much smaller than those used in the preceding studies. However, no systematic investigation has been conducted on the effect of emitter spacing on row crop yields. Thus, growers using surface drip irrigation have relied on practical experience to determine the most appropriate spacings for conditions in their area. Based on experience, growers often use emitter spacings for annual crops ranging from 0.2 m to 0.45 m. In California (USA), an emitter spacing of 0.2 m is generally used for strawberry irrigation, but other spacings of 0.3 m to 0.45 m are used for drip irrigation of vegetables.

Bed and dripline spacings depend on crop type and cultural practices. Vegetable crops such as lettuce, cauliflower, broccoli, and cabbage frequently use bed spacings of about 1 m with one dripline per bed although a bed spacing of 2 m with one dripline per bed also is used. In some cases, however, 1.5-m bed spacing is used with three driplines per bed. In California (USA), strawberry bed spacings of about 1 m and 1.5 m are used. The smaller spacing uses two plant rows and one dripline per bed, whereas the larger spacing uses four plant rows and two driplines per bed. Bed spacings used for drip-irrigated cotton range from 0.76 m to 1 m with 1 dripline per bed.

12.3.7. Installation and Extraction of Surface Driplines

For surface drip irrigation systems, the dripline may be placed on the ground surface or buried 25 to 75 mm below the ground surface to keep the dripline in place during windy conditions when the crop is small. Some other methods to anchor surface dripline to keep it in place during windy conditions include placing it in a small V-shaped depression, anchoring at the head and end of the dripline, or placing soil on the dripline at periodic intervals (Burt and Barreras, 2001).

The dripline is removed prior to harvest of vegetable crops; and in some cases, the extracted dripline is reused on subsequent crops. Removing thin-walled dripline (drip tape) for later reuse is greatly expedited by heat welding to fuse the dripline being extracted to the previous end. In the past, plastic couplers were used to join the driplines, but these caused problems in the rolling-up process. Extraction is done by pulling the dripline from the field and rolling it up on a hydraulically-driven reel. Prior to extraction, water remaining in the dripline may be purged with compressed air, and the dripline is lifted above the crop (Burt and Barreras, 2001).

The effect of thin-walled dripline (drip tape) extraction on its performance was evaluated by Burt and Barreras (2001). They found no correlation between the uniformity of emitter discharge rates and the number of extractions. Some driplines that were reused up to 15 or 16 times showed no decline in performance, whereas others used only once or twice showed a performance decline. The reason for this behavior is unknown.

12.3.8. Patterns of Soil Water Content

Numerous studies have been conducted on water infiltration for surface drip irrigation. These studies were concerned with the soil water distribution patterns during infiltration into a dry soil assuming that a point source or single emitter was supplying water to the soil. Bresler et al. (1971) and Levin et al. (1979) showed that the wetted pattern in a sandy soil to be elongated in the vertical direction compared with the horizontal direction. Bar-Yosef and Sheikholslami (1976) found horizontal elongation of the wetting pattern in a clay soil.

After irrigation, the horizontal advance of the wetting front for a loamy sand was much less than the vertical advance, but water movement in silt loam was relatively uniform in all directions (Hachum et al., 1976). Water movement in a fine-textured soil may be limited, but vertical movement in a coarse-textured soil may be significant.

A 1 L/h emitter discharge rate tended to give greater lateral water lateral movement during infiltration on a dry, bare silty loam than a 4 L/h rate (Mostaghimi et al., 1982). The larger emitter discharge rate resulted in deeper wetting during infiltration. Considerable additional redistribution of water occurred 48 h after the start of irrigation than at the end of the irrigation event.

Under field conditions of continual wetting and drying, patterns of soil water content not only depend on soil texture and emitter discharge rate, but also on water management (irrigation frequency and amount of applied water), emitter spacing, lateral spacing relative to plant row spacing, lateral positioning with respect to the plant row, and plant extraction of soil water. Because of plant extraction of soil water, redistribution of soil water after irrigation may be minimal under some conditions.

Water distribution was more favorable for weekly drip irrigations than daily drip irrigations (Earl and Jury, 1977). Under daily irrigation, lateral movement from the emitter was about 0.6 m and downward movement was about 0.6 m deep. Under weekly irrigation, lateral movement was about 1 m from the emitter and downward movement was about 0.75 m deep.

Soil water patterns were determined in a sandy loam four days after cotton irrigation for driplines spaced every 2 m and place midway between plant rows (1 m plant row spacing) (Yaron et al., 1973). Irrigation amounts were 75% and 100% of the soil water deficit of an adjacent sprinkler-irrigated plot. An emitter discharge rate of 2 L/h and emitter spacing of 1 m was used for the 100% treatment, whereas a 4 L/h discharge rate and 0.75 m spacing was used for the 75%

treatment. Wetting occurred down to at least 1.5 m for the 100% treatment and to about 1.1 m for the 75% treatment. Lateral movement was about 0.6 m for both treatments.

Patterns of soil water content under surface and subsurface drip irrigation (0.4 m deep) of cotton in a clay soil were compared under water applications of 100%, 85%, and 75% of the potential crop evapotranspiration (Plaut et al., 1985). Driplines (2 m spacing) were positioned midway between plant rows (1 m spacing). Emitter spacing of the 2 L/h emitters was 1 m. For the 100% treatment, the soil profile was wet (38% to 42% water content) down to at least 1.35 m beneath the emitters. Soil water content decreased with horizontal distance for all water applications and emitter placements. However, horizontal flow of water under surface drip irrigation was the greatest at about the 0.75 m depth and at 1.05 m for the subsurface system. Soil water content decreased in the upper part of the profile as water application decreased. Water movement above the subsurface dripline was limited for all water applications.

Wetting patterns measured in a sandy loam indicated drier soil under surface drip than with subsurface drip irrigation (Camp et al., 1987). Measurements also revealed little or no redistribution of soil water after irrigation. This lack of redistribution was due to soil water extraction by the crop reducing or preventing any further lateral movement of soil water.

Soil water patterns under surface drip irrigation were determined for two different bed configurations and dripline locations (Hanson and Bendixen, 1998). A narrow bed (1 m spaced bed with 1 dripline centered on bed) had an elongated vertical soil water pattern on a sandy loam (Fig.12.12A) with nearly constant soil water below the dripline to about 0.5 m deep. Soil water content decreased at horizontal distances greater than 0.1 m. Similar vertical elongation patterns were present for the wide bed configuration (1.5 m crop bed with 2 driplines/bed), but tended to have higher soil water contents near the soil surface (Fig. 12.12B). Soil water content again decreased with horizontal distance with more dry areas occurring midway between the dripline and at the edges of the bed.

Results of Hachum et al. (1976) have led to the assumption that lateral movement of water from a dripline is greater in a fine-textured soil than for a medium or sandy soil. However, field measurements and observations have shown that the lateral movement in a fine-textured soil can be very small, sometimes less than about 0.15 m from the dripline. Explanations for this behavior are unclear, but it may be because lateral water flow in a fine-textured soil moves at a relatively slower rate than the rate of plant water uptake. In a bare soil where no plant water uptake occurs, lateral movement in a fine-textured soil may be considerable over a long period.

Pulsed water applications have been advocated for improving distribution of water around driplines. Studies of this concept involved cycling irrigation water with irrigation events ranging from a few minutes to 30 min/h. The main advantages to this approach are: (1) the ability to use emitters with large flow passages, thus reducing clogging problems, while maintaining low average application rates, and (2) better soil aeration. Zur (1976), Levin and Van Rooyen (1977), and Levin et al. (1979) found that soil water distribution around the dripline showed little difference between pulsed and continuous applications with similar average application rates. Camp et al., (1987), however, found a narrower and deeper wetted pattern for the continuous application than pulsed applications.

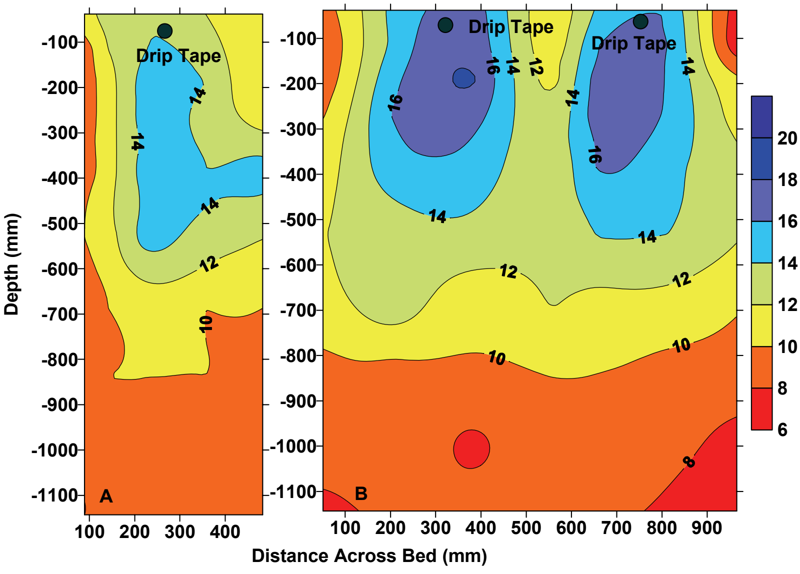

Figure 12.12. Water distribution about surface drip tape in sandy loam soil for two bed configurations. Legend represents gravimetric water content in percent.

Pulsed applications may be suitable for small drip irrigation systems, but can cause management and uniformity problems for large systems. Drip irrigators in California (USA) found that a significant percentage of the irrigation set time was spent filling pipelines when using short, frequent water applications. Also, the frequent applications resulted in substantial amounts of water draining from the irrigation system and collecting at the lower part of the field, thus, contributing to poor field-wide uniformity of applied water. These results indicate that pulsed drip irrigation may only be practical for small fields.

12.3.9 Patterns of Soil Salinity

Soil salinity patterns are also affected by bed configuration and dripline location (Hanson and Bendixen, 1998). Soil salinity was relatively low near the dripline for a narrow bed (1 m bed with one centered dripline/bed), reflecting the leaching occurring in those areas (Fig. 12.13A) As horizontal distance from the dripline increased, soil salinity increased at all depths. Maximum soil salinity was found at edge of the bed. Soil salinity was also low beneath both driplines on a wide bed (Fig. 12.13B). However, salinity increased with horizontal distance and reached a maximum level midway between the driplines and at the edges of the bed.

When water applications are insufficient to cause leaching below driplines, relatively high levels of soil salinity occur in this vicinity due to salt accumulation (Fig. 12.14A). After water applications were increased to provide more leaching, the salinity was lower around the dripline, but increased at the edge of the wetting pattern. This emphasizes the need for good water and salinity management with respect to crop and dripline location.

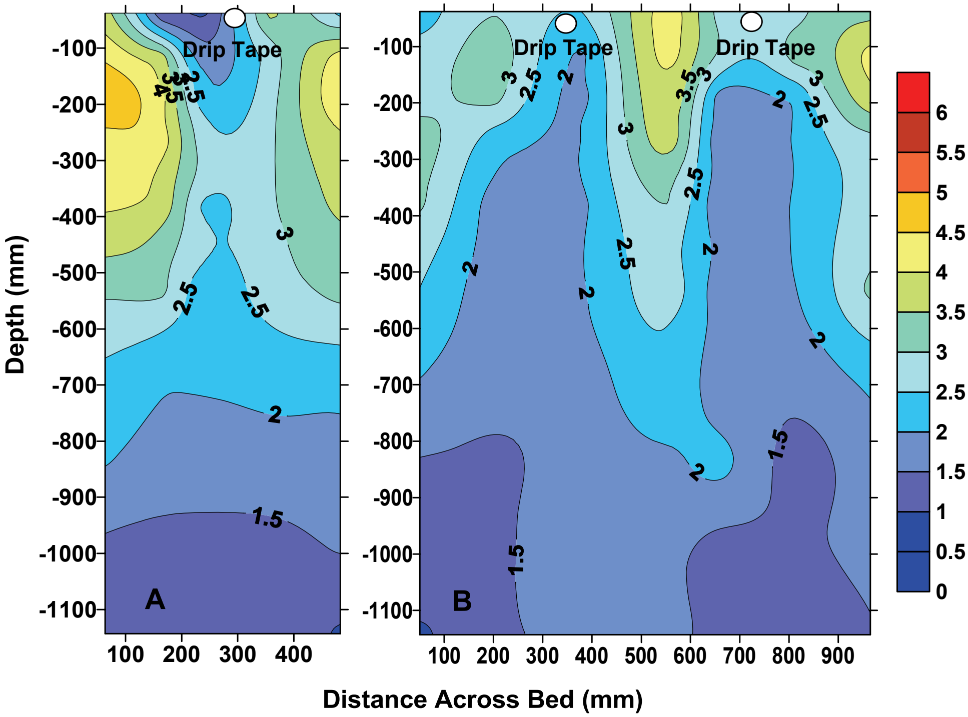

Figure 12.13. Salt distribution about drip tape for two bed configurations. Legend represents EC in dS/m.

In summary, a zone of relatively low soil salinity occurs near and below the dripline for surface drip irrigation (Fig 12.13 and Fig 12.14B). Under subsurface drip irrigation, soil salinity also is relatively low below the dripline. However, soil salinity increases above the subsurface dripline as depth decreases because no leaching occurs above the dripline (Fig. 12.15). For subsurface drip irrigation, leaching above the dripline is accomplished by rainfall or sprinkler irrigation.

These salinity patterns indicate that soil salinity near the dripline is the lowest and increases with horizontal distance from the dripline. For larger leaching fraction, the zone of relatively low soil salinity will be greatest around the dripline (Hoffman et al., 1985); and for a plant row that coincides with the dripline, the root zone will coincide with the zone of low salinity. However, as the distance between plant row and dripline increases, soil salinity in the root zone will probably increase. When the plant row is midway between driplines, the root zone may coincide with the zone of highest salinity. This may not be a short-term problem for salt tolerant crops such as cotton, but it could adversely affect crop yields of salt sensitive or moderately salt sensitive crops. Leaching the relatively high salt zone may be required eventually to maintain crop yield.

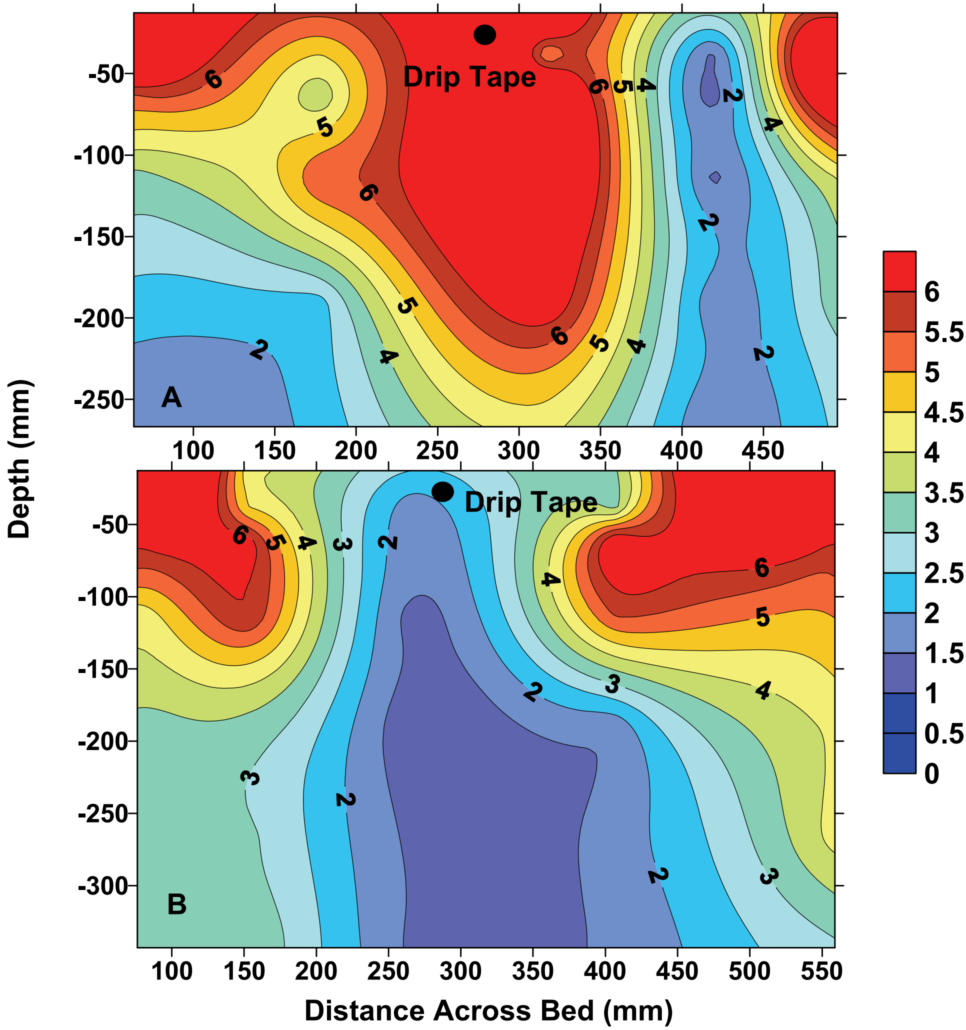

Figure 12.14. Salinity distribution for (A) no leaching, and (B) efficient leaching. Legend represents EC in dS/m.

12.3.10. Crop Response to Surface Drip Irrigation

12.3.10.1. Surface versus subsurface drip irrigation

A few studies have compared crop yields between surface and subsurface drip irrigation. Lettuce yields were similar between surface and subsurface drip irrigation (0.1 m depth) on a clay loam, but potato yield was slightly higher with subsurface drip irrigation (Sammis, 1980). Similar lettuce yields were obtained for surface and subsurface drip irrigation (0.2 m depth) for water application levels ranging from deficit irrigation to overirrigation (Guillen, Hanson, May, 2003. unpublished data). In addition, similar lettuce yields were obtained under furrow, surface drip, and subsurface drip irrigation in sandy loam (Hanson et al., 1996). Sweet corn yield was slightly higher with subsurface than with surface drip irrigation (0.3 m depth), but the difference was not statistically significant (Bar-Yosef et al., 1989). There were no significant differences in cotton yield between surface and subsurface drip (0.40 m depth) for a clay loam soil (Plaut et al., 1985). Davis et al. (1985) also found no significant yield differences in processing tomato between surface and subsurface drip irrigation (0.45 m depth). No field corn yield differences occurred between surface and subsurface drip (0.3m depth) for a given amount of applied water, which ranged from deficit irrigation to adequate irrigation (Howell et al., 1995). Similar yields of processing onions and fresh-market onions were found between surface and subsurface drip irrigation for the same amount of applied water on a silt loam soil (Hanson and May, 2003. unpublished data).

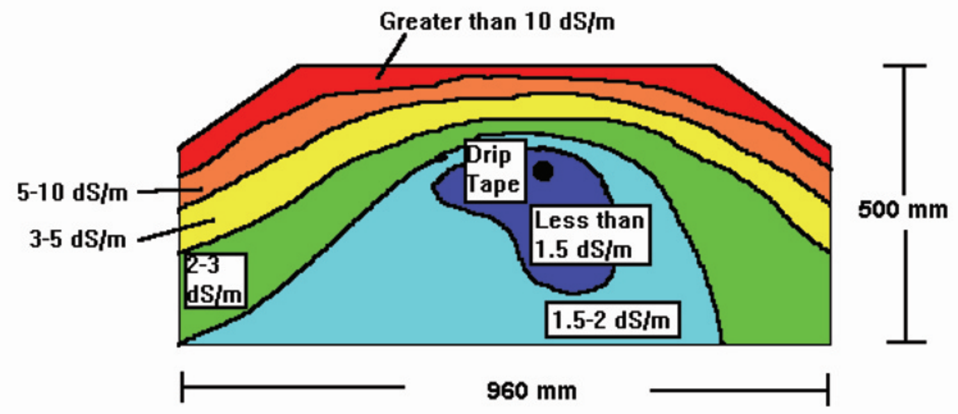

Figure 12.15. Salinity distribution for subsurface drip irrigation.

These results indicate that little yield differences exist between surface and subsurface drip for a given amount of applied water. Thus, the choice of drip irrigation system probably will often depend on factors other than yield and applied water, some of which were considered earlier in this chapter. It is frequently assumed that evaporation of water from the soil will be less under subsurface drip irrigation than surface drip. This is probably true, but the reduced evaporation apparently does not give subsurface drip irrigation an advantage over surface drip in terms of water use and crop yield. In reality, there may be water losses under subsurface drip, such as deep percolation, that offset reduced evaporation.

Caution should be exercised in extrapolating these results to soils that differ considerably in texture from those used in the experiments described for shallow rooted crops. While the previously cited study showed similar onion yields between surface and subsurface drip irrigation on silt loam soil, grower experience has shown lower onion yields under subsurface drip irrigation than surface drip irrigation for other soil textures. For silt loam soil, upward and lateral flow of water readily occurs around the drip line, but such movement may be limited for sandy soil and in some cases, clay loam soils.

12.3.10.2. Irrigation frequency effects

No significant yield and quality differences in processing tomatoes were found with daily or three- and four-day intervals for surface drip irrigations on a clay loam (Davis et al., 1985). Lettuce yields were slightly larger when irrigated with tensiometer values of 0.02 MPa than with 0.06 MPa, but yield differences were not significant (Sammis, 1980). These same irrigation treatments did not affect potato yields in the same study. In another study, best commercial lettuce yield was obtained by maintaining soil water content at about field capacity than with depletions of 20% and 30% (Sutton and Merit, 1993). Highest strawberry yields were obtained by scheduling irrigation at a tensiometer value of 0.01 MPa than 0.03, 0.05, and 0.07 MPa (Serrano et al., 1992). Ellis et al. (1986) drip-irrigated onions with one and three irrigations/week in clay loam and found no significant yield differences. Drip irrigation frequencies of 2 per day, 1 per day, 2 per week, and 1 per week on sandy loam and silt loam soil had no effect on yields of processing tomatoes and peppers, but the 1 per week frequency reduced yields of onions and lettuce compared with other frequencies (Hanson et al., 2003).

Cotton yields on a clay loam soil were not affected by surface drip irrigation frequencies of twice per week or every two weeks for both continuous and pulsed applications (Howell et al., 1987). However, slightly less water was applied for the two-week frequency. Similarly, Ayars et al. (1985) found no cotton yield differences between daily drip irrigations and irrigations every three to four days. Water savings of about 9% were achieved with the three to four-day frequency as compared with the daily irrigations. Similar results were reported by Meiri et al. (1992). They found no differences in cotton yield for a sandy loam soil using daily or twice-per week irrigation frequencies. Howell et al. (1995) found no differences in field corn yield for daily and weekly drip irrigations.

These studies suggest that for deeper-rooted crops on medium- to fine-textured soils, drip irrigation frequency has little or no effect on crop yield. However, for shallow-rooted vegetable crops that are sensitive to water stress, higher yields can be obtained with more frequent irrigations, particularly on sandy soil. Based on these findings, some general recommendations regarding irrigation frequency can be made.

- For crops such as tomato, field corn, and cotton, irrigate at least once per week on medium- to fine-textured soils, and at least twice per week for a sandy soil.
- For crops that are sensitive to water stress, daily or twice weekly irrigations are recommended regardless of soil type.

12.3.11. Managing a Drip Irrigation System of Row Crops

Managing a drip irrigation system requires determining when to irrigate and how much water to apply. The frequency of drip irrigation could be daily to weekly depending on crop, soil type, climatic conditions, and irrigators' preference. In selecting an irrigation frequency, several things should be considered. First, a primary advantage of drip irrigation is its ability to irrigate at a high frequency, thus maintaining soil water content at an optimum level. Drip irrigation management has the potential of improving crop yield with reduced water applications under many conditions. Second, drip irrigation can be unforgiving because of the smaller wetting pattern and smaller active root zone than other irrigation methods. Thus, stored soil water can be quickly depleted to detrimental levels when irrigations are infrequent, especially in arid areas.

Determining how much to water to apply requires estimating crop evapotranspiration *(ET_c)* between irrigations (daily ET_c x days between irrigations). In some areas, a method to estimate crop water use is to obtain reference crop evapotranspiration *(ET_o)* information, and then multiply ET_o by an appropriate crop coefficient *(k_c)*, or

$$ET_c = k_c \bullet ET_o \tag{12.6}$$

ET_o is usually based on grass or alfalfa water use and is determined from data collected by networks of weather stations maintained by state agencies or universities. Extensive discussion about using this approach can be found in Chapter 3, Allen et al. (1998), and Hanson et al. (1999).

The crop coefficient depends on crop type and stage of growth. Two kinds of crop coefficients exist, the mean and basal coefficients. Mean crop coefficients, developed using furrow or sprinkler irrigation where the soil surface is wetted during irrigation, account for the evaporation during and after an irrigation event. Basal crop coefficients assume a dry soil surface. Both types of coefficients are listed in Allen et al. (1998), whereas only mean coefficients are listed in Hanson et al. (1999). Mean crop coefficients could be used during the early growth stages for surface drip irrigation because little difference in crop evapotranspiration was found between furrow irrigation and surface drip irrigation (Pruitt et al., 1984). Basal crop coefficients would be more appropriate for subsurface drip irrigation where little or no surface wetting occurs. However, crop coefficients were similar for furrow and subsurface drip irrigated processing tomatoes once the crop approached maturity (Hanson, 2002).

Evaporation pans can be used for locations lacking information on reference crop evapotranspiration. This approach involves measuring water evaporation in a pan of specific size and appropriate location, and relating this evaporation to reference crop ET using appropriate pan coefficients. Information on using evaporation pans is available in Chapter 3 and Allen et al. (1998). Another method found to be reasonably accurate for estimating reference crop evapotranspiration in arid climates requires air temperature and solar radiation data (Hargreaves and Samani, 1985)

Measuring soil water content between irrigations is used to estimate crop evapotranspiration for furrow, border, and sprinkler irrigation. However, water content measurements are difficult for drip irrigation for two reasons. First, soil water varies considerably with distance from the dripline. A reasonable estimate of crop ET from soil water changes requires measurements across the wetted volume of soil. This is often not practical for farm operations using drip irrigation. One approach is to use a neutron moisture meter, which measures a volume of soil about 0.25 m in diameter. However, this instrument is not appropriate for many irrigators because it is expensive and contains a radioactive source, thereby requiring special licensing and monitoring. Second, the smaller more frequent irrigation events recommended for drip irrigation results in small soil water changes that may be difficult to detect with a neutron moisture meter.

Measuring changes in soil water content between irrigations may not be practical for drip irrigation, but monitoring soil water content can provide valuable information about the management of the irrigation system. The objective is to determine trends in soil water content with time. Measurements that show decreasing soil water content with time suggest insufficient water applications, whereas increasing soil water content indicates potential overirrigation. Little change in water content over time indicates that irrigations are adequate.

Instruments available for monitoring soil water content include tensiometer, electrical resistance block, and dielectric moisture sensors. A comparison of some of these instruments (Hanson et al., 2000 a and b; Hanson and Peters, 2000) indicated that simple, inexpensive instruments such as tensiometers and electrical resistance blocks are suitable for monitoring soil water content during drip irrigations because of their cost, ease of installation, and ease of use. Data loggers can be programmed to record water contents continuously, enabling analysis of changes in soil water content, which may not be readily seen with periodic measurements.

The placement of the water content sensor with respect to dripline is important. In areas where spring rainfall or snowmelt replenishes soil water content to field capacity, field measurements and experience have shown that a drying front moves back toward the dripline as the soil water is depleted beyond the wetted zone of the dripline as the crop matures. Thus, this drying front may influence sensor readings of instruments placed too far from the dripline. On the other hand, sensors placed too close to the dripline may not follow the drying trend, due to insufficient irrigation. As a guide, the sensor should be placed in the plant row of vegetable crops where two plant rows per dripline are used or placed about 0.15 m from the dripline when the dripline coincides with the plant row. For shallow-rooted crops, the depth of the sensor should be between 0.15 and 0.3 m. However, it is recommended that sensors initially be placed at different positions (depths and distances) relative to the dripline to determine the most appropriate location for a specific soil type, emitter spacing, and emitter discharge rate.

An advantage of drip irrigation is that irrigation water can be precisely applied in quantity and location. Precisely applying water with a drip system requires a flowmeter or knowledge of the system's application rate. Many different flowmeters are available. Propeller flowmeters are suitable for most farm conditions because of their low cost, ease of installation and use, and relative insensitivity to turbulence caused by bends and check valves (disk-type) (Hanson and Schwankl, 1998).

The application rate for a dripline can be calculated from the following equation:

$$I = 0.01 \bullet q / B \tag{12.7}$$

where I is the application rate in mm/h, q is the dripline discharge rate in L/h-100 m, and B is the bed spacing in m. The dripline discharge rate can be calculated from field measurements or obtained from the manufacturer provided that the pressure in that part of the field is known. The dripline discharge of surface drip irrigation systems can be calculated by measuring the emitter discharge rates of several emitters, calculating the average emitter discharge rate (q_{avg}) in L/h, and then using the following equation:

$$q = N \bullet q_{avg} \tag{12.8}$$

where N is the emitters/100 m. The emitter discharge rates should be determined in the least watered area of the field so that the calculations will ensure that the entire field is adequately irrigated.

The irrigation set time *(T_s)* in h can be determined when the application rate I in mm/hr, irrigation event frequency, T_e in days, and the mean daily crop evapotranspiration, ET_c in mm/day are known using

$$T_s = ET_c \bullet T_e / I \tag{12.9}$$

A properly managed drip system then applies appropriate amounts of water at frequent and regular intervals as illustrated in Fig. 12.16a. Management of this system involved applying water about twice per week most of the time (black bars). Irrigation set-times (shown by bar width) were nearly equal throughout most of the mid-season growth stage. Shortly after irrigation, soil water tension started increasing indicating that about the right amount of water had been applied. Soil moisture tension were less than about 30 kPa just before an irrigation until near the end of the irrigation at which time, drying of the soil was allowed to improve crop quality (processing tomato). Irrigations were somewhat regular throughout most of the irrigation season in Fig. 12.16b. However, soil water tension remained near zero most of the time indicating a saturated soil, probably the result of overirrigation. An improperly managed drip system is presented in Fig. 12.16c. Frequency of irrigation is highly irregular, and duration of some of the irrigations was excessive (up to five consecutive days). Soil water tension frequently was between 80 kPa and 90 kPa just before irrigation and considered too high for drip irrigation.

12.3.12. Using Plastic Mulch with Surface Drip Irrigation

Plastic mulch sometimes has been used effectively with surface drip irrigation. Potential advantages of this practice include increased yield due to factors such as warmer early season soil temperatures, reduced soil evaporation, reduced fertilizer and herbicide losses, and less fruit rotting due to reduced contact between fruit and wet soil. Potential disadvantages include increased production costs and the decreased yields that can be caused by high soil temperatures in some climates.

The effect of plastic mulch on crop yield is unpredictable because of the role the microclimate plays in any yield response. Tarara (2000) points out that the lack of microclimatic data in most studies prevents an understanding of crop yield response to mulch for a given set of conditions. Variable results have been obtained when mulch is used with microirrigation. For example, Rubiez and Freiwat (1995) found a 31% increase in tomato production in one field where mulch was used compared with an unmulched treatment, but no difference in another field. Shrivastava et al., (1994) observed little tomato yield differences between mulched and unmulched drip irrigation. Safadi (1991) found no statistically significant cucumber yield differences between mulched and unmulched treatments, but found statistically significant squash yield differences with higher yields for the mulched treatments. Thus, irrigators desiring to use plastic mulch may need to conduct their own field trials to determine the benefits of plastic mulch for their site-specific conditions when local research results do not exist.

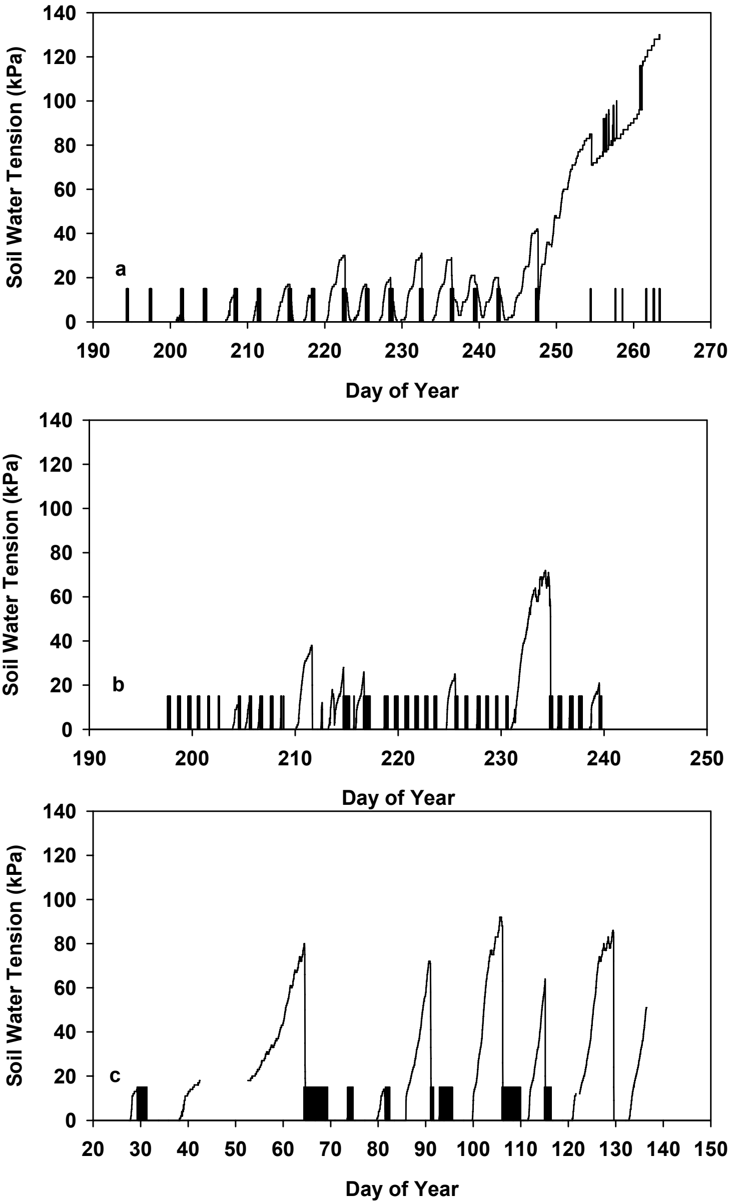

Figure 12.16. Examples of (a) properly managed drip system, (b) improperly managed system resulting in overirrigation, and (c) improperly managed system with infrequent irrigations and excessive irrigation set times. Vertical lines represent irrigation events and continuous lines represent soil water tension.

LIST OF TERMS AND SYMBOLS

A	tree or vine growing area, m^2
B	bed spacing, m
CV	manufacturer's coefficient of variation
ET_c	crop daily water use, mm/day
ET_o	reference crop daily water use, mm/day. Reference crop is grass or alfalfa.
EU	design emission uniformity, percent
EU_f	field-measured emission uniformity, percent
I	application rate, mm/h
k	constant varying by drip emitter model and units used
k_c	crop coefficient
n	number of emitters/plant
N	number of emitters/100 m of dripline
P	emitter operating pressure, kPa
q	dripline discharge rate, L/h-100 m
q_{lq}	average discharge rate of the lowest 25% of field-data emitter discharge values, L/h
q_{avg}	average of all the emitter discharge rates, L/h
q_{min}	minimum emitter discharge rate, L/h
Q	emitter discharge rate, L/h
Q_c	tree or vine daily water use, L/day
s	standard deviation of emitter discharge rates, L/h
T_e	irrigation frequency, day
T_s	irrigation set time, h
x	emitter discharge exponent

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13. SUBSURFACE DRIP IRRIGATION

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13.1. APPLICATION AND GENERAL SUITABILITY

Subsurface drip irrigation (SDI) is defined as the application of water below the soil surface by microirrigation emitters. The discharge rate of the emitters is usually less than 7.5 L/h (ASAE S526.2, 2001). SDI is different from, and should not be confused with, subirrigation where the root zone is irrigated by controlling the height of the water table.

The desirable installation depth for the subsurface driplines varies with crop, soil type, water source, pests, climate, and irrigator's preference. Some shallow subsurface systems (< 20 cm depth) are retrieved and/or replaced annually and are very similar to surface drip irrigation. Many research reports refer to these systems as surface drip irrigation, and reserve the term SDI for systems intended for multiple-year use that are installed below tillage depth (Camp and Lamm, 2003). Discussion will concentrate on SDI systems with driplines deeper than 5 cm. This arbitrary 5-cm depth is slightly greater than the 2-cm depth selected by Camp (1998) for a comprehensive review of SDI. The slight distinction may help limit the discussion to SDI systems that have more similarity in design characteristics and operational properties.

SDI is suitable for a wide variety of horticultural and agronomic crops, and, in many respects is applicable to those crops presently under surface drip irrigation (DI) as discussed in Chapter 12. Although DI is now used more intensively than SDI, microirrigation probably started with water application below the soil surface (Davis, 1974). The first experiments with SDI began in the 1860s in Germany, where short clay pipes with open joints were used to provide both irrigation and drainage (Howell et al., 1983; Keller and Bliesner, 2000). In essence, SDI methodology evolved from the subirrigation method. The earliest SDI research in the United States that did not use subirrigation techniques was conducted at Colorado State University in 1913 by House (1918), who concluded that it was economically impractical.

SDI has been a part of modern agricultural irrigation since the early 1960s. Investigations of both SDI and DI with citrus crops and potatoes were conducted by Sterling Davis, an irrigation engineer with the United States Salinity Laboratory, in 1959 (Davis, 1974; Hall, 1985). At about the same time in Israel, Blass (1964) was reporting early experiences with SDI. SDI performance was often plagued by problems such as emitter clogging (chemical precipitation, biological and physical factors, and root intrusion) and poor distribution uniformity. However, as improved plastic materials, manufacturing processes, and emitter designs became available, resurgence in SDI occurred, both in research activities and commercial operations.

SDI has been used primarily for high-valued horticultural crops (fruits, vegetables, and ornamentals), tree crops (nuts and fruits), vineyards, and sugarcane. As system reliability and longevity improved, SDI has begun to be used with lower-valued agronomic crops (cotton, peanuts, and cereal crops). This is primarily because SDI system's longevity has increased to the point that investment costs can now be amortized over longer periods.

13.1.1. Advantages of SDI

Potential advantages exist for SDI when properly managed and/or when site conditions and cropping systems allow the advantages to be fully realized. Certain positive and negative aspects of SDI must be considered by the grower before its selection. For example, there are opportunities for improved cultural practices with SDI, whereas, there may be fewer tillage alternatives. These advantages may be further divided into arbitrary groupings of water and soil issues, cropping and cultural practices, and system-infrastructure issues.

Advantages of SDI related to water and soil issues include the following:

- <u>More efficient water use</u> – Soil water evaporation, surface runoff, and deep percolation are greatly reduced or eliminated. Infiltration and storage of seasonal precipitation can be enhanced by drier surface soils with less soil crusting. In limited instances, the system can be used for a small irrigation application for germination, depending on dripline depth, flowrate, and soil constraints. The inherent ability to apply small amounts of water can allow flexible irrigation decisions near the end of the cropping season. In widely spaced crops, a smaller fraction of the soil volume can be wetted, thus further reducing unnecessary irrigation water losses.
- <u>Fewer water quality hazards</u> – Runoff into streams is reduced or eliminated, and, with proper management, less nutrient and chemical leaching occurs due to deep percolation.
- <u>Improved opportunities in using degraded waters</u> – Smaller and more frequent irrigation applications can maintain a more consistent and lower soil-matric potential that can reduce salinity hazards. Subsurface wastewater application can reduce pathogen movement, odors, and human and animal contact with such waters.
- <u>Better water application uniformity</u> – Improved in-field uniformities lead to better control of the water, nutrients, and salts. Widely spaced crops can benefit from water application closer to the crop, provided sufficient soil wetting is achieved.

Advantages of SDI related to cropping and cultural practices include:

- <u>Enhanced plant growth, crop yield, and quality</u> – Many crops respond positively to SDI.
- <u>Improved plant health</u> – Problems with plant pathogens are reduced because of drier and less-humid conditions around the crop canopy. The SDI system can also be used for soil fumigation.

- Improved fertilizer and pesticide management – Precise and more timely application of fertilizer and pesticides through the system can increase chemical efficacy.
- Better weed control – Reductions in weed germination and weed growth often occur in arid regions, particularly in drier inter-rows.
- Improved double-cropping opportunities – Crop timing can be enhanced because the system does not require removal at harvest and reinstallation before planting.
- Improved farming operations and management – Many field operations can be conducted during irrigation events. Field operations on drier soil surfaces result in less soil compaction, and soil crusting caused by irrigation is greatly reduced. Variability in soil water regimes and redistribution is often less with SDI than DI. In addition, there are fewer weather-related application constraints such as high winds, freezing temperatures, and wet soil surfaces. Fertilizers can be applied as needed in small irrigation events, even when irrigation requirements are low. The ability to irrigate during freezing conditions can be particularly beneficial where preseason irrigation is used to effectively increase seasonal irrigation capacity. Subsurface irrigation equipment is less exposed to vehicular damage. Hand laborers can benefit from the drier soils that tend to reduce manual exertion and injuries and from less exposure to agrochemicals that are applied with SDI.

Advantages of SDI related to system infrastructure include:

- Automation – The closed-loop, pressurized characteristic of the system that can reduce variability of application and soil water and nutrient redistribution variability is ideally suited for automation and advanced irrigation control technologies.
- Decreased energy costs – Operating pressures are often less than for some types of sprinkler irrigation. Any water savings attributable to SDI will also reduce energy costs.
- System integrity issues – Fewer mechanized parts are used in an SDI system than in mechanical-move sprinkler irrigation systems. Most components are plastic and are corrosion resistant. SDI systems do not need to be removed and installed between crops, and thus equipment damage is reduced. Also, the potential for vandalism is greatly reduced.
- Design flexibility – Increased flexibility exists with SDI designs in matching field shape and field size than with center pivot sprinkler irrigation systems. The SDI system can be easily and economically sized to the available water supply. In widely spaced crops, driplines can be placed for optimum water and nutrient uptake. Pressure-compensating SDI systems have fewer slope limitations than surface irrigation systems.
- System longevity – SDI installations can have a long economic life when properly designed and managed. Long system life allows for amortizing investment costs over many years, thus allowing lower-valued commodity crops to be economically grown with SDI.
- Less pest damage – In some situations, less pest damage (wildlife and insect) occurs with SDI than DI systems. However, this requires careful consideration because pest damage to SDI systems may require more effort to detect and to repair.

13.1.2. Disadvantages of SDI

Alternatively, circumstances and situations exist that present disadvantages for an SDI system. These disadvantages also may be arbitrarily divided into groupings of water and soil issues, cropping and cultural practices, and system-infrastructure issues.

Disadvantages of SDI related to water and soil issues include:

- Smaller wetting pattern – Water redistribution may be too low on coarse-textured soils, resulting in a limited wetted zone. This situation can make system capacity and system reliability extremely critical issues because there is less ability to buffer and overcome insufficient irrigation capacity or system breakdown.
- Monitoring and evaluating irrigation events – Water applications may be essentially invisible so that it is more difficult to evaluate system operation and application uniformity. System mismanagement can lead to underirrigation, with reduced crop yield and quality, or overirrigation, with poor soil aeration and deep percolation problems.
- Soil/Application rate interactions – Emitter discharge rates can exceed the ability of some soils to redistribute the water under normal redistribution processes. In such instances, water pressure in the region around the outside of the emitter may exceed atmospheric pressure, thus altering emitter flows. Also, water may inadvertently "surface" (tunneling of the emitter flow to the soil surface) causing undesirable wet spots in the field. Small soil particles may be carried through "surfacing," causing a "chimney effect," providing a preferential flow path. The "chimney" may be difficult to correct because a portion of the "chimney" remains above the dripline even after tillage.
- Reduced upward water movement – Germination may become a problem with SDI, depending on the installation depth and soil properties. This may be particularly troublesome on soils with vertical cracking or for coarse-textured soils and shallowly planted seeds. Salt accumulation may be increased above the dripline, thus creating a salinity hazard for the emerging seedlings or small transplants.

Disadvantages of SDI related to cropping and cultural practices include:

- Fewer tillage options – Primary and secondary tillage operations may be limited by dripline placement.
- Restricted plant root development – Smaller root zones can make irrigation and fertilization critical issues from both timing and quantity perspectives. The restricted volume may not be sufficient to supply water to the plant so that diurnal crop water stresses can be avoided. Application of nutrients through the SDI system may be required for optimum yields. Application of micronutrients may also become more critical because the smaller soil volume is depleted of these nutrients in a shorter time.
- Row spacing and crop rotation issues – Because SDI systems are fixed spatially, it is difficult to accommodate crops of different row spacing. Some crops may require very close dripline spacing that may be economically impractical. Additional caution must be taken at the time of annual row-crop planting to ensure that crop orientation and spacing are appropriately matched to dripline location. Shallow driplines can also be damaged by wheel traffic during harvesting in wet soil conditions.

- Plant development issues – Certain crops may not develop properly under SDI in some soils and climates. Peanuts may not peg properly into dry soil. Tree crops may benefit from a larger wetting pattern.

Disadvantages of SDI related to system infrastructure include:

- Costs – SDI has a higher initial investment cost than other irrigation systems. In many instances, the system has no resale value or minimal salvage value. Lenders may require greater equity and more collateral before approving SDI system loans. Such large investments may not be warranted in areas with uncertain water and energy availability, particularly where crop price outlook is poor. SDI systems typically have a shorter design life than alternative irrigation systems, which requires that the annualized depreciation costs must increase to provide for system replacement.
- Filtration issues – As with all microirrigation systems, water filtration is critical in ensuring proper system operation and system longevity. However, this issue becomes even more important for long-term SDI systems where duration of greater than 10 years is desired. SDI may require more complex water quality management than surface microirrigation systems because there are no opportunities to clean emitters manually.
- Other maintenance issues – Timely and consistent maintenance and repairs are required. Leaks caused by pests can be difficult to locate and repair, particularly for deeply installed SDI systems. The driplines must be monitored for root intrusion, and system operational and design procedures must employ safeguards to limit or prevent further intrusion. Roots from perennial crops may pinch driplines and stop or reduce flows. Periodic flushing is necessary to remove soil particles and other precipitates that may accumulate in the driplines.
- Operational issues – Operation and management require more consistent monitoring than alternative irrigation systems. Visual indicators of system operation and application uniformity are limited. Irrigation scheduling procedures are required to prevent underirrigation and overirrigation. Careful monitoring of system flowmeters and pressure gauges is required to determine that the system is operating properly.
- Design issues – SDI is a less-developed technology than other types of irrigation systems. This is evident in some regions where growers have little exposure and experience with these systems. Often, turn-key systems are not readily available. In some regions, the lack of contractor capacity can result in less than optimal installation timing during wet periods. Design errors are more difficult to resolve because most of the SDI system is below ground. More components are typically needed for SDI than DI systems. Soil materials can possibly enter the driplines (soil ingestion) at system shutdown if a vacuum occurs. Air relief/vacuum breaker devices must be installed and be operating correctly to prevent this problem. As with any microirrigation system, zone size and length of run will be limited by system hydraulics. Compression of the dripline due to soil overburden can occur in some soils, causing adverse effects on flow. SDI systems are not typically well suited for Site Specific Variable Application *(SSVA)*.
- Abandonment issues – Concerns have been raised on waste plastic product (driplines) in the subsoil when the SDI system is abandoned.

13.1.3. Suitability Considerations

The adaptation and adoption of SDI systems into diverse cropping systems are unpredictable and depend on the geographical region, soils and climate conditions, and, to a large extent, on how potential advantages are balanced against potential disadvantages. In some circumstances, just a few advantages are expressed for a given cropping system, but are expressed so strongly that they provide adequate counterbalance to the potential disadvantages. Many diverse uses of SDI occur throughout the world for a multitude of crops on multiple soil types in various climates. In addition, cultural differences, traditions, skills, and perceptions can have a large influence on whether SDI will be accepted. SDI requires concentrated and consistent management of both water and nutrients to assure adequate crop performance and is also less forgiving than other irrigation systems (Phene, 1996).

13.1.3.1. Suitable crops

SDI is suitable for most all crops where DI is used (See also Chapter 12.). Exceptions may exist when a particular inherent difference between SDI and DI expresses itself in a negative way. For example, some crops such as sweet potato, celery, asparagus and permanent crops that have a long period when irrigation is minimal or terminated, may exhibit high root intrusion into SDI emitters (Burt and Styles, 1999). However, asparagus is often also considered a good crop for SDI because damage can occur to DI during the multiple harvests. Conversely, root crops such as potato and onion can present unique crop harvest challenges for SDI, and, as a result, may not be good candidates for continuous, multiple-year SDI systems, although efforts have been made to overcome these obstacles (Abrol and Dixit, 1972; DeTar et al., 1996; Shock et al., 1998). Although peanuts are successfully grown with SDI in some regions (Sorenson et al., 2001), the plant process of pegging can be inhibited in arid regions and in cracking soils (Howell, 2001). Horticultural crops grown in a multiple, annual cropping system are considered good candidates for SDI because the irrigation system does not have to be removed between crops (Bucks et al., 1981). Similarly, lower-valued commodity crops, such as cotton and corn, may only be profitable with SDI instead of DI because of the ability to amortize SDI system and installation costs over the multiple years of operation (O'Brien et al., 1998; Lamm et al., 2002a). Alfalfa is also a good crop for SDI because it is deep rooted, and because irrigation can continue during the harvest period (Hutmacher et al., 1992; McGill, 1993). Alfalfa yields with SDI were approximately 22% higher than surface flood-irrigated fields while still reducing irrigation requirements by approximately 6%. Water use efficiency was increased, mainly due to increased alfalfa yield, not less water use (Ayars et al. 1999).

13.1.3.2. Geographical and topographical considerations

SDI can be, and is, used worldwide. Areas with variable or shallow soil overlaying rock may not be suitable for SDI because of shallow or restricted depth. Coarse sands and non-bridging soils may also be unsuitable for SDI. When using thin-walled driplines, the weight of the overburden may collapse or deform the dripline, which will reduce the flowrate. Undulating or rolling topography presents design challenges that may limit SDI suitability because of the added hazard of backsiphoning soil material into the dripline when the system shuts down. SDI installed on cracking and heavy clay soils may cause soil water distribution problems that may limit its use on the crops of the region. This can sometimes be avoided with alternative irrigation systems that apply water to the soil surface. In arid and semiarid regions, the limitations on SDI use for crop establishment and salt leaching are added suitability considerations. Crop establishment with SDI can also be a problem on coarse-textured soils or when short drought periods occur at planting in the more humid regions.

Cropping practices of a region may affect the perceived suitability of SDI. In regions where high-value horticultural, tree, and vine crops are grown, the grower may have an erroneous perception that SDI presents more economic risk than DI because of the lack of easily observed indicators of SDI system operation and performance. Although many of these negative perceptions can be overcome, growers may be unwilling to change their cultural practices or management (Phene, 1996). Conversely, in regions where lower-valued commodity row crops are grown, SDI may be the only economically viable microirrigation system option (Lamm, 2002). As early as 1982, SDI was suggested as a good, economical, irrigation system alternative for the small farmer in the United States (Mitchell and Tilmon, 1982). The components of SDI systems can be easily and economically designed to accommodate the field size (Bosch et al., 1992; O'Brien et al., 1998). SDI systems also have lower energy requirements than some of the other irrigation systems used on smaller farms (e.g., high-pressure big-gun traveler systems). Adoption of SDI in a new region can be hampered by the lack of good information on design, management, maintenance, and crop performance, along with the lack of qualified equipment distributors and installers.

13.1.3.3. Water supply and quality

SDI operation is usually based on an on-demand water supply that allows application of small amounts of water frequently and as needed. This permits a consistent soil water environment for the growing crop. However, SDI systems can be operated using seasonal water supplies that vary in quantity and quality and with supplies that are subject to scheduled deliveries. The importance of frequency of SDI depends heavily on the crop, soil, and weather conditions and will be discussed in greater detail later in this chapter (Section 13.3.2.2) and also in Chapters 3 and 7. All irrigation systems should be designed to meet the peak evapotranspiration (ET_c) needs of the crop, either fully through the system capacity or in combination with the anticipated precipitation and soil water reserves. However, this design requirement can differ with climatic zone. Arid regions traditionally use only the irrigation system capacity, whereas humid regions often rely upon the combination of all water sources. Irrigation systems for coarse-textured soils with low water-holding capacity (e.g., sands) should also be designed to meet peak ET_c with only the irrigation system capacity to avoid severe water stress.

Water quality is an extremely important consideration for SDI because most of these systems are planned for multiple-year use. No opportunities exist for manual cleaning of the emitters. Clogging prevention and remediation with chemicals are not always feasible while sensitive crops are growing. Replacement of a clogged dripline is also difficult and time consuming. The added cost of complex water filtration and chemical treatment of marginal-quality water might further reduce the feasibility of SDI use on lower-value crops. However, the filtration and water treatment systems are not design areas in which to reduce cost; improper or insufficient filtration or water treatment can lead to emitter clogging. Severely clogged SDI systems may be difficult or impossible to remediate. More details on general filtration and maintenance practices are discussed in Chapter 11, and chemical application is discussed in Chapter 8.

Saline water application through SDI may result in adverse salt buildup at the edge of the wetted soil volume or above the dripline in the seed or transplant zone, which can hamper crop establishment and plant growth. Care must be taken in plant placement relative to the dripline position to avoid these high-salinity zones. Leaching of the salinity zone above the dripline is often necessary. In some regions, these difficulties in salinity management have reduced or prevented the adoption of SDI. Salinity management issues are further discussed later in this chapter and in Chapter 4.

Considerable research is currently being conducted on the application of biological effluents through SDI systems, particularly in the water short regions surrounding the Mediterranean Sea. The use of SDI to apply these waters can potentially reduce water treatment requirements and human exposure to the effluent, compared to other irrigation systems. The use of biological effluent through SDI is presented in greater detail later in this chapter (Sections 13.2.4.2 and 13.3.1.6.3) and in Chapter 9.

13.1.3.4. Maintenance and longevity

SDI systems must have good and consistent filtration, water treatment, flushing, and maintenance plans to ensure long economic life. Microirrigation systems are usually designed to provide filtration of particles to approximately one-tenth the size of the smallest emitter passageway. The extent of required filtration is determined from the specifications of the dripline manufacturer, whereas the type of filtration system is often chosen according to the water source and quality. Typical SDI filtration of 75 or 100 μm (140 to 200 mesh) does not remove the silt and clay particles and bacteria. These particles may settle out and accumulate or conglomerate in the dripline. Accumulated sediments must be periodically flushed from the SDI system. In many instances, the assurance that adequate water flushing velocities can be obtained throughout the proposed SDI system will be the controlling factor in the sizing of irrigation zones, pipelines, driplines, and emitter flowrates (Burt and Styles, 1999). The flushing requirement and associated components add considerable complexity and cost to the SDI system, but are integral to a successful system. Flushing velocities and other related design parameters are discussed in detail later in this chapter (Section 13.2.2.4). Maintenance of microirrigation systems is also discussed in Chapter 11.

Record keeping is an important aspect in monitoring and ensuring the long-term performance of SDI systems because there are fewer easily observable indicators of performance than with DI. Flowmeters, pressure gauges, and other system operational sensors (e.g., automated backflush controllers, soil water sensors) are used to monitor SDI system operation and performance. Baseline flowrates and pressures for each irrigation zone should be determined at the initiation of new SDI systems. A deviation from these flowrate and pressure baselines, which occurs either abruptly or gradually as part of a trend, is a signal to the grower that a problem (clogging, root intrusion, or a leak) is occurring. A hypothetical example of how flowrate and pressure records can be used to detect problems is shown in Fig. 13.1. Successful repairs and/or remediation depend on the early detection of problems. Fully or severely clogged emitters are much more difficult to remediate than partially clogged emitters (Ravina et al., 1992). Rodent damage can also be reduced when the problem is recognized early, and steps are taken to reduce rodent habitat and activity in the field.

Anomaly A: The irrigator observes an abrupt flowrate increase with a small pressure reduction at the Zone inlet and a large pressure reduction at the Flushline outlet. The irrigator checks and finds rodent damage and repairs the dripline.

Anomaly B: The irrigator observes an abrupt flowrate reduction with small pressure increases at both the Zone inlet and the Flushline outlet. The irrigator checks and finds an abrupt bacterial flare-up in the driplines. He immediately chlorinates and acidifies the system to remediate the problem.

Anomaly C: The irrigator observes an abrupt flowrate decrease from the last irrigation event with large pressure reductions at both the Zone inlet and Flushline outlet. A quick inspection reveals a large filtration system pressure drop indicating the need for cleaning. Normal flowrate and pressures resume after cleaning the filter.

Anomaly D: The irrigator observes a gradual flowrate decrease during the last four irrigation events with pressure increases at both the Zone inlet and Flushline outlet. The irrigator checks and find that the driplines are slowly clogging. He immediately chemically treats the system to remediate the problem.

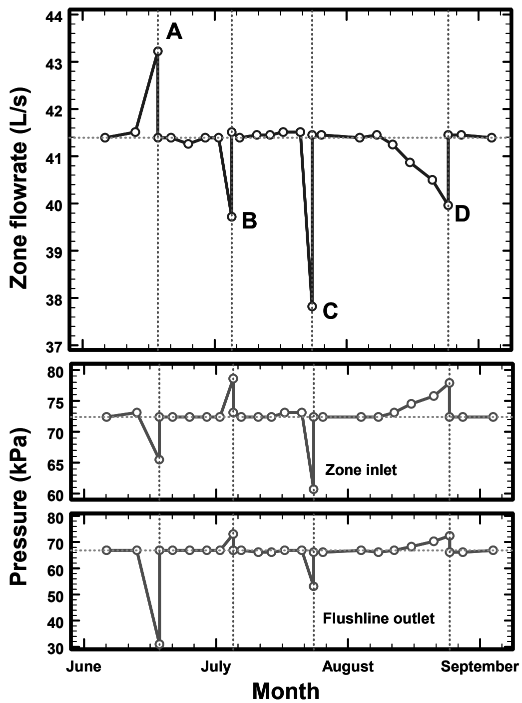

Figure 13.1. Hypothetical example of how pressure and flowrate measurement records could be used to discover and remediate operational problems.

Maintenance, system design, management, and the quality of the water supply are key factors in determining the durability of an SDI system. Because most of the components are below ground, there are fewer concerns about plastic degradation caused by solar exposure. All exposed PVC components that are located on the surface in an SDI system should be painted to protect them from ultraviolet radiation (UV) and to reduce the chance for algal blooms that might start with even limited sunlight penetration into the exposed PVC plastic. Schwankl et al. (2000) suggest that most DI system components should last 15 to 20 years. Less information is available about longevity of SDI systems, but a system installed for research at the Kansas State University Northwest Research-Extension Center, Colby, Kansas in 1989 was still fully functional and performing well in 2006 after 17 years of operation. Zone flowrates for 21 of 23 separate zones are within 5% of the initial values recorded at the close of the first season (Fig. 13.2). In 2005, Sundance Farms in Coolidge, Arizona was still using an SDI system installed in 1983 to grow grains and cotton (Wuertz, 2005). This 76-ha block has sustained clogging of about 25 to 30%, but produces equivalent crop yields and 30 to 40% water savings compared with furrow-irrigated fields. A commercial SDI system installed in 1984 near Fort Collins, Colorado was still in operation in 2006 (Larson and Peterson, 2006), although the owner admitted some reduction in SDI system uniformity due to clogging. At that time, the SDI system was being used for irrigated pasture.

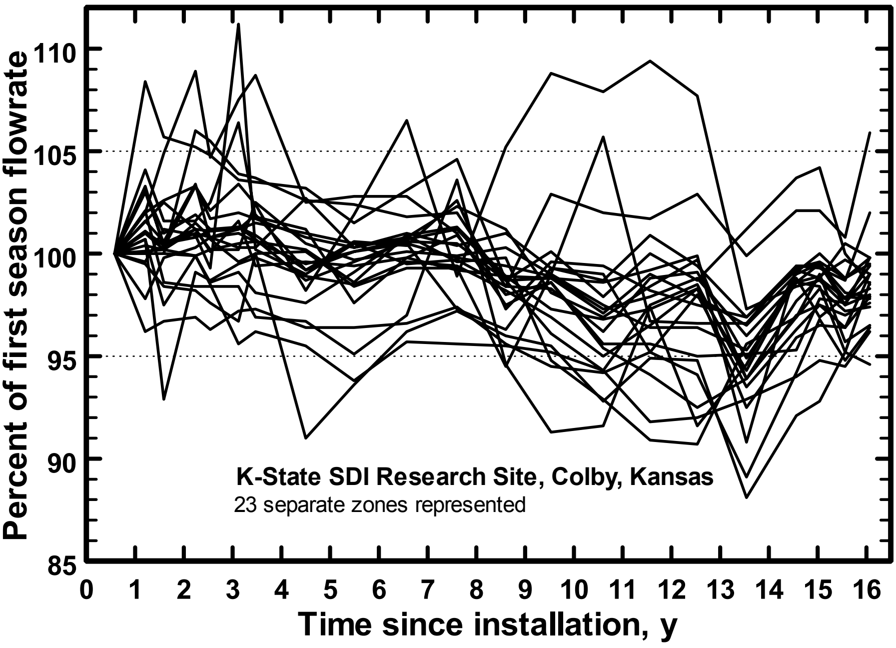

Figure 13.2. Stability in zone flowrates from the initial season, as related to time, for an SDI system at Kansas State University, 1989-2005. Unpublished data from F. R. Lamm, 2005.

13.1.3.5. System uniformity considerations

The effect of system uniformity on microirrigation is discussed in detail in Chapter 10 and in relation to DI in Chapter 12. Those discussions will not be duplicated here, but some additional discussion of microirrigation uniformity issues specific to SDI is warranted. Microirrigation systems actually apply irrigation water in a nonuniform manner by only wetting a portion of the crop root zone. The primary goal of microirrigation is to provide each plant an equal opportunity to access applied water. Discussion of SDI uniformity in this section of the chapter will be strictly limited to hardware performance (i.e., dripline emitter flowrate and variation), fully recognizing that it is ultimately the uniformity of the resultant soil water distribution that is of importance in crop production.

Emitter flowrates can be affected by clogging (internally from physical, chemical, or biological hazards or externally from soil ingestion caused by backsiphoning), root intrusion, root pinching of the dripline, leaks caused by mechanical or pest damage, soil overburden and/or compaction, soil hydraulic conductivity, and related parameters. Qualitative information about irrigation system uniformity can be continually observed from surface wetting with DI, but this is not true for SDI. Therefore, it is imperative that SDI system performance be regularly observed and recorded to monitor flowrate and pressure changes that can reduce system uniformity.

13.1.3.5.1. System uniformity considerations related to emitter clogging

Emitter clogging and its prevention are discussed in Chapter 11, but some unique situations can occur with SDI. Because the driplines are buried, emitter clogging related to elevated water and dripline temperature, and accumulation of salts at the emitter caused by evaporation is reduced. Lamm and Trooien (2005) reported installation depths as shallow as 20 cm reduced the dripline temperatures as much as 12°C, compared with soil surface temperatures (Fig. 13.3). The Langelier Saturation Index *(LSI)*, which indicates the potential of chemical precipitation, is reduced at lower water temperatures (See discussion in Chapter 11 and Tab. 11.7). Hills et al. (1989a) also reported less chemical clogging with SDI (depth, 10 cm) than with DI conducted either during the day or night. The absence of an evaporation face reduces the salt concentration at the subsurface emitter and thus can limit or prevent chemical precipitation. Some types of biological clogging also are exacerbated by high water temperatures, which may accelerate the growth and decay cycles of bacteria and slimes. Conversely, clogging of emitters by soil ingestion caused by backsiphoning at system shutdown can occur with SDI and does not usually occur with DI. Prevention of soil ingestion in SDI is usually approached through installation of air/vacuum relief valves at the high elevation points in the system and through improved emitter characteristics, such as closing slits or flaps that may provide a "checkvalve" feature at shutdown. Continued improvements in emitter design that limit soil ingestion will be an important factor in adoption of SDI on undulating soils, where the addition of sufficient air/vacuum relief valves can be a significant design impediment due to added cost and/or system complexity.

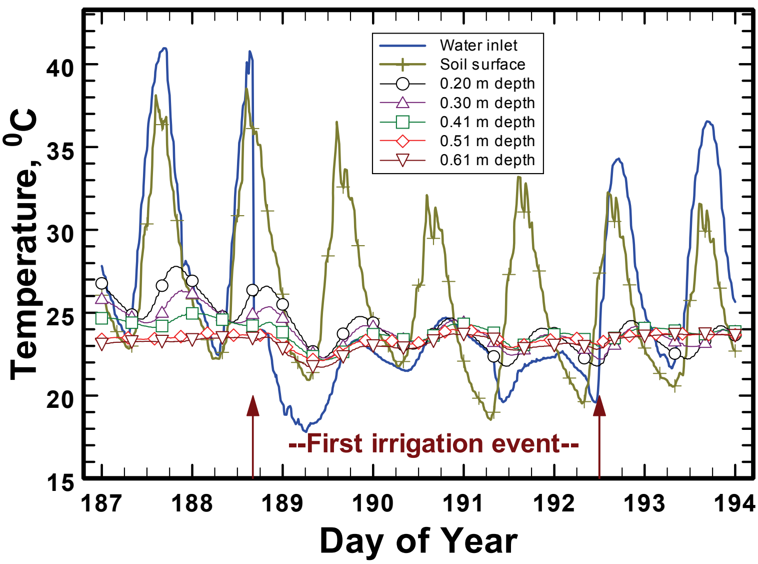

Figure 13.3. Temperatures at the water inlet, near the soil surface, and near the dripline for the five dripline depths before corn canopy closure and the first irrigation event (July 8-11, 2003). Note that water inlet temperature during non-irrigated periods would represent an estimate of the ambient air temperature. After Lamm and Trooien, (2005).

13.1.3.5.2. System uniformity considerations related to root intrusion and root pinching

Root intrusion and root pinching of the dripline are unique problems to SDI that can reduce system uniformity. Although these SDI problems have long been recognized, few published, detailed research studies are available. In a literature review of SDI, Camp (1998) cited only 4 of 61 reports that provided management guidelines discussing root intrusion.

Root intrusion tends to be of greater significance under some crops than others. Perennials often present root intrusion problems when roots continue to grow and utilize some water in winter or semi-dormant periods when irrigation is usually not practiced (Schwankl et al., 1993; Hanson et. al., 1997). Root intrusion can become a serious problem in a very short time (Figs. 13.4 and 13.5). Bermuda grass has caused serious root intrusion problems in less than one year (Suarez-Rey et. al., 2000). Greater processing-tomato yield with DI than SDI was attributed to serious root intrusion in SDI (Tan et al., 2003).

Figure 13.4. Single coffee plant root entering an emitter can enlarge into a large root mass once inside the emitter and dripline. Photo courtesy of Rubens Duarte Coelho, University of Sao Paulo, ESALQ / Brazil.

Coelho and Faria (2003) measured root intrusion of coffee and citrus roots into 14 different emitter models placed in containers. Although all tested emitters experienced root intrusion under the harsh conditions of this container study, there were differences in the overall effect on flowrate and variability. They concluded that nonpressure-compensating emitters performed better than pressure-compensating emitters. Pressure-compensating emitters tended to be unstable, initially increasing, and then decreasing the average flowrate when the emitter became clogged with root and soil particles. Nonpressure-compensating emitters were stable, gradually decreasing the average flowrate as roots and soil particles began to clog the emitter. Ingestion of soil was correlated with increased root intrusion. Emitters that undergo gradual flowrate reduction display more advance warning to the grower, who can then alter irrigation management or use chemical methods to prevent or remediate the root-intrusion problem. Root intrusion may disturb or distort the shape of the elastic membrane on pressure-compensating emitters and thus exacerbate flowrate variations. Coffee was more aggressive than citrus, with greater root intrusion into emitters at a 30-cm depth than 15-cm (Coelho and Faria, 2003). They also noted that root intrusion was greatest under dry conditions as listed in numerous publications (Schwankl et al., 1993; Hanson et al., 1997; Burt and Styles, 1999; Van der Gulik, 1999). Most crop roots do not grow into saturated soils. Consequently, frequent SDI can create a small saturated zone around the emitter that will deter root intrusion. Celery is an exception to this rule, and thus some growers prefer DI or have used chemicals to prevent root intrusion (Schwankl et al., 1993; Hanson et al., 1997). Coelho and Faria (2003) concluded that there was no preferential growth toward the emitter orifice within the wetted soil volume and that root intrusion was just the result of random exploration. However, the ingestion of soil was correlated with increased root intrusion which may lead to capillary formation directing the hair roots towards the emitter opening.

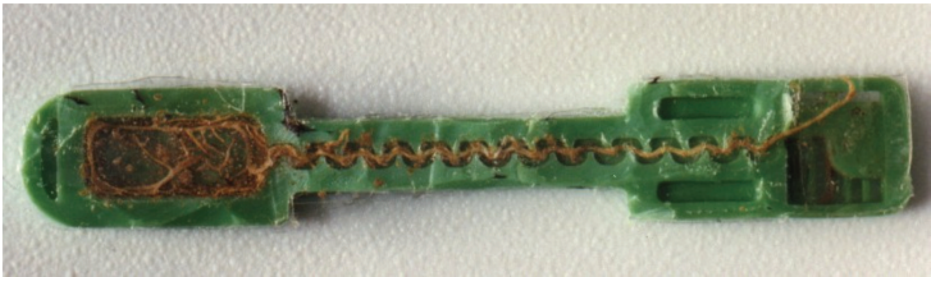

Figure 13.5. A sugarcane root entering the outlet chamber on the left can intricately grow through the labyrinth and the emitter inlet filter on the right and into the dripline. Photo courtesy of Z. Golan, Plastro Irrigation.

The extent of root intrusion varies with different dripline and emitter construction techniques (Bui, 1990). Manufacturers that still use seamed construction have tended to discontinue placing the emitter orifices in the dripline seam because this has been noted as a common root path, once it is located by random root exploration (Schwankl et al., 1993). Manufacturers are marketing a variety of emitter design techniques to avoid root intrusion, such as closing flaps, closing slits, raised protrusions that deflect roots, or oversized water outlets that protect the much smaller emitter orifices below.

Chemical protection of the emitter with herbicide (trifluralin) is another good method of preventing root intrusion. Ruskin and Ferguson (1998) discussed the three primary trifluralin herbicide methods in which the herbicide is injected directly into the irrigation water, incorporated into the emitter at manufacturing, or incorporated into the filter components. Trifluralin acts by stopping cell growth as the root tip encounters the herbicide, but does not kill the plant when properly used for root intrusion (Zoldoske, 1999). Careful and safe use of these herbicide methods according to label instructions is necessary to protect the environment from contamination while attempting to reduce the root-intrusion hazard. The use of acids, acid-based fertilizers, and chlorine may also help to prevent root intrusion or help to remediate partially clogged emitters by oxidizing the roots (Schwankl et al., 1993; Burt, 1995; Hanson et al., 1997; Ayars et al., 1999; Burt and Styles, 1999; Van der Gulik, 1999).

Tree and grape vine roots can grow around and pinch SDI driplines, which either greatly reduces or stops flow (Fig 13.6). This phenomenon has reduced the effectiveness of some SDI systems in California (Burt and Styles, 1999).

Figure 13.6. Subsurface dripline pinched by peach tree root in California, USA. Photo courtesy of T. Trout, USDA-ARS, Parlier, California.

13.1.3.5.3. System uniformity considerations related to mechanical or pest damage

Mechanical (system installation and crop tillage) and pest (burrowing mammals and insects) damage can cause leaks that reduce system uniformity when they are not located and repaired. Minor leaks on deeper SDI systems may not wet the soil surface, and may be discovered only by a chance observance of differential plant growth along the damaged dripline during the growing season. Large leaks are easier to locate than small ones, particularly when no crop is present. Many growers routinely start their SDI system before the cropping season to inspect for leaks and make repairs. Holes in the dripline can allow soil and debris to enter the dripline, decreasing the flow in the larger dripline chamber and possibly clogging other emitters downstream.

Mechanical leaks can be caused by faulty installation equipment or procedures that either immediately result in a leak (punctures and faulty connections) or cause nicks that weaken the dripline which later leak under system pressure. High-quality dripline injector shanks that do not have metal burrs, sharp edges, or corners should be used to avoid damaging the dripline. The shanks should be routinely inspected for wear and corrosion to avoid installation damage. Many commercial shanks are constructed of stainless steel and/or use high-density polyethylene (HDPE) or polyvinyl chloride (PVC) plastic for parts that come in contact with the dripline. Before installation, dripline rolls should always be inspected for mechanical damage that may have occurred during shipping and handling. Care should also be used with sharp knives or scissors when removing the paper and plastic wrapping that protects the dripline rolls. Connections between the dripline and the header or manifold have been the source of leaks in several SDI systems used for research (Kruse and Israeli, 1987; Copeland and Yitayew, 1990; Feistel, 1992; Schoneman et al., 1992; Lamm et al., 1997b). A discussion of many of the common installation problems with SDI systems was provided by Lamm et al. (1997b). Careful quality control and quality assurance during SDI system installation will help to ensure a reliable and uniform system that is easy to manage and maintain for the long term.

Tillage and other cultural practices can also damage driplines, resulting in leaks that reduce system uniformity. SDI systems should be installed at the specified dripline depth uniformly throughout the field so that tillage and cultural practices can be planned to accommodate this depth without causing damage. The location of the dripline within crop beds and with respect to tillage operations also is an important factor in avoiding damage. Ayars et al. (1995) reported an instance where several hundred meters of dripline had to be replaced because the bedding operation damaged dripline that had been improperly placed (inconsistent depth and location). For SDI driplines installed at an 8-cm depth, Chase (1985) reported damage by planting and weeding operations. Heavy alfalfa-harvesting equipment damaged SDI driplines at a 10-cm depth in Hawaii (Bui and Osgood, 1990), whereas driplines at 35 cm were not damaged. Cultural operations with tractors and harvesters during wet soil conditions may damage driplines in shallow SDI installations, especially if installed in the inter-row area where wheel traffic occurs.

Burrowing mammals, principally of the rodent family, can cause extensive leaks that reduce system uniformity. Most rodents avoid digging into wet soil, so dripline leaks presumably are not caused by the animals looking for water. Rather, rodents must gnaw on hard materials, such as plastic, to wear down their continuously growing teeth. The difficulty in determining the actual location of a dripline leak caused by rodents is compounded by the fact that the leaking water may follow the burrow path for a considerable distance before surfacing. Anecdotal reports from the U. S. Great Plains can be used to describe some of the typical habitat scenarios that tend to increase rodent problems. These scenarios include the close proximity of permanent pastures and alfalfa fields, railroad and highway easements, irrigation canals, sandy soils, crop and grain residues during an extended winter dormant period, or absence of tillage.

Cultural practices such as tillage and crop residue removal from around SDI control heads and above-ground system apparatus seem to decrease the occurrence of rodent problems. Some growers have tried deep subsoiling and/or applying poison bait around the SDI system field perimeters as a means of reducing rodent subsurface entry into the field. Isolated patches of residue within a barren surrounding landscape will provide an “oasis” effect conducive to rodent establishment. After the smaller rodents become established, other burrowing predators such as badgers can move into the field, further exacerbating the damage. Caustic, odoriferous, pungent, and unpalatable chemical materials have been applied through SDI systems in attempts to reduce rodent damage, but none of these trials has obtained adequate control. Periodic wetting of the soil during the dormant period has been suggested as a possible means of reducing rodent damage. Steele et al. (1996) reported extensive rodent damage at an SDI depth of 28 cm on a sandy loam soil in North Dakota. When rodents encountered a dripline, they tended to follow it for a distance, continually chewing holes in it. Replacement of dripline sections up to 3 m in length was required after one winter period. Deeper SDI depths (45 cm or greater) may avoid some rodent damage (Van der Gulik, 1999). Many of the burrowing mammals of concern in the United States have a typical depth range of activity that is less than 45 cm (Tab. 13.1). Ayars et al. (1999) reported greater rodent damage to thin-walled, collapsible driplines than to thicker-walled, hard-hose products. One thin-walled product was underirrigated during the study, and this might have led to greater rodent activity around the dripline.

Table 13.1. Burrowing depths and habitat preferences of some burrowing mammals in the United States. Adapted from Cline et. al. (1982).

Species	Maximum tunneling depths (cm)	Preferred habitat	Soil
Cynomys ludovicianus black-tailed prairie dog	91-427	upland prairies	fine textured
Spermophilus townsendi ground squirrel	50-80	grassland	--
Thomomys bottae pocket gopher	5-35	valleys to mountain meadows	loam to sandy
Thomomys talpoides pocket gopher	10-30	prairies to pine forests	fine texture
Geomys bursarius plains pocket gopher	23 mean	grasslands	coarse, sandy
Pappogeomys castanops yellow-faced pocket gopher	17 mean; 132 max	shortgrass prairies	deep, sandy
Perognathus longimembris pocket mouse	52-62	arid scrub	fine or sandy
Perognathus parvus Great Basin pocket mouse	35-193	sagebrush – chaparral	fine or sandy
Dipodomys spectabilis kangaroo rat	40-50	arid scrub	fine or sandy
Dipodomys microps banner-tailed kangaroo rat	24-45	arid scrub	fine or sandy
Dipodomys merriami Merriam's kangaroo rat	26-175+	arid scrub	deep or sandy
Taxidea taxus badger	150+	grasslands	--

Burrowing insects can cause dripline leaks that decrease system uniformity. Several incidents of wireworm damage to SDI systems have been reported in the United States. These reports indicated that the damage is most often associated with the initial SDI system installation period and with a delay in wetting the soil after installation. Some growers irrigate immediately after installation, and others have injected fumigants and insecticides to prevent wireworm damage (Burt and Styles 1999). The use of insecticides through SDI systems to control insects that cause leaks is a controversial environmental practice because of possible grower health hazard when repairing any remaining leaks. Growers should always read and carefully follow the pesticide label and precautions. Wireworm activity is usually greatest at the 20- to 35-cm depth (Bryson, 1929), so deeper SDI system installation may help to prevent wireworm damage. Fire ants were reported as a problem on shallow depth (8 to13 cm) SDI systems in Hawaii (Chase, 1985).

13.1.3.5.4. System uniformity considerations related to soil overburden and/or compaction

Driplines can be deformed by soil overburden and/or compaction that will decrease flowrates and reduce system uniformity. This is especially true for thin-walled driplines.

Compression of driplines from their normal circular shape into an elliptical shape increases the friction head loss and thus will reduce the flowrate from the design condition (Hills et al., 1989b). The flowrate reduction can become significant when the amount of compression is great (Fig. 13.7).

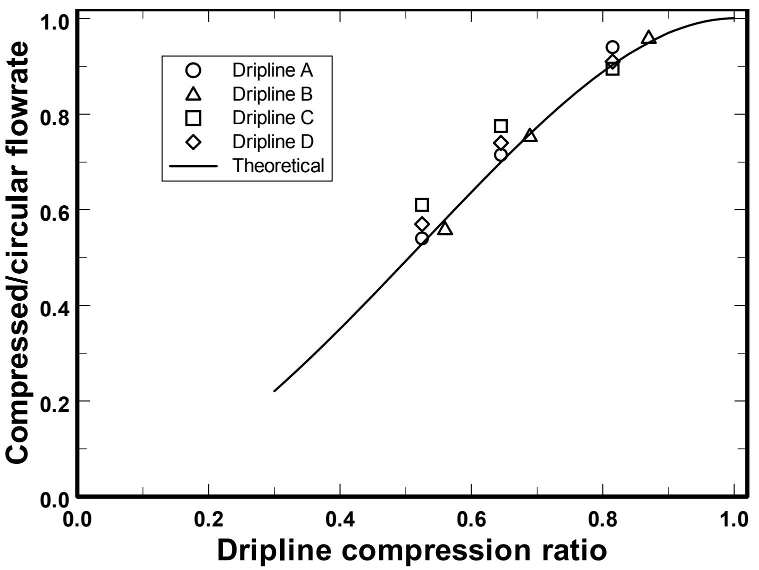

Figure 13.7. Decrease in flowrate resulting from deforming a circular cross-section into an elliptical cross-section. The dripline compression ratio is equal to the minor axis of the elliptical (compressed) dripline divided by the original circular dripline diameter. The solid line represents the theoretical relationship, and the data points are for the four driplines tested. After Hills et al. (1989b).

When soil compaction is likely to occur, dripline lengths may need to be reduced to maintain the initial system uniformity. SDI system operation for extended periods (Hills et al., 1989b) and initiation of the system after large precipitation wetting events can remediate some of the dripline compression problems by reducing soil compaction in the immediate vicinity of the dripline. Soil compaction can be avoided by limiting mechanized field operations when soil water conditions are most conducive to compaction (i.e., usually slightly drier than field capacity for many soils). In bridging soils, deeply placed driplines are usually less susceptible to compression by soil compaction. However, in nonbridging soils, soil overburden at deeper depths is a concern for SDI systems.

Excavation of a sandy loam soil from driplines at a 30-cm depth increased flowrate 2.8 to 4%, compared with the *in situ* flowrate (Sadler et al., 1995). They concluded that changes of this magnitude may not have a large effect on uniformity. However, these differences could have an effect on large SDI systems where the pumping plant and pipe design must take into account the actual flowrates. Decreasing flowrate with distance from the inlet, caused by increased friction losses due to dripline deformation, was reported by Steele et al. (1996) for an SDI system on a fine sandy loam soil in North Dakota. The causes for deformation of the driplines at a depth of 28 cm were soil overburden and compaction, frozen soil conditions during the winter and associated freeze/thaw action, and tillage operations. The problem of overburden in sandy soils may require the use of heavy-walled, compression-resistant driplines (hard hose) instead of the less expensive thin-walled, collapsible driplines used in many systems. Mechanical compaction with tractor traffic on volcanic soils in Hawaii not only increased soil bulk density by 33%, but also increased emitter clogging by 75% on an SDI system installed at 13 cm (Chase, 1985).

13.1.3.5.5. System uniformity considerations related to soil hydraulic parameters

SDI system uniformity can be reduced when the soil is unable to redistribute water away from the emitter fast enough to prevent backpressure on the emitter. Reductions in emitter flowrates of 9.5, 17.5, and 29.6% due to backpressure were calculated for design emitter flowrates of 1, 2, and 4 L/h, respectively, for the hydraulic properties of a sandy loam in Israel (Warrick and Shani, 1996). This resulted in corresponding Christiansen's uniformity *(UC)* values of 95, 91, and 85 for the SDI system. When the emitter flowrate increases or the soil hydraulic conductivity decreases, the pressure head increases around the emitter and reduces the emitter discharge, depending on the severity of the mismatch between the emitter and soil characteristics. Soil type, emitter flowrate, presence of cavities around the emitter, and SDI system hydraulic properties were listed by Shani et al. (1996) as the controlling factors for the existence of backpressure and the subsequent emitter flow reduction. In a preliminary study, they reported emitter flow reductions of as much as 50% were attributable to backpressure. Modeling procedures to account for the effect of backpressure on emitter flow have been developed by Lazarovitch et al. (2005). The interrelationship between this backpressure phenomenon and SDI surfacing (i.e., a mismatch of excessive emitter flowrate and insufficient soil water redistribution creates or uses an existing preferential flow path to the soil surface) will be discussed later in the chapter (Section 13.3.1.3). SDI surfacing can affect soil water distribution and cause cropping problems, but does not affect SDI system uniformity (hardware components) in the absence of soil water backpressure (i.e., column of soil water above the emitter).

13.1.3.5.6. System uniformity and longevity

The system uniformity considerations discussed in sections 13.1.3.5.1 through 13.1.3.5.5 can, individually or in combination, reduce system uniformity over time. Few comprehensive surveys have been conducted specifically on commercial SDI system performance. Some surveys of microirrigation systems may have included SDI systems or may indicate the most pertinent factors reducing system uniformity.

In a study that included 174 microirrigation systems in California, Pitts et al. (1996) reported an average lower-quartile distribution uniformity (DU_{lq}) of 70. The most common problems were emitter clogging, excessive pressure variation, and poor maintenance. Emitter clogging was related to insufficient filtration, inadequate chemical treatment of water, and infrequent flushing. Excessive pressure variation can be caused by improper operation or by removal of system components such as regulating valves. System uniformity did not seem to be related to the age or the size of the farming operation. In this large study of 385 systems, which also included sprinkler and furrow irrigation systems, 80% of the evaluations led to recommendations for improvements, and 90% of the farmers implemented at least one recommendation. The average improvement in DU_{lq} was 18% for a selected number of systems that were retested, indicating the importance of design, management, and maintenance on long-term system uniformity.

Distribution uniformity was greater for perennial crop microirrigation systems (average DU_{lq} of 73 for 458 systems) than in systems used for annual row crops (average DU_{lq} of 63 for 23 systems) in another survey conducted in California (Hanson et al., 1995). Pressure variation and emitter clogging were major contributing causes to nonuniformity for the annual row crop systems. Although it is generally assumed that microirrigation systems have greater uniformity, this study found similar DU_{lq} for sprinkler, surface, and microirrigation systems. DU_{lq} greater than 80 was measured on 38% of the microirrigation systems indicating high uniformity is possible with proper design, management, and maintenance. System uniformity was poorly correlated with microirrigation system age ranging from 0 to 30 years, with irrigated land area up to 230 ha, and with emitter discharge rates as great as 200 L/h.

A few evaluations of long-term performance of SDI systems used for research are available. In a California study, high Christiansen uniformity coefficients (*UC*) greater than 90 were reported for four dripline products two years after installation (Phene et al., 1992). The lower *UC* for a fifth dripline product was only 76, but this lower value was attributed to leaks caused by burrowing animals, which was related to a limited irrigation schedule for this product (Ayars et al., 1999). In another study, Ayars et al. (1999) reported *UC* values higher than 95 for SDI after 9 years of use, provided that clogging and root intrusion were kept under control with acid water treatment. System uniformity was determined for new, unused driplines, and for DI and SDI driplines used for 8 years in South Carolina (Camp et al., 1997a). System uniformity was greatly reduced for SDI (30-cm depth for a loamy sand), primarily because of the presence of a few completely clogged emitters in the three tubes that were examined (Table 13.2). Uniformity calculations that excluded clogged emitters resulted in similar high values ($DU_{lq} > 95$) for new, unused driplines and SDI driplines. Clogging was primarily attributed to entry of soil particles into the system during construction and/or repair operations. This emphasizes the importance of careful installation and maintenance of SDI systems.

Table 13.2. System uniformity parameters as affected by age and placement of driplines. Calculations werer based on measurements from 20 consecutive emitters. After Camp et al. (1997a).

Dripline sampling method	No. of emitters	Uniformity coefficient *(UC)*	Distribution uniformity *(DU_{lq})*
New, unused driplines			
Dripline #1	20	99.1	98.8
Dripline #2	20	98.8	98.2
Dripline #3	20	98.5	98.3
Mean	--	98.8	98.4
Combined driplines, #1-3	60	98.1	98.6
Surface driplines (DI) after 8 years			
Dripline #1	20	98.7	97.8
Dripline #2	20	98.0	97.1
Dripline #3	20	92.4	86.1
Mean	--	96.4	93.6
Combined with clogging	60	96.8	93.7
Combined without clogging	59	98.4	97.5
Subsurface driplines (SDI) after 8 years			
Dripline #1	20	88.6	78.8
Dripline #2	20	50.1	0.2
Dripline #3	20	82.3	65.8
Mean	--	73.7	48.2
Combined with clogging	60	74.2	51.3
Combined without clogging	51	97.5	95.4

13.2. SYSTEM DESIGN AND INSTALLATION

13.2.1. Materials and Components

13.2.1.1. Emitter and dripline characteristics

An excellent discussion of the various materials used in microirrigation components and their suitability is presented in section 15.2.1 of Chapter 15. In many respects, the emitters and driplines used for SDI are the same as those used for DI. The physical description and characteristics of these emitters and driplines are thoroughly discussed in sections 12.2.4, 12.3.3 and 12.3.4 of Chapter 12 and will not be repeated here. However, a brief discussion of the few differences in emitters and driplines when used in SDI is warranted.

SDI driplines must be free of significant protrusions, such as emitters, that might become damaged during system installation. Emitters for SDI are always inside the dripline, so there is no opportunity for growers to add additional emitters as the crop grows or to replace a defective emitter without splicing the dripline.

Entry of soil particles into driplines (soil ingestion) can be a problem (See also section 13.1.3.5.1) for SDI. Some manufacturers have changed dripline designs in attempts to reduce or eliminate this problem. Instances have been reported of soil trapped under the elastic membrane in pressure-compensating (PC) emitters that results in unregulated flow. PC emitters are sometimes not used for SDI for this reason. Manufacturers have also responded to SDI root intrusion problems by altering dripline and emitter physical characteristics or through addition of chemical inhibitors (See also section 13.1.3.5.2).

The wall thickness of SDI driplines is often greater than for DI because of the added risk of dripline damage during installation and because the SDI system is usually planned to have an extended, multiple-year life. In situations where soil compaction or soil overburden may cause dripline deformation, thick-walled tubing (hard hose) may be selected. Thicker-walled products allow higher maximum dripline pressures that can be used to open partly collapsed driplines caused by soil compaction or overburden, or to increase flow of chemically treated water through partly clogged emitters. In addition, there have been anecdotal reports of greater insect damage to driplines with thinner walls. The thin-walled, collapsible driplines (commonly referred to as drip tapes in the United States) also are used extensively in SDI. In most cases for SDI, wall thicknesses of 254 to 635 μm are selected instead of the thinner-walled models often chosen for single-year use in DI.

SDI use is increasing in lower-valued commodity crops, such as cotton and corn, and as a result, there is an increased need for lower-cost systems with reliable designs and installations. Manufacturers have responded to this need by providing larger-diameter driplines and driplines with lower nominal flowrates, so that longer lengths of run and larger zone sizes can be designed with high uniformity. These larger-diameter driplines, although costing more per unit length, can often result in a less expensive installation through reduction of trenching and system controls. Dripline diameters up to 35 mm are now available and are often used in the larger fields to decrease the number of required zones and obstructions posed by additional valve boxes. Each SDI system design is different, however, and the grower should not automatically choose the larger dripline diameter. Larger driplines require longer fill and drain times, which can adversely affect water and chemical application uniformity and redistribution within the soil. The nominal dripline flowrate can be reduced by reducing the emitter flowrate or by increasing the emitter spacing. Physical limitations exist on reducing emitter flowrates because smaller passageways are more easily clogged. There also are limitations on increasing the emitter spacing related to adequately supplying the crop its water needs. Driplines with lower emitter flowrates of 0.5 to 0.6 L/h and larger emitter spacing of 0.3 to 0.6 m are economically attractive (reduced design and installation costs) on deeper, medium-textured soils for crops with extensive root systems. Care must be used in matching emitter flowrates and emitter spacing to the soil hydraulic characteristics in order to avoid problems such as backpressure and water surfacing (See also sections 13.1.3.5.5 and 13.3.1.3.

13.2.1.2. Additional SDI system components

SDI systems require additional components that are either not required or not used to the same extent for other types of microirrigation systems. Flushlines are header or manifold pipelines installed at the distal end of the zone that allow for jointly flushing of a group of driplines (Fig.13.8). In addition to flushing, the flushline also serves to equalize pressure between driplines during normal operation and to reduce the potential for entry of soil-laden water by providing positive water pressure on both sides of a severed dripline. It should be noted that the flushline allows for the convenient flushing of a group of driplines but does not increase the effectiveness of flushing. Hydraulically, it is more effective to flush a single dripline, and, as a result, flushlines are not typically used on the high-valued perennial crops such as grapes and tree crops. Air/vacuum relief valves are required on all irrigation systems, but are needed to a greater extent on SDI systems to minimize backsiphoning of water into the emitters (See also section 13.1.3.5.1). Because direct visual indications of water application are not possible with SDI, pressure gauges and flowmeters are very important indicators of system performance (See also Sections 13.1.3.4 and 13.1.3.5).

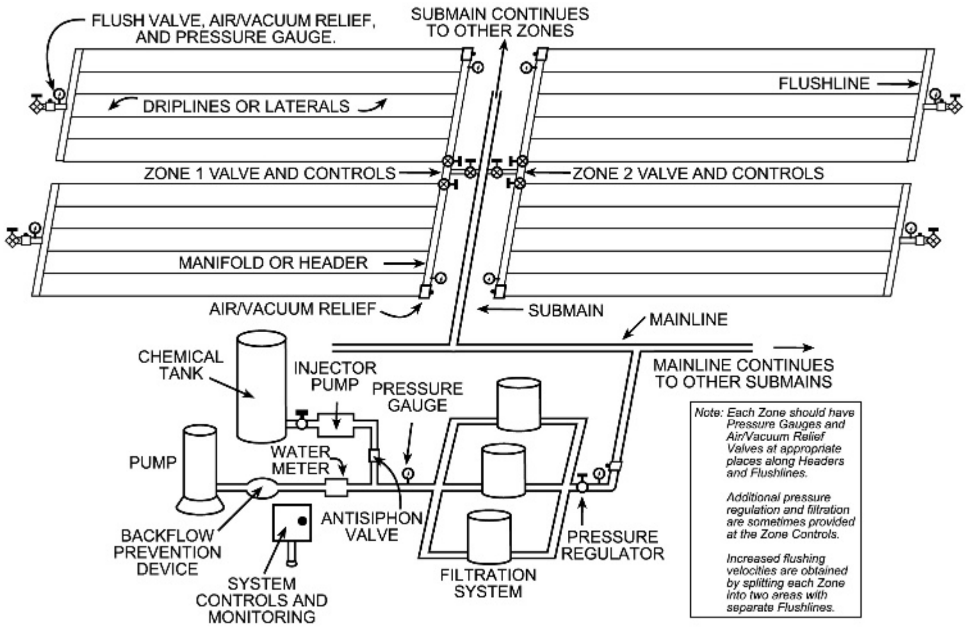

Figure 13.8. Schematic of a SDI system. Courtesy of F. R. Lamm, Kansas State University.

13.2.2. Dripline and Manifold Design Issues

13.2.2.1. Dripline, crop row, and emitter spacing

Crop row or bed spacing is usually set by cultural practices for a given crop in a given region and by planting and harvesting equipment specifications. As a general rule, SDI dripline spacing is a multiple of the crop row spacing, whereas emitter spacing is usually related to the plant spacing along the row. Providing the crop with equal or nearly equal opportunity to the applied water should be the goal of all SDI designs. This presents a conflicting set of constraints when crops with different row spacing are grown with SDI. Mismatched crop row/bed and dripline spacing may not only result in inadequate irrigation and salinity problems, but also in increased mechanical damage to the SDI system (Ayars et al., 1995) as discussed in Section 13.1.3.5.3. Adoption of similar row/bed spacing for crops on a farming enterprise may be advantageous, provided that the crops produce adequate yields under that spacing.

Dripline spacing is usually one dripline per row/bed or an alternate row/bed middle pattern (Fig. 13.9) with one dripline per bed or between two rows. SDI systems on some widely spaced tree crops may have multiple driplines between tree rows to wet a larger portion of the canopy floor. In a review of SDI, Camp (1998) reported dripline spacing from 0.25 to 5.0 m, with narrow spacing used primarily for turfgrass and wide spacing often used for vegetable, tree, or vine crops on beds. The soil and crop rooting characteristics affect the required lateral spacing, but there is general agreement that the alternate row/bed dripline spacing (about 1.5 m) is adequate for most of the deeper-rooted agronomic crops on medium- to heavy-textured soils. Wider dripline spacing may be suitable in soils with layering, allowing increased horizontal soil water redistribution above the soil layer, and in regions that are less dependent on irrigation for crop production. Average corn yields were 100, 93, and 94% of maximum for dripline spacing of 0.91, 1.83, and 2.74 m in the humid region of Virginia under adequate irrigation on an Uchee loamy sand (Powell and Wright, 1993). Spacing that is too wide can lead to excessive deep percolation below the crop root zone (Darusman et al., 1997), however, and large yield reduction or crop failure in rows that are furthest from the dripline (Lamm et al., 1997a). Some crops (sugarcane, pineapple, and cotton) are grown with alternating row spacing patterns, and, in this scenario, driplines laterals are located about 0.8 m from each row, usually in the narrow spacing of the pattern. Closer dripline spacing has been suggested for high-valued crops on sandy soils (Phene and Sanders, 1976) and/or in arid areas to ensure adequate salinity management and consistent crop yield and quality (Devitt and Miller, 1988). Soil water redistribution models can be used to determine the optimum dripline spacing, but are seldom used for this purpose because of the domination of grower preferences in crop row/bed configurations and the interrelationship with dripline spacing. Soil texture can affect soil wetting in ways that are difficult to predict. Thorburn et al. (2003) suggested that there is no basis for adopting different dripline and emitter dripper spacing in soils of different textures in the absence of site-specific information on soil wetting. A field test to aid in selecting emitter flowrate, emitter and dripline spacing, and dripline depth has been developed by Battam et al. (2003). The test requires observation of water movement from a subsurface emitter to an exposed face of a soil pit by field personnel.

Emitter spacings ranging from 10 to 76 cm are readily available (Chapter 12, Tab.12.3) from the manufacturers, and other spacings can be made to meet a specific application. Increasing the emitter spacing can be used as a technique to allow larger emitter passageways less subject to clogging, to allow for economical use of emitters that are more expensive to manufacture, or to allow longer length of run or increased zone size by decreasing the dripline nominal flowrate per unit length. The rationale for increased emitter spacing must be weighed against the need to maintain adequate water distribution within the root zone. An excellent conceptual discussion of the need to consider the extent of crop rooting in irrigation design is presented by Seginer (1979). Although the effective uniformity of microirrigation experienced by the crop is high, the actual detailed uniformity within the soil may be quite low. It should be noted that using the widest possible emitter spacing consistent with good water redistribution can cause significant problems when emitters become clogged. When that occurs, some plants will be inadequately watered. Selection of emitter spacing and the dripline nominal flowrate also need to take into account the soil hydraulic characteristics, as discussed in Sections 13.1.3.5.5 and 13.3.1.3.

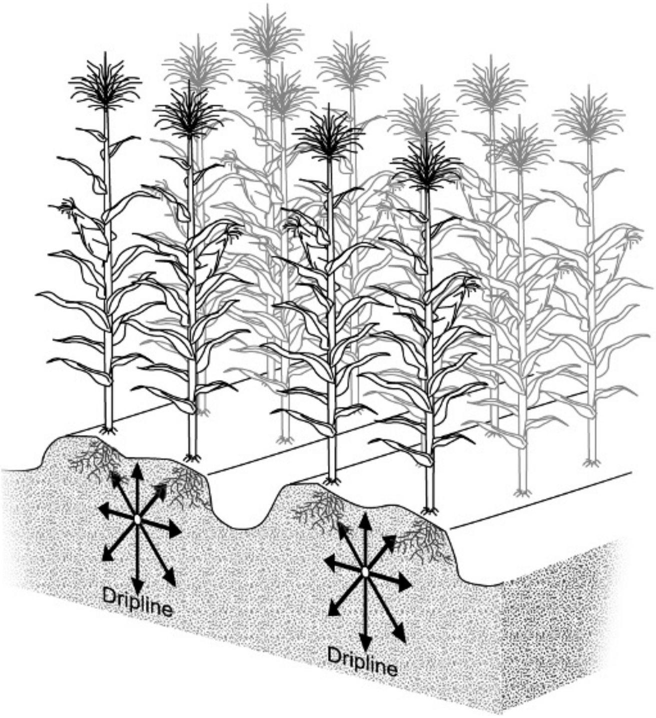

Figure 13.9. Alternate row/bed 1.5-m SDI dripline spacing for corn rows spaced at 0.75 m. Each plant row is approximately 0.38 m from the nearest dripline and has equal opportunity to the applied water. Courtesy of F. R. Lamm, Kansas State University.

13.2.2.2. Emitter flowrate

Wide ranges of emitter flowrates are available from the various dripline manufacturers. The evapotranspiration (ET_c) needs of the crop have little influence on the choice of emitter flowrate because most emitter flowrates at typical emitter and dripline spacings have application rates well in excess of peak reference ET_c (Tab. 13.3). Some designers prefer emitters with greater flowrates because they are less subject to clogging and allow more flexibility in scheduling irrigation. When emitters with greater flowrates are chosen, the length of run may need to be reduced to maintain good uniformity (See also Section 13.2.2.3.) and to allow for adequate flushing within the maximum allowable operating pressure (See also Section 13.2.2.4.2.). In addition, the zone size may need to be reduced to keep the total system flowrate within the constraints of the water supply system. Decreasing the length of run or the zone area increases the cost of both installation and operation. The choice of emitter flowrate must take into account the soil hydraulic properties (See also Sections 13.1.3.5.5 and 13.3.1.3) to avoid backpressure on the emitters and surfacing of water.

Table 13.3. Application rate, mm/h, for various combinations of emitter flowrates and emitter and dripline spacings.

Emitter spacing, cm	Dripline spacing, m	Emitter flowrate, L/h							
		0.20	0.50	0.60	0.80	1.00	2.00	3.79	7.57
10.2	0.50	3.92	9.80	11.76	15.69				
20.3		1.97	4.93	5.91	7.88	9.85			
30.5		1.31	3.28	3.93	5.25	6.56	13.11		
45.6		0.88	2.19	2.63	3.51	4.39	8.77	16.62	
61.0		0.66	1.64	1.97	2.62	3.28	6.56	12.43	
76.2		0.52	1.31	1.57	2.10	2.62	5.25	9.95	
10.2	0.75	2.61	6.54	7.84	10.46	13.07			
20.3		1.31	3.28	3.94	5.25	6.57	13.14		
30.5		0.87	2.19	2.62	3.50	4.37	8.74	16.57	
45.6		0.58	1.46	1.75	2.34	2.92	5.85	11.08	
61.0		0.44	1.09	1.31	1.75	2.19	4.37	8.28	16.55
76.2		0.35	0.87	1.05	1.40	1.75	3.50	6.63	13.25
10.2	1.00	1.96	4.90	5.88	7.84	9.80			
20.3		0.99	2.46	2.96	3.94	4.93	9.85	18.67	
30.5		0.66	1.64	1.97	2.62	3.28	6.56	12.43	
45.6		0.44	1.10	1.32	1.75	2.19	4.39	8.31	16.60
61.0		0.33	0.82	0.98	1.31	1.64	3.28	6.21	12.41
76.2		0.26	0.66	0.79	1.05	1.31	2.62	4.97	9.93
10.2	1.50	1.31	3.27	3.92	5.23	6.54	13.07		
20.3		0.66	1.64	1.97	2.63	3.28	6.57	12.45	
30.5		0.44	1.09	1.31	1.75	2.19	4.37	8.28	16.55
45.6		0.29	0.73	0.88	1.17	1.46	2.92	5.54	11.07
61.0		0.22	0.55	0.66	0.87	1.09	2.19	4.14	8.27
76.2		0.17	0.44	0.52	0.70	0.87	1.75	3.32	6.62
10.2	2.00	0.98	2.45	2.94	3.92	4.90	9.80	18.58	
20.3		0.49	1.23	1.48	1.97	2.46	4.93	9.33	18.65
30.5		0.33	0.82	0.98	1.31	1.64	3.28	6.21	12.41
45.6		0.22	0.55	0.66	0.88	1.10	2.19	4.16	8.30
61.0		0.16	0.41	0.49	0.66	0.82	1.64	3.11	6.20
76.2		0.13	0.33	0.39	0.52	0.66	1.31	2.49	4.97
10.2	3.00	0.65	1.63	1.96	2.61	3.27	6.54	12.39	
20.3		0.33	0.82	0.99	1.31	1.64	3.28	6.22	12.43
30.5		0.22	0.55	0.66	0.87	1.09	2.19	4.14	8.27
45.6		0.15	0.37	0.44	0.58	0.73	1.46	2.77	5.53
61.0		0.11	0.27	0.33	0.44	0.55	1.09	2.07	4.14
76.2		0.09	0.22	0.26	0.35	0.44	0.87	1.66	3.31

13.2.2.3. Dripline length

A guiding principle in microirrigation design is to obtain and maintain high water application uniformity along the length of the driplines. Dripline and emitter characteristics and hydraulic properties, the system operating pressure, and the land slope are the major governing factors controlling the hydraulic design. These factors determine the acceptable dripline lengths for the SDI system with respect to the field size and shape and grower preferences. Longer driplines may result in a less expensive system to install and operate, which is of great importance to those growers using SDI on lower-valued crops (See also Section 13.2.2.1 and 13.2.2.2). Longer dripline length is less important to growers of higher-valued crops, however, and may limit the grower when applying precise water and chemical applications to remediate site-specific crop and soil problems or to elicit a site-specific crop response.

Many different design criteria and procedures are used to calculate the maximum dripline length. Two uniformity criteria often used in microirrigation design are emitter flow variation, q_{var}, and design emission uniformity, *EU,* and are given by

$$q_{var} = \frac{q_{max} - q_{min}}{q_{max}} \tag{13.1}$$

and

$$EU = 100\left[1.0 - \frac{1.27\,CV}{\sqrt{n}}\right]\frac{q_{min}}{q_{avg}} \tag{13.2}$$

where q_{max}, q_{min}, and q_{avg}, are the maximum, minimum, and average emitter flowrates (L/h) respectively, along the dripline, *EU* is the design emission uniformity, n is the number of drip emitters per plant or 1, whichever is greater, and *CV* is the manufacturer's coefficient of variation.

Emitter flow variation of 10% or less is generally desirable, between 10% and 20% is acceptable, and greater than 20% is unacceptable (Bralts et al., 1987). Design emission uniformities of 80 to 90 are recommended for line-source emitters on uniform slopes and 70 to 85 on steep or undulating slopes (ASAE EP405.1, 2003). It should be noted that the use of these recommended q_{var} and *EU* criteria will give different results. Both criteria are reasonable for design purposes, however, and there are interrelationships for many of the design criteria used in microirrigation (See also Section 10.2.). Chapter 5 presents a dripline design procedure based on q_{var} (Section 5.3.3.1) and Chapter 12 discusses design from an *EU* perspective (Sections 12.2.4.4 and 12.3.4. Other hydraulic design procedures are available (Burt and Styles, 1999), and many of the dripline manufacturers provide their own software programs for system design. Some of these software programs will be used here to demonstrate important factors related to dripline design.

Emitter flow variation increases and design emission uniformity decreases as the emitter flowrate and dripline length increase (Fig. 13.10). In this example, for a small inside diameter *(ID)* dripline, only the 100-m long driplines have q_{var} values less than 10% for the range of emitter flowrates tested. The acceptable 20% q_{var} criterion would allow the 0.6 and 0.8 L/h emitters to be used for a 200-m dripline length. Figure 13.10 also shows that there is some discrepancy in the acceptable ranges between the q_{var} and *EU* design criteria, with a larger number of emitter flowrate and length combinations providing an acceptable *EU*. There has been discussion in recent years that the ASAE EP405.1 design emission uniformity criteria for line-source emitters may need to be increased to values similar to those for point-source emitters. Manufacturing processes for line-source emitters have improved over the years and lower *EU* values for these products may no longer be necessary. A portion of the rationale for allowing reduced *EU* for line-source products is related to the typical single-year use of these products for DI where the long-term effects (season to season) of reduced uniformity would not occur. Thus, greater *EU* values may have more importance for multiple-year SDI systems.

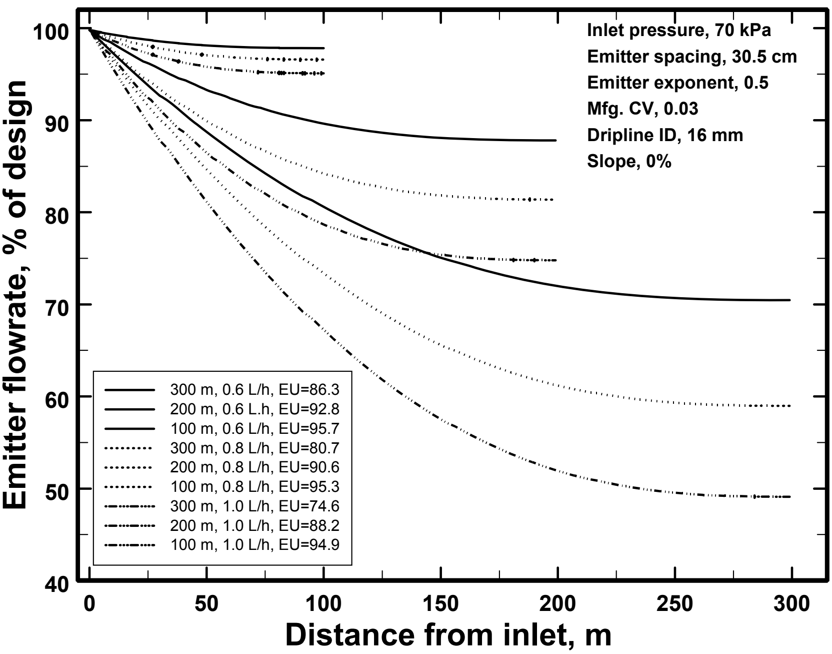

Figure 13.10. Calculated emitter flowrate and emission uniformity *(EU)* as affected by dripline length and nominal design emitter flowrate. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

Longer driplines with higher uniformity can be designed by increasing the dripline diameter while holding the emitter flowrate constant (Fig. 13.11). This design technique is popular for larger SDI systems used on the lower-valued commodity crops (fiber, grains and oilseeds) because it can help to reduce installation costs through fewer pipelines, controls, and trenches. This design technique is not without its concerns, however, because larger dripline diameters increase the propagation time of applied chemicals (Fig. 13.12), and flushing flowrates can become quite large (See also Section 13.2.2.4.2). Chemigation travel times for the larger-diameter driplines can exceed the period of the planned irrigation event on coarse-textured soils and thus lead to leaching and/or improper chemical application.

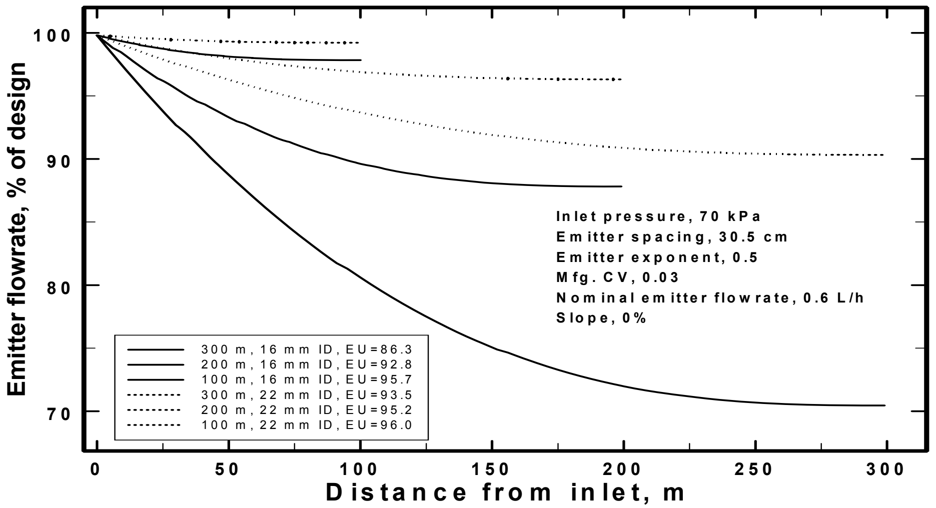

Figure 13.11. Calculated emitter flowrate and emission uniformity *(EU)* as affected by dripline length and inside diameter. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

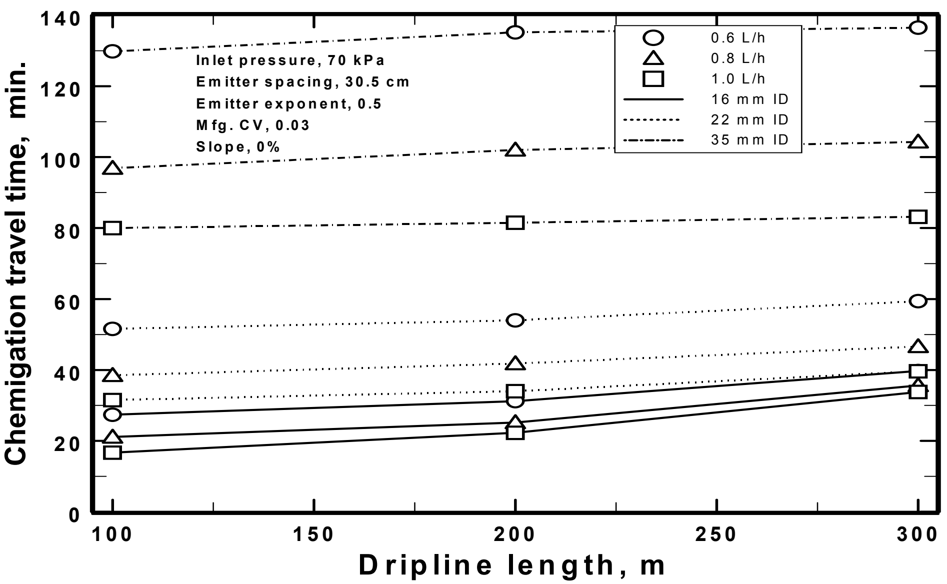

Figure 13.12. Approximate chemigation travel times as affected by dripline length and diameter, and emitter flowrate. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

System uniformity can also be increased by increasing the emitter spacing while holding the emitter flowrate constant (Fig. 13.13). This is also a popular design technique for larger SDI systems used on lower-valued crops, but is limited because the emitter spacing must be consistent with uniform water uptake by the crop. Emitter spacing would become too great as random emitters begin to clog.

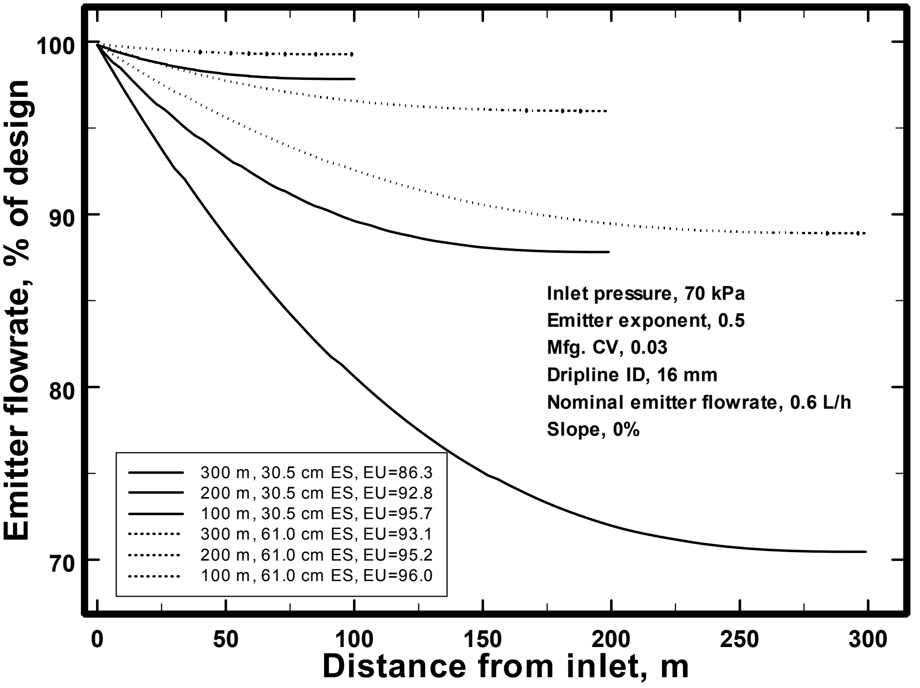

Figure 13.13. Calculated emitter flowrate and emission uniformity *(EU)* as affected by dripline length and emitter spacing *(ES)*. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

The land slope can have either a positive or negative effect on the emitter flowrate along the dripline lateral (Fig. 13.14). Driplines running uphill will always result in increasing pressure losses along the dripline and thus lower system uniformity. When the downhill slope is too great, the flowrate at the end of the dripline becomes unacceptably high. In the example shown (Fig. 13.14), the optimum slope is 2% downslope, but this will vary with dripline and emitter characteristics. Designers may even use these hydraulic factors to their advantage to balance elevation head gains with increased friction losses from smaller diameter driplines. When slopes are too great, designers may recommend that the driplines be installed across the slope or along the contour. Pressure-compensating emitters are also widely used on steep land slopes, but may not be cost competitive for lower-valued commodity crops.

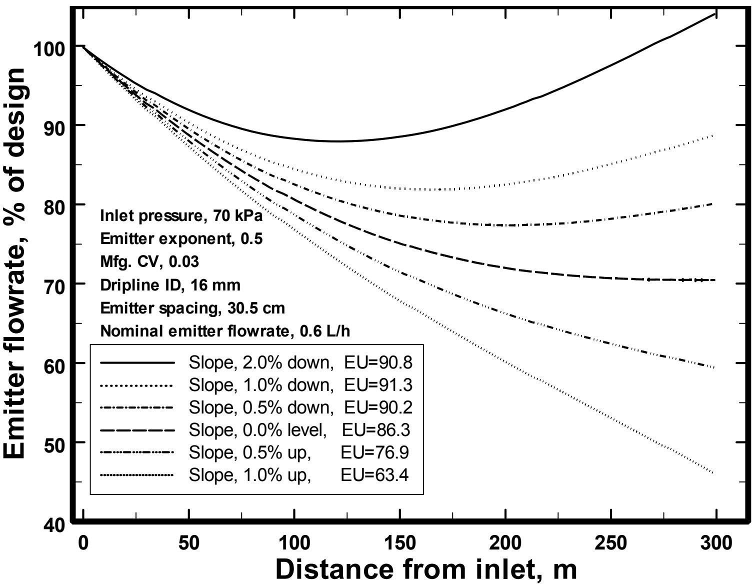

Figure 13.14. Calculated emitter flowrate and emission uniformity *(EU)* of a 300-m dripline as affected by topography. Results for hypothetical dripline calculated with software from Roberts Irrigation Products (2003).

13.2.2.4. Flushing requirements and flushline design.

13.2.2.4.1. Flushing velocity

A minimum flushing velocity of 0.3 m/s is recommended for microirrigation systems by the American Society of Agricultural Engineers (ASAE EP405.1, 2003). However, there is disagreement on the recommended flushing velocity for SDI systems, with values ranging from 0.3 to 0.6 m/s (Burt and Styles, 1999). There is some practical rationale for a higher flushing velocity for SDI that perhaps could consequently have better overall flushing of materials. Many of these systems are used for multiple years, and system longevity is very important in determining SDI economic feasibility, especially for lower-valued crops. However, scientific documentation indicating the rationale for a flushing velocity greater than the ASAE value is difficult to find. Settling velocities of quartz grains (Specific gravity, 2.65) of greater than 0.2 mm diameter cannot be accurately approximated using Stokes Law, and settle with velocities that change with the square root rather than the square of the particle diameters (Rubey, 1933). Experimental results and an equation presented by Rubey indicate that quartz grains as large as 8 mm in diameter can be transported by a water velocity of 0.3 m/s. The ASAE criterion seems appropriate for SDI in the absence of a stronger scientific reason for the higher velocities. The required flushing velocity and flushline hydraulics greatly affect the SDI system design. Higher velocities require shorter lengths of run to keep the flushing pressures below the maximum allowable dripline operating pressure and also require large supply lines and flushlines. The general guideline is that the required flushing velocity be maintained in all segments of the SDI system, but there are locations where this guideline cannot be followed. The water velocity in the flushline at the furthest point from the flush valve is very low because only a single dripline is contributing flow at this point. Decreasing the flushline diameter at this point in the system could help maintain a higher velocity, but would also increase the downstream pressure on the dripline. It is more important to maintain adequate flushing velocity in the driplines because the emitters are subject to clogging.

13.2.2.4.2. Dripline inlet pressure and flowrate during flushing

Some pressure usually exists on the end of driplines during flushing for those SDI systems that use a flushline common to a group of driplines. This downstream pressure represents the sum of elevation changes between the dripline and the point where the water exits the flush valve, friction losses in the flushline, friction losses in the flush valve, and the friction losses associated with the dripline/flushline connection. It is difficult to design for a dripline downstream pressure during flushing of less than 5 kPa, and values of 20 kPa are reasonable under some circumstances. Downstream pressures that are greater than 20 kPa during flushing will often require driplines with higher maximum allowable operating pressure or that the designer must reduce dripline length and/or emitter flowrates. The inlet pressure during flushing often has more restriction on design dripline length and emitter flowrate than system uniformity (Fig. 13.15). Adjustable pressure regulators or other design characteristics may be required to accommodate the higher inlet pressure requirements during flushing.

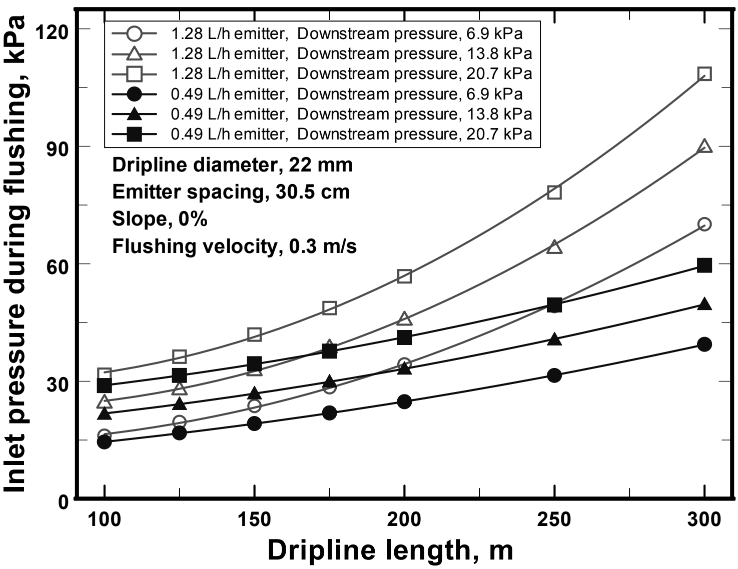

Figure 13.15. Required inlet pressure to maintain a 0.3 m/s dripline flushing velocity, as affected by the nominal emitter flowrate, dripline length, and downstream pressure. Results for hypothetical dripline calculated with software from Toro Ag Irrigation (2002).

The required flowrate during flushing can be considerably higher than the nominal dripline flowrate (Fig. 13.16). This may require larger pipe size (mains, submains and headers), adjustments to the pumping plant to provide the larger flow, and/or splitting the normal irrigation zone into more than one flushing zone (Fig. 13.8).

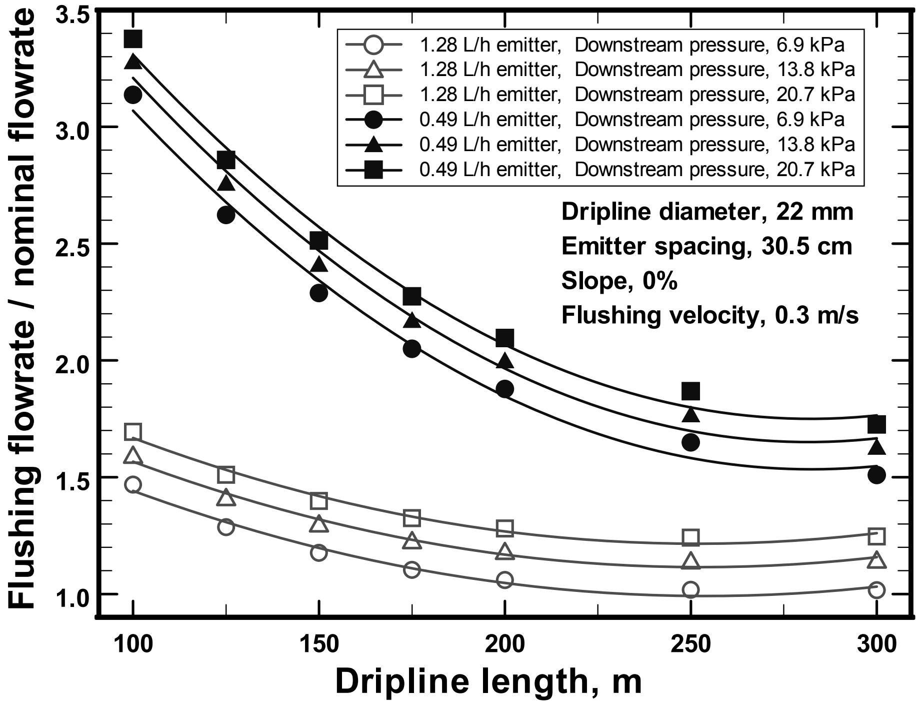

Figure 13.16. Ratio of required flushing flowrate to nominal design flowrate to maintain a 0.3 m/s dripline flushing velocity as affected by nominal emitter flowrate, dripline length, and downstream pressure. Results for hypothetical dripline calculated using software from Toro Ag Irrigation (2002).

13.2.2.4.3. Sizing the flushline and flush valve

It is desirable that the flushline be on a level grade to ensure that the flushline does not significantly influence the flow characteristics of the SDI system during the normal irrigation process. Similarly, unequal dripline lengths, as is the case in irregular-shaped fields when connected to a common flushline, will result in some spatial variation on operating pressures within the SDI system.

Friction losses through the various connections and the supply tube between the dripline and the flushline must account for the flushing velocity (Fig. 13.17). These losses can be calculated using the Darcy-Weisbach equation (See Sections 5.3.1.3.1 and 5.3.1.3.3 of Chapter 5) or estimated to be approximately 1 to 2 kPa.

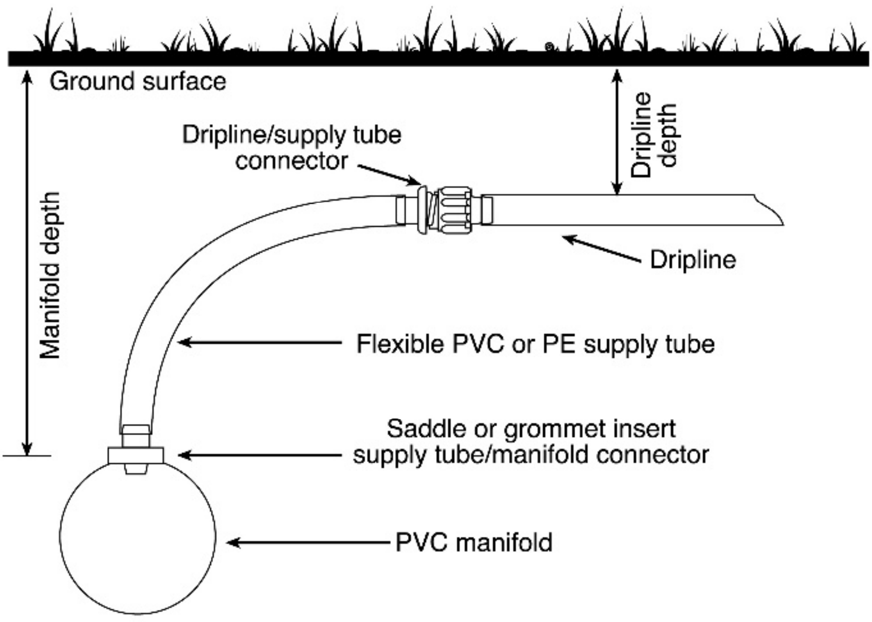

Figure 13.17. Typical arrangement of manifold, supply tube, connectors, and driplines for an SDI system. This arrangement is suitable for both the inlet supply line and the flushline. Courtesy of F. R. Lamm, Kansas State University.

Placing the flush valve assembly at the center of the flushline (Fig. 13.18) helps reduce friction losses and thus reduce the overall flushline diameter. However, there are situations in which the SDI zone is split and two flushlines are used. In those cases, producers often choose to bring both risers (flush valve assemblies) up at the same location, or alternatively, at the field edge, which helps to reduce the number of field obstructions (Fig. 13.19).

The dripline connection, flushline, and flush valve should be sized so that the total downstream dripline pressure during flushing is as low as economically and operationally practical, typically less than 10 to 15 kPa. The size or cross-sectional area of the flushline can be related to the cumulative cross-sectional area of all the driplines that contribute flow to that portion of the flushline. A flushline cross-sectional area of 25% or more of the cumulative cross sectional area of the driplines is typically acceptable for a 0.3 m/s dripline flushing velocity. This sizing procedure will maintain friction losses within the flushline at approximately 5 kPa or less. The sizing guideline is adequate for dripline diameters of 16 to 35 mm and typical dripline spacings. In some cases, particularly for very small or very large diameter driplines, a more formal flushline sizing procedure (friction loss calculation) may be required. The guideline can still be used to determine an initial trial diameter, with the more formal friction loss calculation procedure then being used on the next smaller and larger pipe diameters. Assuming a 0.3 m/s dripline flushing velocity, a simple equation for determining the guideline flushline diameter, D_f, is

$$D_f = 0.5 D_d \sqrt{N_d} \quad \{Note: Round\ D_f\ upward\ to\ the\ next\ available\ pipe\ size\} \tag{13.3}$$

where D_d , is the dripline diameter, and D_f are both in mm, and N_d is the number of driplines flowing in that branch of the flushline towards the flush valve. For branched flushlines (Fig. 13.18), N_d represents only the driplines on the left or right flushline section. Whenever practical, N_d should be the same for both sections of the flushline, which helps to ensure even flushing.

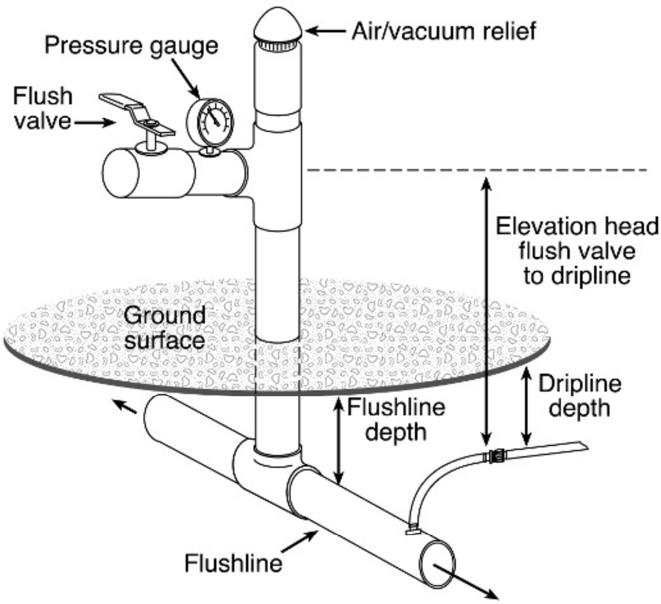

Figure 13.18. Typical flush valve assembly for a branched flushline. Flushline size is determined from cumulative dripline flow contributing to that branch of the flushline. Courtesy of F. R. Lamm, Kansas State University.

The friction loss for a level-grade flushline, h_f, in m can be calculated with the Hazen-Williams equation and by using the multiple outlet factor as

$$h_f = (F)(L_f)\left(1.212 \cdot 10^{10}\right)\left(\frac{Q_f}{C}\right)^{1.852}(D_f^{-4.87}) \tag{13.4}$$

where F is the multiple outlet factor, L_f is the length of the flushline section in m, Q_f is the cumulative flowrate in L/s for all the driplines flowing into that section of the flushline at a specified flushing velocity, C is the friction coefficient (150 for smooth plastic pipe), and D_f is the diameter of the flushline in mm. The multiple outlet factor can be assumed to be 0.36 for most large flushlines or can be determined from Tab. 5.4 in Chapter 5. Equation 13.4 can also be rearranged to solve for D_f when using the criterion of a maximum allowable h_f. The slope of the flushline must be accounted for in the overall calculation of the total downstream dripline pressure.

Designers may desire to reduce pipeline costs by stepwise increases in flushline diameter from the most distant dripline to the flush valve assembly. This may be accomplished while still maintaining a relatively small flushline friction loss (e.g., <5 kPa) by limiting the stepwise increases to three equal-length sections and limiting the smallest pipe size to approximately two-thirds of the largest flushline diameter as calculated by Eqs. 13.3 or 13.4. More formalized design procedures may allow for other acceptable flushline arrangements

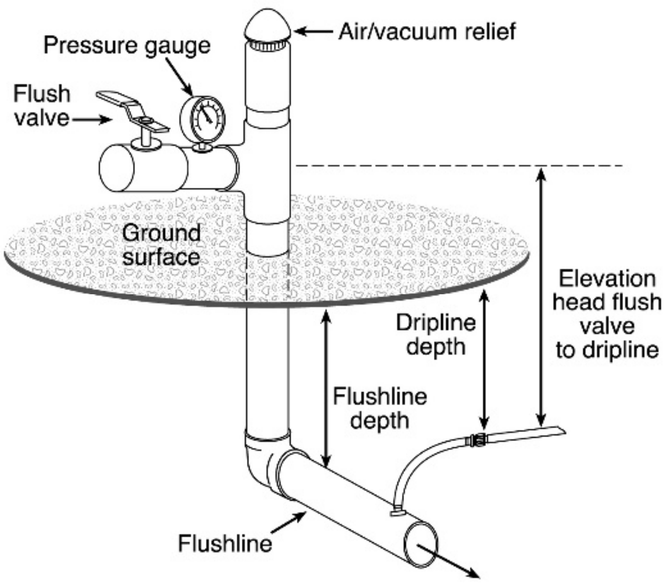

Figure 13.19. Typical flush valve assembly at one end of the flushline that is often used when SDI zones are split or when producers want the riser to be located at the edge of the field. Flushline sizing is determined from the total flows from all driplines connected to the flushline. Courtesy of F. R. Lamm, Kansas State University.

The friction loss for the flush valve assembly can be calculated using the Darcy-Weisbach equation by determining the various fitting friction losses and the friction loss for short sections of pipe (See Sections 5.3.1.3.1 and 5.3.1.3.3 of Chapter 5). However, for the typical assemblies shown in Figs.13.18 and 13.19, the flush valve size, D_v, in mm can be calculated as

$$D_v = K_v\,(Q_v^{0.5} / P_v^{0.25})\ \ \{Note: Select\ nominal\ valve\ size\ closest\ to\ D_v\} \qquad (13.5)$$

where the valve coefficient, K_v, is 35.7 for the branched (Fig. 13.18) and 33.4 for the unbranched flush valve assemblies (Fig 13.19), Q_v is the total flowrate in L/s through the flush valve at a dripline flushing velocity of 0.3 m/s, and P_v is the allowable pressure loss through the flush valve assembly in kPa during flushing. Limiting the allowable pressure loss through the assembly to 3 kPa or less is desirable to help minimize the overall downstream dripline pressure. A graphical solution to Eq. 13.5 for a maximum allowable pressure loss of 3 kPa is given in Fig. 13.20. After the flush valve is sized using Eq. 13.5 or Fig. 13.20, the actual pressure loss through the flush valve assembly can be calculated by rearranging Eq. 13.5 to solve for P_v.

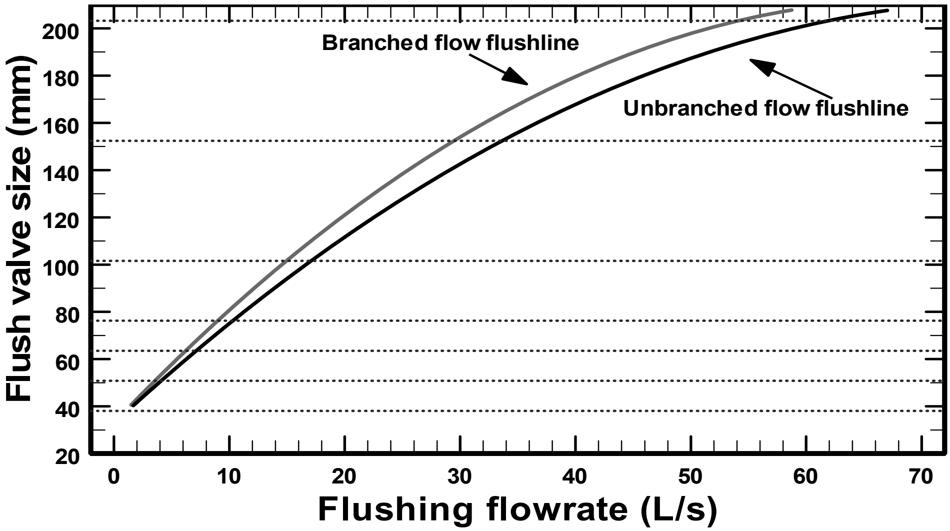

Figure 13.20. Appropriate flush valve size, as related to the total flush valve flowrate for a 0.3 m/s dripline flushing velocity and an allowable flush valve assembly pressure loss of 3 kPa. Dotted horizontal grid lines represent nominal valve sizes. Branched and unbranched flow flushlines are illustrated in Figs. 13.18 and 13.19.

Example 13.1

Determine the most appropriate diameter (D_f) for a level-grade, branched flushline and flush valve diameter (D_v) that serve one-half of an SDI zone that is 450 m wide with dripline spacing (S_d) of 1.5 m and a dripline inside diameter (D_d) of 25 mm. In addition, determine the downstream pressure on the dripline, which is installed 1 m below the flush valve outlet. The desired dripline flushing velocity, V_f, is 0.3 m/s, and the flush valve is located at the center of the branched flushline. The friction loss in the dripline/flushline connection is estimated to be 1.5 kPa during flushing. The allowable pressure loss through the flush valve, P_v, is 3 kPa for design purposes.

The zone has two flushlines of equal length (one-half of the zone width) with the flush valve assembly at the center of the branched flushline (Fig 13.18). Flushline friction loss is calculated for one-half the flushline length because of branching.

$L_f = (1/2)(\text{Zone width} / 2 \text{ flushlines/zone})$

$L_f = 0.5(450\ m/2) = 112.5\ m$

The number of driplines, N_d, flowing into each equal-length branch of the flushline is

$$N_d = L_f / S_d = 112.5\ m/1.5m = 75$$

The flushline diameter, D_f, using the guideline calculation (Eq. 13.3) is

$$D_f = 0.5 D_d \sqrt{N_d} = (0.5 \bullet 25mm)\sqrt{75} = 108\ mm$$

The next larger available pipe size has an inside diameter of 130 mm (SDR 26 Class 160 PVC).

The flushline has more than 35 outlets (driplines) flowing into each branch of the flushline so that a multiple outlet factor, F, of 0.36 is appropriate for the friction loss calculation (See Tab. 5.4 in Chapter 5).

The flushing flowrate, Q_f, into each equal-length branch of the flushline for a dripline flushing velocity, V_f, of 0.3 m/s is

$$Q_f = V_f N_d \left[\frac{\pi D_d^{\,2}}{4}\right] = 0.3\ m/s \cdot 75\left[\frac{\pi(0.025\ m)^2}{4}\right] = 0.01104\ m^3/s = 11 L/s$$

Using the guideline flushline diameter of 130 mm, the friction loss (Eq. 13.4) is calculated as

$$h_f = (F)(L_f)\left(1.212 \cdot 10^{10}\right)\left(\frac{Q_f}{C}\right)^{1.852}(D_f^{-4.87})$$

$$= 0.36 \cdot 112.5\ m \cdot \left(1.212 \cdot 10^{10}\right)\left(\frac{11 L/s}{150}\right)^{1.852}(130\ mm^{-4.87}) = 0.197\ m \approx 1.9\ kPa$$

The same friction loss calculations on the next smaller (106 mm ID) and larger pipe sizes (155 mm ID) result in friction losses of 5.2 kPa and 0.8 kPa, respectively. The original guideline flushline diameter of 130 mm is preferable because there is a larger reduction in friction loss than that with the next smaller pipe size, and an acceptable friction loss increase when compared to the next larger pipe size.

The total flow through the flush valve is two times the flowrate through each branch

$$Q_v = 2Q_f = 2(11 L/s) = 22\ L/s$$

The flushline is branched, so K_v is 35.7 and the valve size is calculated (Eq. 13.5) as

$D_v = K_v\,(Q_v^{0.5}/P_v^{0.25}) = 35.7(22\ L/s^{0.5}/3\ kPa^{0.25}) = 127\ mm$

The closest nominal valve sizes are equidistant at 102 and 152 mm, so either could possibly be selected. A greater pressure loss would occur through the smaller valve. As a check on the calculation, determination of valve size from Fig 13.20 indicates D_v is between 125 and 130, which is consistent with the calculated value.

The actual pressure losses through the two valve size options are

$$P_v = [K_v\,(Q_v^{0.5}/D_v)]^4 = [35.7(22\ L/s^{0.5}/102\ mm)]^4 = 7.3\ kPa \text{ for } 102\ mm \text{ valve}$$
$$= [35.7(22\ L/s^{0.5}/152\ mm)]^4 = 1.5\ kPa \text{ for } 152\ mm \text{ valve}$$

The larger 152 mm diameter flush valve is selected so that a lower downstream dripline pressure can be maintained.

The total downstream dripline pressure, P_d, is estimated as the sum of the following pressure/head loss components:

Dripline/flushline connection friction losses = 0.3 kPa
Elevation head along flushline = 0 kPa for zero slope
Flushline friction loss = 1.9 kPa
Flush valve assembly friction loss = 1.5 kPa
Elevation head from flushline to flush valve outlet = 1 m = 9.8 kPa

$P_d = (0.3+0+1.9+1.5+9.8) = 13.5\ kPa$

13.2.2.5. Dripline depth

The choice of the appropriate dripline depth is affected by crop, soil, and climate characteristics, anticipated cultural practices, grower experiences and preferences, the water source, and prevalence of pests.

Camp (1998) reported in an extensive review of SDI that the placement depth of driplines ranged from 0.02 to 0.7 m. The depth was determined primarily by crop and soil characteristics. In most cases, dripline depth was probably optimized for the local site by using knowledge and experiences about the crop for the soils of the region. Crop yield was similar in experiments in which several dripline depths were evaluated. Dripline depths usually ranged from 0.20 to 0.70 m for systems planned for multiple-year use and where tillage was practiced. When tillage was not a consideration (e.g., turfgrass, alfalfa), driplines were often placed closer to the surface (0.10 to 0.40 m). However, considerable variation in depth exists regionally. For example, driplines for alfalfa are sometimes installed at deeper depths so that irrigation can continue during harvest. When irrigation is required for seed germination and seedling establishment, sprinkler or surface irrigation is often used in research studies, but the need for two systems would increase expense and decrease net income. In some regions, sprinkler systems can be rented on a temporary basis for germination. Deeply placed driplines may require an excessive amount of irrigation for germination and can result in excessive leaching and off-site environmental effects. Sprinkler irrigation may also be required in some areas to control salinity when precipitation is inadequate to meet leaching requirements.

Dripline depth is often in the 0.05- to 0.2-m range for shallow-rooted horticultural crops for which yield and quality can be affected by deeper dripline depths. Often, these systems use annual retrieval and/or replacement of the driplines and are similar in many respects to DI systems (See also Section 12.3.7). These systems are sometimes classified as DI, and the term SDI is only applied to systems that remain in place for multiple years. Seed germination of tomato was better at dripline depths of 15 and 23 cm than at 30 cm (Schwankl et al., 1990) on a Yolo clay loam soil in California. Higher zucchini squash yields (34%) were obtained with SDI at 15 cm than at 5-cm depth on a calcareous, coarse loamy soil in Arizona (Rubeiz et al., 1989). Water and phosphorus (P) fertilization savings of 50% were obtained with the 15-cm SDI depth than with furrow irrigation. The results were attributed to better water and nutrient (N and P) utilization during hot weather from deeper SDI, whereas greater evaporation losses occurred for the near-surface dripline placement. Shallow subsurface placement may be used for securing the dripline in place during the season, protection from insects and wildlife, and reducing the water temperature and its effects on chemical and biological clogging. Subsurface dripline placement may also be used in horticultural crops for fumigation and insectigation (Felsot et al., 2000; Trout and Ajwa, 2003). Melon growers often use a dripline depth sufficient to prevent wetting of the soil surface, and thus avoid diseases and fruit rotting. Other crops, such as onion or potato, may require shallow placement because they need soil water in close proximity to the bulb or tuber.

SDI systems for lower-valued commodity crops (fiber, grains, and oilseeds) and perennial crops (trees and grapes) are usually set up exclusively for multiple-year use with driplines installed in the 30- to 50-cm depth range. Most of these crops have extensive root systems that function properly at these greater depths. Safflower seed and oil yields were greater for SDI at 25- and 35-cm depths than at shallower 15-cm or deeper 45-cm depths on a loamy sand in Saudi Arabia (Al-Nabulsi et al., 2000). The lowest water use and highest water use efficiency were obtained at the 25-cm depth. Emitter depth did not affect depth or distribution of safflower roots. Cotton lint yields were 1292, 1380, and 1465 kg/ha for dripline depths of 20, 31, and 41 cm, respectively, on a Varina loamy sand with a clay hardpan at the 25- to 32- cm depth in South Carolina (Khalilian et al., 2000). However, more weeds were noted for the 20-cm dripline depth. Furthermore, in that humid climate, there were no yield differences between every-row and alternate-row dripline placements. Dry matter production of faba beans was higher for driplines at 30- and 45-cm depths than at the 60-cm depth on a Panoche clay loam soil (Bryla et al., 2003). The 60-cm dripline depth was deeper than the faba bean root system for the first few months of the growing season, but there were no consistent differences in water use efficiency related to dripline depth. Corn yields were unaffected by dripline depths ranging from 20 to 50 cm, and there was only a slight yield reduction at the 61-cm depth on a deep Keith silt loam soil in Kansas (Lamm and Trooien, 2005). In a study on a sandy loam soil comparing DI to SDI at depths of 30 and 60 cm, Oron et al. (1999a) concluded that the 30-cm dripline depth was optimal at providing favorable water and salinity distributions for the pear tree root zone of 20 to 70 cm. A soil-column study with a loessial brown loam soil indicated that cotton roots can develop under partial wetting of the upper soil profile to soil water potentials of 0.1 MPa (Plaut et al., 1996). They suggested that a reasonable dripline depth for cotton would be 40 to 50 cm. However, in a study on a fine sandy loam soil in a semiarid region, cotton root development and distribution was not affected by dripline depths of 0, 15, 30, and 45 cm (Kamara et al., 1991). Their results suggest that, in regions that typically receive precipitation during the growing season, dripline depth will not be the overriding factor in root development and distribution.

Soil hydraulic properties and the emitter flowrate affect the amount of upward and downward water movement in the soil and thus are factors in the choice of dripline depth. When surface wetting by the SDI system is not needed for germination or for salinity management, deeper systems can reduce soil water evaporation and weed growth. Decreases in annual evaporation losses of 51 and 81 cm were predicted for 15- and 30-cm dripline depths, respectively, compared with DI in a field and modeling study for corn on a Pullman clay loam soil in Texas (Evett et al., 1995). Annual irrigation water savings of 18 to 58 mm were estimated for a mature olive orchard in the semiarid Mediterranean climate of Spain by switching from DI to SDI (Bonachela et al., 2001). Models to calculate the minimum dripline depth with respect to minimizing soil water evaporation losses are available (Lomen and Warrick, 1978; Philip, 1991a). By using the developments of Lomen and Warrick (1978), the minimum dripline depth, z_d, in cm for a maximum potential evaporative loss fraction, L_e, is calculated as

$$z_d = \frac{-\ln\left[L_e /[m/(2+m)]\right]}{\alpha} \tag{13.6}$$

where α is the inverse of the capillary length (Gardner fitting parameter, see also Tab. 2.4) in cm^{-1} and m is defined as

$$m = 2E_s / K_s \tag{13.7}$$

where E_s is the maximum anticipated evaporation rate under saturated soil conditions in mm/d, and K_s is the saturated hydraulic conductivity, also in mm/d. Equation 13.6 was developed for conditions representing the upper bound on irrigation water losses through evaporation. The minimum dripline depth for three soil types calculated using Eq. 13.6 is given in Tab. 13.4.

Deeper dripline placement will minimize soil water evaporation losses, but this must be balanced with the potential for increased percolation losses, while considering the crop root-zone depth and rooting intensity (Gilley and Allred, 1974; Thomas et al., 1974; Philip, 1991b).

Surfacing is an SDI phenomenon in which excessive emitter flowrate, coupled with insufficient soil water redistribution, creates or uses an existing preferential flow path to allow free water to reach the soil surface. Surfacing can sometimes be avoided with deeply-placed driplines (See also Section 13.3.1.3), but this is only an acceptable solution when the mismatch of emitter flowrate and soil properties is small and the added soil depth provides a larger soil volume for water redistribution.

Soil layering or changes in texture and density within the soil profile affect the choice of dripline depth. Driplines should be installed within a coarse-textured surface soil overlaying fine-textured subsoil so that there is greater lateral movement perpendicular to the driplines. Conversely, when a fine-textured soil overlays a coarse-textured subsoil, the dripline should be installed within the fine-textured soil to prevent excessive deep percolation losses. An excellent discussion of how soil texture and density affect soil water redistribution is provided by Gardner (1979).

The dripline should be deep enough that the anticipated cultural practices can be accommodated without untimely delays, soil compaction, or damaging the SDI system (See also Sections 13.1.3.5.3 and 13.1.3.5.4). The grower's depth preference must be considered with respect to rooting characteristics of the crop and the soil's water redistribution properties. Some growers prefer that the soil surface be periodically wetted with SDI as an indicator of system performance, even though this promotes greater soil water evaporation losses and weed germination. Some growers in the Salinas and Santa Maria valleys of California have abandoned SDI in favor of DI for broccoli, cauliflower, celery, and lettuce rather than contend with harvesting issues associated with buried driplines (Burt and Styles, 1999). Pests such as rodents and insects are often more troublesome at the shallow dripline depths (See Section 13.1.3.5.3).

Table 13.4. Minimum dripline depth, cm, to minimize the potential irrigation evaporation losses to a specified percentage for various anticipated soil water evaporation rates for three soils.

Upper bound on evaporative losses, %	Anticipated maximum soil water evaporation rate, mm/day						
	2	4	6	8	10	12	14
Yolo clay [α = 0.0367 cm^{-1} K_s=0.00000933 cm/s]							
5	38	52	58	63	66	68	69
10	19	33	40	44	47	49	50
15	8	22	28	33	36	38	39
20		14	21	25	28	30	31
35			5	10	12	15	16
50					3	5	6
Ida silt loam [α = 0.026 cm^{-1} K_s=0.0000292 cm/s]							
5	15	39	52	60	67	72	76
10		12	25	34	40	45	49
15			10	18	25	29	33
20				7	13	18	22
35							1
50							
Dackley sand [α = 0.513 cm^{-1} K_s= 0.0001 cm/s]							
5			1	1	1	2	2
10							1
15							
20							
35							
50							

Saline waters and biological effluents often impact the choice of a dripline depth (See also Chapter 4 and 9 and Sections 13.2.4.2 and 13.3.1.2). The application of saline water at shallow dripline depths may create a zone of high salinity near or at the soil surface that is detrimental to seedling and transplant growth and establishment. In arid areas where precipitation is insufficient, it may become necessary to leach this zone with sprinkler irrigation. Some growers have used tillage to scrape off or displace this salinity zone before each planting. The dripline depth for application of biological effluents is chosen so that the pathogen exposure paths at the soil surface are reduced, but with a depth that would not prevent normal biological decay.

The use of SDI in regions subjected to freezing and frozen soils adds an additional dripline depth consideration. Deeply placed SDI systems are less likely to freeze, but supporting system components (e.g., valves and filters) sometimes may freeze and limit operation (Converse, 2003). Snow cover can insulate and protect the SDI system from very cold air temperatures. SDI was durable enough to withstand winters in the U. S. Northern Great Plains when temperature at the 30-cm dripline depth was below freezing for 90 consecutive days in 1993-94 and the frost depth reached 90 cm (Steele et al., 1996).

13.2.3. Installation Issues

SDI systems with shallow depths (less than 20 cm) are often installed and retrieved after every season for horticultural crops. The installation and retrieval of these systems have many similarities to DI systems and are discussed in Chapter 12 (Section 12.3.7).

Driplines are usually installed with commercially available, shank-type injector implements that are drawn by tractors (Fig. 13.21). In some instances, powered vibratory shanks have been used to install driplines along established perennial vine and tree crops, which avoids excessive draft requirements (power) and excessive root pruning.

Figure 13.21. Tractor-drawn SDI installation implement installing dripline in Kansas. Courtesy of F. R. Lamm, Kansas State University.

The structural strength of the dripline installation implement must be sufficient for the planned dripline depth with respect to the soil type and physical characteristics. The shanks and dripline reels must be in good working condition, without excessive wear or corrosion (See also Section 13.1.3.5.3). The installation depth should be consistent throughout the field so that any planned tillage operations can be safely performed without damaging the dripline. For systems with depths greater than 30 cm, some installers are recommending that growers deeply till the field in multiple directions before dripline installation to help ensure that a consistent dripline depth can be obtained. The dripline should always be installed with the emitter facing upward, although this is not possible to maintain in installations that require round, hard-hose driplines. Upward emitter orientation permits sediments to accumulate at the bottom of the dripline to prevent emitter clogging. It may be useful to obtain dripline rolls from the manufacturers with a user-specified length so the installer does not have to make splices within the field.

Appropriate consideration must be given not only to the accessibility of field valves, controls, and other above-ground components, but also to protect them from weather, human, and pest activities. Growers often prefer that the location of these components is centralized and/or installed subsurface so that the impact on cultural operations is minimized.

The PVC headers, submains, and mainlines are usually installed below the frost-free depth because they are more susceptible to freeze damage than the polyethylene (PE) driplines. When this design guideline is not followed, the system design must provide for pipeline drainage. The trenches for the pipelines must be sufficiently wide to allow for easy and clean assembly of the pipeline and dripline connections (Lamm et al., 1997b). Trenches should be straight, properly marked, and their location recorded, so that a subsequent trenching operation could be performed along beside the pipeline if the driplines need replacement. Appropriate standardized installation procedures should be followed for all pipelines (ANSI/ASAE S376.2, 2004).

System component reliability, durability, and ease of installation and repair become significant quality and maintenance-control concerns when the system is underground, where leaks and other problems are difficult to detect, find, and repair (Lamm et al., 1997b). A multitude of dripline connectors and connection procedures are commercially available. Selection of a connector that properly matches the dripline characteristics with an easy and reliable connection procedure is important for ensuring a successful installation. Because of the variation in individuals' ability to make watertight connections, quality control and assurance are recommended during installation. The connections should be pressure-tested with water to locate leaks before the trenches are backfilled. Thus the pump and filtration system must be operational before SDI installation.

13.2.4. Special or Unique Design Considerations

13.2.4.1. SDI design and electrical technologies

Microirrigation and electrical technologies complement each other. These complementing factors include efficient on-farm energy use, opportunities for automation, electrical-load management, scale factors, and alternative energy sources (Lamm et al., 1997c). Inherent characteristics of SDI are especially important with the latter three factors. A properly designed SDI system can apply very small volumes of water in a very efficient manner that can eliminate irrigation evaporation and deep percolation. This makes SDI an excellent candidate for electrical load management and for solar and wind energy pumping schemes that are subject to intermittent interruption. Alternative systems such as surface microirrigation, gravity, and sprinkler irrigation can also be interrupted, but the transactional costs, such as increased evaporative losses or decreased distribution uniformity, usually will be greater. It also is easy to scale SDI systems economically to the size of the field. Thus, SDI systems can be used on smaller irrigated areas and irregularly shaped fields that require smaller irrigation water supplies and pumping plants. On smaller irrigation systems, a wider range of continuous-duty electric motors are available for pumping than internal combustion engines. In some instances, small SDI systems can use less expensive single-phase electric motors, wind (Vick et al., 2000), or solar energy.

13.2.4.2. SDI design issues for recycled waters and biological effluent

Recycled waters and biological effluent are sometimes applied through SDI systems. Clogging concerns are important when using these waters for SDI because of the difficulty of replacing or remediating subsurface driplines (See also Chapter 9). Filtration needs are usually greater for recycled waters and biological effluents. The capacity of the filtration system and degree of filtration may be increased over the anticipated needs to provide a larger margin of clogging protection for the subsurface emitter. A disc filtration system used for SDI application was sized to filter a beef lagoon effluent flowrate of approximately 25% of the manufacturer's specifications for freshwater (Trooien et al., 2000). More research is needed to closely determine the filtration requirements of SDI systems when using recycled waters and biological effluent.

Limited research has been conducted on emitter selection when using recycled waters and biological effluents. Driplines with emitter discharges of 1.5, 2.3, and 3.5 L/h had flowrate declines of approximately 4% after two seasons of biological effluent application compared with approximately 18% flowrate reduction for smaller 0.6 and 0.9 L/h emitters (Trooien et al., 2000). After four seasons of use, the driplines with the smaller 0.6 and 0.9 L/h emitters had experienced approximately 40 and 30% flow reductions, respectively, relative to driplines with less than 13% reduction for the larger emitters (Lamm et al., 2002b). The largest emitter in the study (3.5 L/h) was also a pressure-compensating *(PC)* emitter. Laboratory testing of two sections of dripline, each containing 12 of these *PC* emitters, at the close of the field study revealed one emitter with an approximately 25% flowrate reduction and two emitters with flowrates approximately 40 and 60% higher than the nominal 3.5 L/h discharge. These differences were attributed to differential clogging in the *PC* emitters and wastewater particles becoming stuck within the flexible diaphragm of the *PC* emitter (Lamm et al., 2002b). Wastewater particles that inadvertently increase flows of *PC* emitters have been reported anecdotally and some manufacturers discourage their use for wastewater applications. Shorter and wider emitter flow paths may be subjected to less clogging than longer labyrinth-style emitters (Adin and Sacks, 1991). Emitters that were molded or attached to the dripline were superior to driplines where emitter pathways were formed by indentation when using pretreated secondary effluent, (Hills and Brenes, 2001). Additional discussion on emitter selection and biological effluent is provided in Chapter 9, Section 9.6.1.

SDI installation depth may need further consideration when using recycled waters and biological effluent. Human exposure to wastewater pathogens may be decreased with deeper installations, but increasing the dripline depth may sometimes decrease the amount of biological treatment and remediation of the wastewater (See also Chapter 9). Salinity management of recycled waters and biological effluent also may affect the dripline depth (See also Section 13.2.2.5).

13.2.4.3. Use of SDI in fully enclosed subirrigation (FES) systems

Although SDI and subirrigation are different, a special type of subirrigation can use SDI for water table management. The use of SDI driplines to supply irrigation water to crop beds for establishing and maintaining shallow water tables was first proposed by Clark et al. (1990) as the fully enclosed subirrigation (FES) system. This system was proposed as an environmentally sound alternative to the conventional semi-closed seepage systems that use open field ditches to provide irrigation to many of the crops in Florida (USA). Additionally, by providing water through subirrigation to widely spaced crop beds, FES systems would be less expensive to install than DI systems that require a dripline for every plant bed. Additional research evaluated application rates necessary to maintain the target water table level under crop water use conditions of approximately 4.6 mm/d (Clark and Stanley, 1992). An application rate between 6.4 and 7.7 mm/d achieved the target water table level on this sandy soil and saved approximately 30 to 40% of the irrigation required by conventional (ditch) seepage irrigation systems. Although the FES system can also be accomplished with surface driplines (DI), Clark and Stanley (1992) point out the more permanent aspects of using SDI, such as avoiding bird and insect damage. FES systems avoid surface runoff of irrigation, improve irrigation uniformity along the length of the field, allow for improved surface drainage, reduce soil erosion, increase surface water storage, and improve effectiveness of rainfall (Clark and Stanley, 1992; Smajstrla et al., 1996). Potato production was compared for three seasons using both conventional seepage irrigation and FES using subsurface driplines (Smajstrla et al., 2000). No significant differences in potato yields were obtained, but the FES system used 36% less water. Energy costs for the FES system were 70% higher because of the higher operating pressure. The estimated conversion cost from seepage irrigation to the FES system was $990/ha. The researchers concluded that there was no monetary incentive for conversion to the FES system for this cropping system. This emphasizes that, although improved irrigation practices can reduce water use and environmental concerns, it may be necessary for society to provide incentives for such conversion. The Southwest Florida Water Management District is encouraging growers to adopt either FES or drip irrigation systems as an improvement over conventional seepage irrigation systems (Clark et al., 1993).

13.3. SOIL AND CROP MANAGEMENT

13.3.1. Soil Issues

13.3.1.1. Soil physical characteristics and soil water redistribution

The soil type and structure can greatly affect the performance of SDI for a given crop. System design characteristics, such as dripline type, depth, length and spacing, emitter flowrate and spacing, and intended system use must be considered with respect to soil type and structure. These design characteristics were discussed in detail in Section 13.2. Some of the unique advantages and disadvantages of SDI are closely connected to system design with respect to soil type. Soil water redistribution with SDI continues to be a very important topic in both modeling, and field research (Gilley and Allred, 1974; Thomas et al., 1974; Bresler, 1977; Raats, 1977; Bresler, 1978; Dirksen, 1978; Ghali and Svehlik, 1988; Philip, 1991 a and b; Coelho and Or, 1996; Or, 1996; Or and Coelho, 1996; Mmolawa and Or, 2000 a and b; Cote et al., 2003; Thorburn et al., 2003).

The possibility of controlling the soil wetted volume by regulating emitter discharge in relation to soil properties was suggested in a modeling study by Bresler (1978). Ghali and Svehlik (1988) extended and further modified this concept by concluding that, for optimized water use, a water application rate equal to root-zone depletion is only optimal when all losses except plant water uptake are minimized. Through modeling, they found that continuous irrigation at a rate equal to evapotranspiration was optimal for medium textured soils. A greater water application rate was required for coarse-textured soils to minimize cumulative deep percolation losses. Thus to maintain an optimal soil water regime on sandy soils, short, frequent pulses of water were required. They demonstrated a marginal decrease in water losses from the root zone for SDI than with DI that they attributed to more uniform SDI wave propagation near the root zone center. This is similar to the results of Ben-Asher and Phene (1993) and Phene and Phene (1987). They found that, for a given amount of irrigation, the wetted soil volume in an SDI system would have less water content than DI, and thus deep percolation would be less with SDI. Zur (1996) has extended the wetted soil volume concept into the design process. He suggested an inverse design procedure in which a management-controlled soil water volume is estimated as the first design step. This control volume is primarily affected by the available soil water-holding capacity and the peak ET_c rate, but also is affected by irrigation frequency and management.

Soil hydraulic properties can greatly affect soil water redistribution. In an anisotropic soil, horizontal conductivity was greater than vertical (Dirksen, 1978). The rate of redistribution seemed to depend mainly on the conditions in the immediate vicinity of the emitter. The redistribution differences were more closely related to the wetting-front advance rate than to changes in water content. Smaller, more-frequent SDI events are often used on sandy soils for shallow-rooted crops to prevent deep percolation losses from dominating the soil water redistribution process (Camp, 1998). Field soil water distribution can differ greatly from the results obtained in models because of spatial variability in measured soil properties (Or, 1996). Modeling results should be used as first approximations with regard to soil water potential and water content (Or, 1996). Although soil water redistribution in SDI systems is typically correlated to some degree to soil texture (i.e., percentages of sand, silt, and clay) for soils with little structure, wetting can be very different for layered soils of similar texture (Cote et al., 2003; Thorburn et al., 2003). These wetting differences for layered soils can affect not only irrigation management, but also SDI design aspects such as dripline and emitter spacing (See Section 13.2.2.1) and dripline depth (See Section 13.2.2.5).

Soil wetting patterns with SDI were more suitable to the rooting pattern of a pear orchard on a sandy loam with a uniform profile (51% silt, 9% clay, and 40% sand) than to DI in Israel (Oron et al., 1999a). They concluded on this soil, which has an approximately 24% volumetric water content at field capacity, that a 0.3-m dripline depth gave the most favorable soil water conditions in the active root zone of the pear trees. In a complementary experiment on bare soil, the shape of the wetting pattern was relatively complex (Fig. 13.22) and the researchers expressed doubts that spherical or hemispherical models, as used by Ben-Asher and Phene (1993) could adequately describe field conditions.

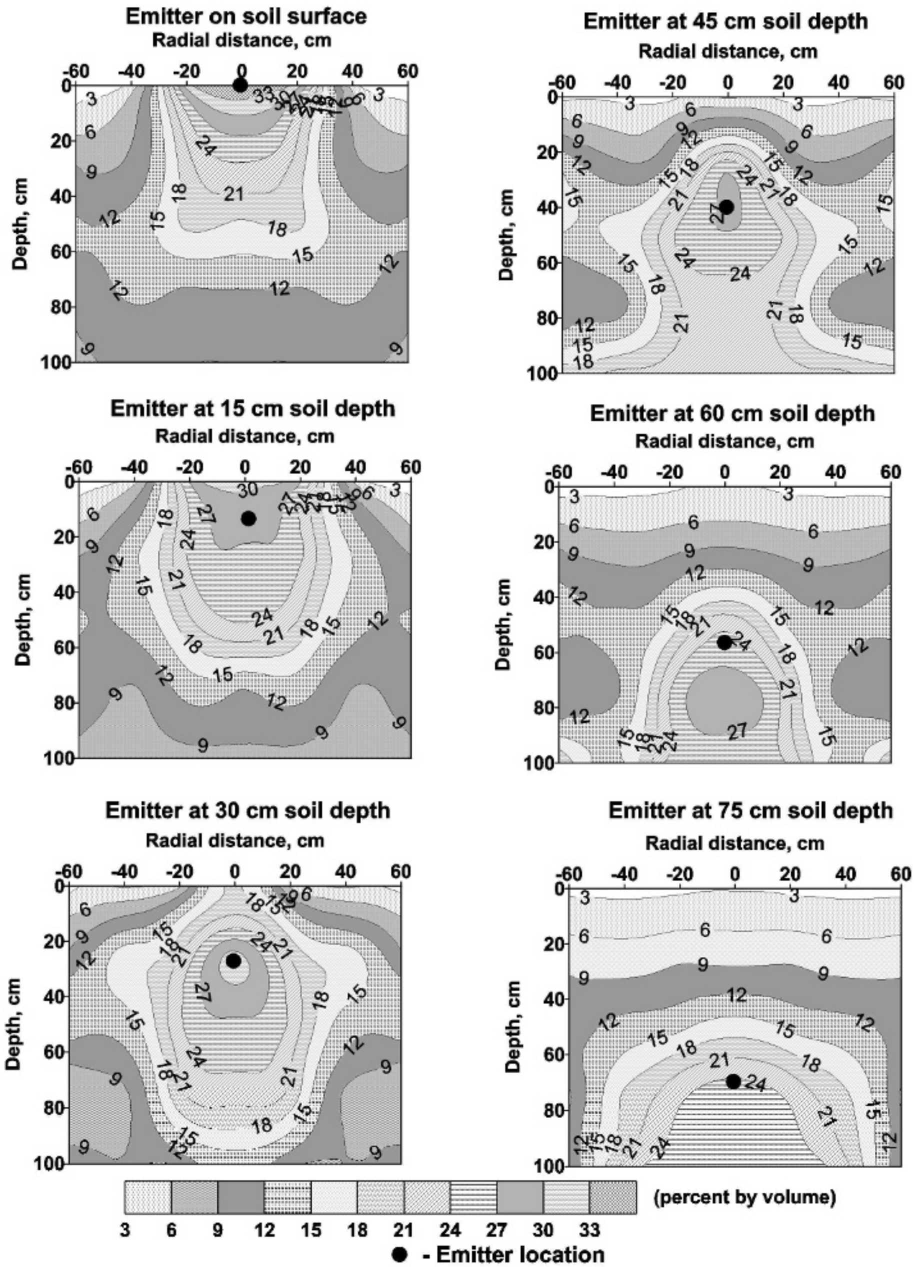

Figure 13.22. Soil volumetric water content as affected by dripline location for bare soil. After Oron et al. (1999a).

Microsprinklers may be more suitable than SDI or DI for irrigation of trees on coarse-textured soils because they provide a larger wetted volume for developing root systems. Tree trunk diameters and almond yields were generally greater with microsprinklers than with SDI or DI on gravelly loamy sand in California (Edstrom and Schwankl, 1998a). The researchers concluded that, if drip irrigation is used, it might be advantageous to install driplines on both sides of the tree to wet a larger soil volume.

Less salt accumulation was present in the active root zone and denser root systems with SDI than with DI for both tomato and cucumber on a calcareous soil in Egypt (El-Gindy and El-Araby, 1996). This was attributed to better soil water redistribution within the root zone. Greater horizontal movement of the water occurred with the larger 4 L/h emitters compared with greater downward movement for 2 L/h emitters. However, there was still concern that SDI may cause an excessive salt accumulation in the seed and transplant zone for the next crop. Profile soil water redistribution with SDI was better than with DI on a slowly permeable soil subject to surface sealing in California (Grimes et al., 1990). Grape yield increases of 4 to 7% for SDI compared to DI were attributed to better plant water status and less surface evaporation.

Adequate soil water for crop germination with SDI is important in semiarid and arid regions and in other regions prone to drought during crop establishment. Dripline depth is important in affecting the surface and near-surface soil water conditions (See also Section 13.2.2.5) with shallower dripline depths providing wetter conditions. Tillage and planting practices can sometimes be used to prevent or avoid dry soil conditions for crop germination and establishment. When applied irrigation does not move into the loosely consolidated soil surface layers in a bed cropping system, the dry soil can be removed to the traffic furrow, thus exposing wetter and firmer soils for crop establishment. Using emitters with a greater discharge rate also can improve soil water conditions for crop establishment but may negatively affect system design and installation costs and exacerbate soil water surfacing (See Sections 13.2.2.2 and 13.3.1.3).

Pulsing the SDI system, which involves applying small increments of water multiple times per day rather than applying a larger amount for a longer duration, has been advocated as a procedure to improve surface and near-surface wetting for crop establishment. Although considerable research and theory to support this technique for improved wetting patterns are available for DI (Zur, 1976; Levin and van Rooyen, 1977; Levin et al., 1979), little research and few operational guidelines exist for SDI. A comparison of continuous and pulsed SDI at a depth of 0.2 m on a Hanwood loam soil in New South Wales (Australia) indicated very little difference in the width of wetting at the soil surface for irrigation amounts up to approximately 700 mm (Miller et al., 2000). Continuous irrigation was performed over a four-day period, and the pulsed irrigation consisted of 11.25 minute events every 45 minutes that took 13 days for the entire application. Gravimetric soil water content increases above the dripline (0 to 0.2 m) for a horizontal distance of 0 to 0.6 m from the dripline reached similar asymptotes of approximately 8% after about 50 hours of irrigation for both pulsed and continuous irrigation. The pulsed SDI treatment, however, retained about twice as much water as the continuous irrigation treatment in the 0.2 to 0.5 m depth range immediately below the dripline (2 and 4% water content increases, respectively). Initial soil water contents for the upper and lower blocks were 12 and 22%, respectively, and this may have caused more deep percolation below the lower block. In clay or heavier soils that tend to experience water surfacing (See Section 13.3.1.3), pulsing may make little difference in the amount of surface soil water redistribution. Surfacing was reported to occur consistently within

15 minutes of the start of the irrigation cycle on an established alfalfa crop on a clay loam soil in Australia (Battam et al., 2002). More research is needed to establish criteria and timing guidelines for the use of pulsing of SDI for improving soil water for crop establishment. These guidelines will be affected by soil type, soil layering, soil hydraulic conductivity and associated parameters, initial soil water contents, emitter flowrates, and SDI system capacities. Engineering and operational problems are involved with the frequent filling and draining of large SDI systems that will need to be overcome when and if successful pulsing guidelines are developed.

Surface and near-surface soil water redistribution has also been enhanced by the addition or incorporation of impervious plastic barriers immediately below the dripline (Welsh and Byles, 1993; Barth, 1995; Welsh et al., 1995; Brown et al., 1996; Welsh et al., 1997; Barth, 1999; Charlesworth and Muirhead, 2003). These barriers have three basic functions: (1) the creation of a small, perched water table above the barrier that enhances horizontal wetting; (2) the improvement in wetting between adjacent emitters, and (3) the reduction in deep percolation. Attempts have been made to commercialize some of these systems, but it is uncertain whether they will be economical because of the additional cost of the barrier and its installation.

13.3.1.2. Salinity aspects

The advantages of using microirrigation for saline irrigation waters have long been recognized (Goldberg and Shmueli, 1970; Bernstein and Francois, 1973 and 1975; Shalhevet, 1994, Hanson et al., 2003a; See also Chapter 4). When choosing an irrigation system for saline irrigation waters, the resultant salt and water distribution in the soil, crop sensitivity to foliar wetting, and the practicality of frequent irrigation application are three major considerations (Shalhevet, 1994).

Both DI and SDI have the advantage of avoiding salinity damage caused by foliar wetting. With saline water, bell pepper yield was 50% greater for DI than for sprinkler irrigation (Bernstein and Francois, 1973). However, there was no difference in pepper yield with good quality water between irrigation systems. In some instances, although the salinity threshold might be affected very little by selecting DI instead of sprinkler irrigation, the rate of yield decline with increased salinity is greatly reduced for DI. Potato yields were unaffected at salinity levels of 0.9 and 1.3 dS/m for sprinkler and drip irrigation, respectively (Meiri et al., 1982). At a salinity level of 3.5 dS/m, however, potato yields were reduced approximately 21% and 9% for sprinkler and DI, respectively. Wang and Shannon (2000) conclude that drip irrigation may be more suitable for plants susceptible to foliar damage, but that sprinkler irrigation can create more leaching, thus leaving less salt in the soil profile at the end of the season.

DI and SDI also have an advantage over other irrigation methods in their ability to maintain consistently high soil matric potentials and zones of soil salinity that are essentially equal to the salinity of the irrigation water (Shalhevet, 1994). Accumulation of salts does occur at the periphery of the wetted soil volume. These salt accumulations must be avoided by locating crops in non-saline zones and/or removed by periodic leaching with precipitation or use of other secondary irrigation systems (Hanson and Bendixen, 1993).

Both temporal and spatial soil salinity and water distributions can be important for SDI. Upward water movement from subsurface driplines can create a highly saline zone above the emitters that can be toxic to transplants and seedlings. The same level of salinity at this depth may be of little consequence to an established crop provided that the saline zone does not move into the active root zone. Growers may remediate the problem of salinity in the seeding or transplanting zone by dormant season leaching with precipitation or sprinkler irrigation (Nelson and Davis, 1974). Another method is to build up the crop bed to a greater height than normal, move the salts into this higher peak through irrigation, and then remove the salt accumulation in the peak location through tillage before planting (Hanson and Bendixen, 1993). The management of crop location with respect to dripline location can be important for even moderately saline waters with SDI systems that are used for multiple years unless periodic leaching is provided. Root activity was limited to the wetted soil volume for drip-irrigated tomato and peanut on a sandy soil, but the rooting patterns were different for fresh and saline water (Ben-Asher and Silberbush, 1992). When freshwater was used, a relatively high root density occurred around the periphery of the wetted volume, but with saline water limited root activity existed at the periphery. Most root activity occurred in the leached zone beneath the emitter. In the humid region of Virginia, dormant-season rainfall was sufficient to alleviate long-term problems with sodic irrigation water for both SDI (0.35- to 0.4-m depth) and sprinkler irrigation. SDI required about 30% less water for corn and 65% less water for peanut than sprinkler irrigation (Adamsen, 1989 and 1992). The deeper-placed SDI was particularly beneficial for peanut because sprinkler irrigation of sodic water into the peanut pegging zone decreased both the number of pods and the size of peanut kernels (Adamsen, 1989). In another study in Israel, no significant differences were observed between DI and SDI (0.45 m depth) in soil chloride content and soil sodium absorption ratio (*SAR)* to a depth of 0.6 m after two irrigation seasons because winter rainfall was sufficient to remove salinity (Aloni et al., 2000). The timing and amount of precipitation will affect whether SDI salinity problems can be managed naturally without human intervention.

SDI system design can also affect the severity of salinity problems. Soil salinity was 4.4, 8.0, 10.5, and 18.9 dS/m on a sandy loam soil for Bermuda grass for a surface irrigation treatment and SDI dripline spacings treatments of 0.6, 0.9, and 1.2 m, respectively (Devitt and Miller, 1988). They concluded that selection of SDI dripline spacing must allow for adequate leaching and uniformly high soil water contents that will decrease buildup of salts in the active rootzone. In some situations, SDI can be appreciably better than other irrigation systems for use with saline waters. Little correlation was found for processing-tomato yield and soil salinity level for SDI in a study in California (Hanson and May, 2003). They concluded that soil salinity under SDI may affect tomato yield less than with other irrigation methods. Tomato yields in this study were 12.9 to 22.6 Mg/ha higher with SDI than with sprinkler irrigation for similar irrigation amounts. Pear yield and quality was improved with a 0.3-m depth SDI system, but not for a 0.6-m depth SDI system, when compared with DI for saline water use in Israel (Oron et al., 1999a and 2002). Pear yield was 11 to 19% higher for freshwater applications with SDI at 0.3-m depth than with DI. A similar comparison with saline water (4.4 dS/m) gave SDI a 32 to 42% yield increase. When the SDI depth was increased to 0.6 m, however, DI had 9 to 11% yield advantage with freshwater and 36 to 46% yield advantage for saline water (Oron et al., 2002). Saline water use through SDI tended to increase pear quality in both greater sugar content and acidity. In a related experiment on bare soil, the soil salinity distributions (Fig. 13.23) were measured for DI and SDI with dripline depths up to 0.75 m (Oron et al., 1999a). Although the average profile salinity is higher with SDI than with DI, more favorable soil water conditions within the effective root zone (Fig 13.22) can offset the osmotic effect on water uptake. These reports emphasize the importance of matching system design parameters with crop characteristics when saline water is used.

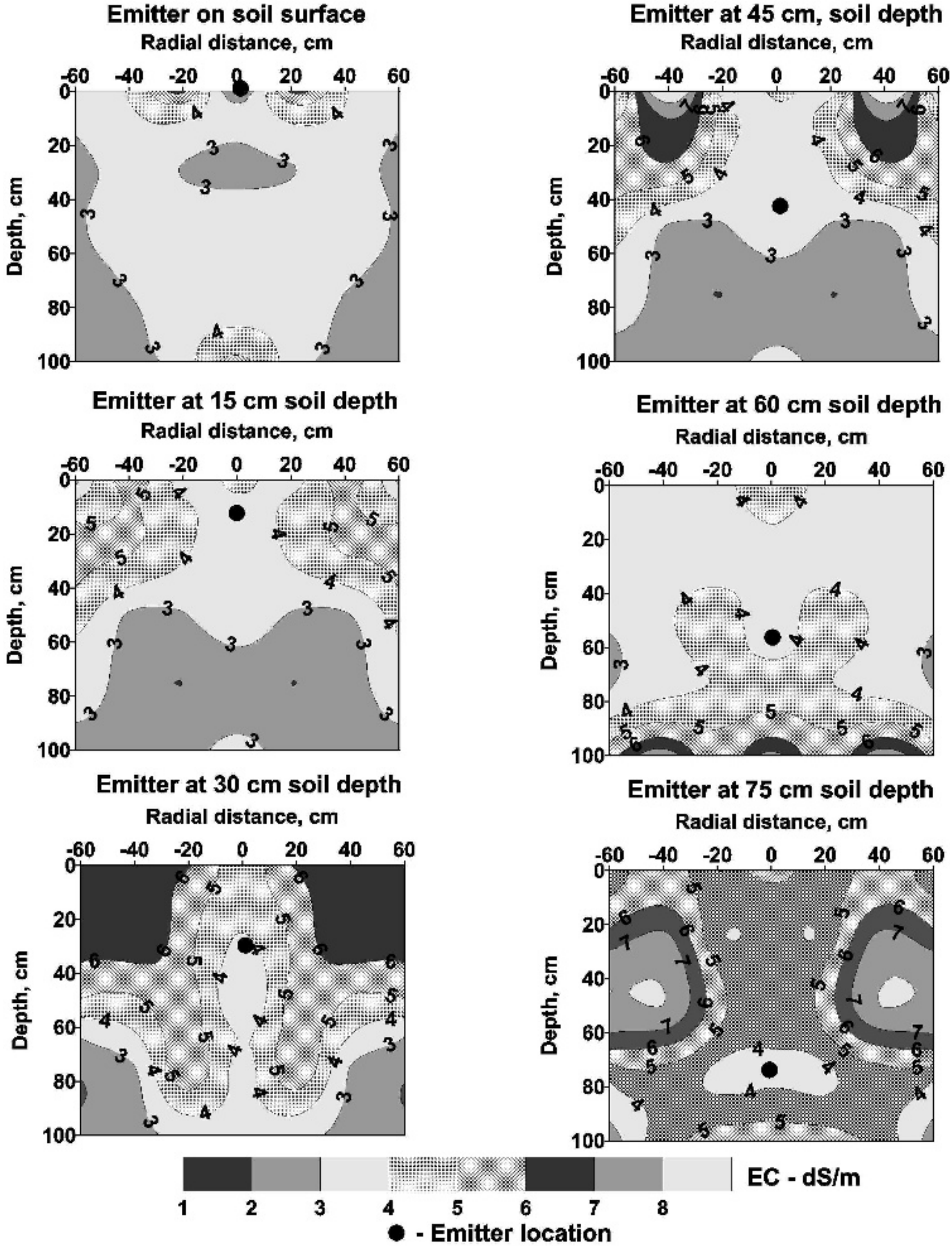

Figure 13.23. Soil salinity as affected by dripline location for bare soil. After Oron et al. (1999a).

13.3.1.3. Soil water redistribution problems caused by backpressure

In some situations, the SDI emitter discharge is greater than the saturated hydraulic conductivity of the soil in the immediate vicinity of the emitter. Backpressure on the emitters can occur and, as a result, emitter discharge and SDI system uniformity will be affected as discussed in Section 13.1.3.5.5. The water from the emitter discharged with a pressure greater than atmospheric may also seek a path of least resistance to release its energy. Sometimes the path of least resistance is upwards and the water will travel to the soil surface causing differential soil water redistribution, wet spots that may interrupt farming operations, increased soil water evaporation, and possibly irrigation runoff. This “surfacing” phenomenon also may be directly associated with a “chimney effect” in which small, fine soil particles are carried to the surface in the preferential flow path or macropore. The sorting of soil particles and deposition into the walls of the chimney will further reinforce the preferential flow path and surfacing may become worse. These depositional crusts that are formed within the soil profile can have hydraulic conductivities that are reduced by 2 to 3 orders of magnitude (Shainberg and Singer, 1986; Southard et al., 1988). The chimney can be disrupted by tillage, but will often reappear because the flow channel still exists in the region around the emitter which was undisturbed by tillage. The surfacing and chimney effects are somewhat analogous to volcanic activity (Zimmer et al., 1988), and the point where free water exits the soil has even been called a caldera (Fig. 13.24). Surfacing can be a significant problem on some soil types and is particularly troublesome when it occurs in alfalfa fields resulting in wet spots at harvest (Hutmacher et al., 1992; McGill, 1993).

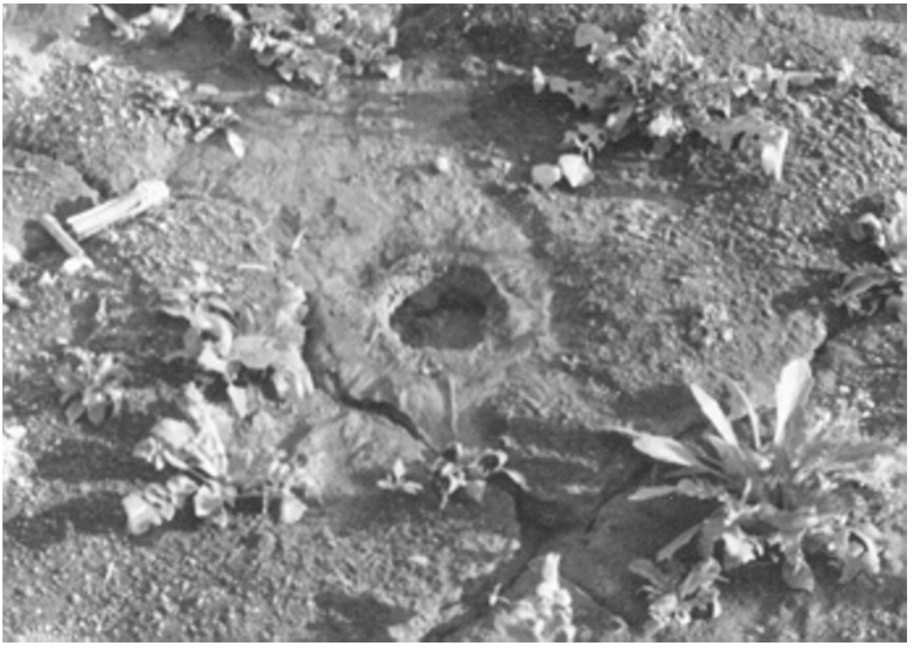

Figure 13.24. Caldera resulting from surfacing of water from an SDI emitter in California. Photo courtesy of F. R. Lamm, Kansas State University.

Application of biological effluent through SDI systems can cause blockage of soil pores in the immediate vicinity of the emitters and further exacerbate the surfacing phenomenon (Fig. 13.25). Application of biological effluent increased soil water retention, decreased the number of large-radius pores, and decreased saturated soil hydraulic conductivity significantly on a sandy loam soil, but had only a minimal effect on a silty clay loam soil (Jnad et al. 2001). There was a greater influence of effluent application on soil hydraulic properties in transects parallel to the dripline than perpendicular to the dripline. The largest influence on saturated soil hydraulic conductivity occurred at about 20 cm below the dripline, with a 30% decrease observed at one field site and 70% at two other sites (Jnad et al. 1999).

Figure 13.25. Surfacing of biological effluent from an SDI emitter in a sugar cane field in Hawaii and the resulting caldera. Photo courtesy of F. R. Lamm, Kansas State University.

The preferential flow path or macropore does not necessarily exist before installation of SDI. Rather, the macropore can be caused by the SDI-applied water forcing an outlet (Battam et al., 2002). The extent of surfacing is dependent on soil type, dripline depth, and emitter flowrate (Zimmer et al., 1988; Shani et. al., 1996; Battam et al., 2002). Decreasing the emitter spacing will allow reduced emitter flowrates, while maintaining the SDI system design flowrate and thus may be a primary method of preventing surfacing problems. Using shorter-duration irrigation events (pulsing) may reduce the amount and magnitude of unwanted surface water problems, but may not prevent surfacing (Battam et al., 2002). They suggested that a partial remedy to an existing surfacing problem would be to reduce operating pressures, thus reducing emitter flowrates. Increasing the hydraulic conductivity of the soil around the emitter by using a gravel-filled cavity was examined by Ben-Gal et al. (2004). Greater horizontal redistribution with SDI occurred within the gravel-filled cavities than with SDI alone. Although the gravel-filled cavity may be justified in some situations, cheaper solutions might be obtained by more careful matching of emitter spacings and flowrates to the inherent soil hydraulic conductivity. The gravel-filled cavity method may be warranted where surfacing is unacceptable, such as when biological effluent is being applied Ben-Gal et al. (2004). Reducing the formation of internal depositional crusts by SDI application of soil conditioners may also help to reduce surfacing problems (Shaviv and Sinai, 2004.) Laboratory trials have confirmed that this technique is feasible, but further field work is required to evaluate the process and to determine its cost effectiveness and longevity.

Growing plants and their resultant uptake of water by roots, can help prevent and possibly even reverse the phenomenon of backpressure on the emitters (Lazarovitch, 2001; Ben-Gal and Lazarovitch, 2003). This technique may be applicable when the mismatch between emitter flowrate and soil hydraulic conductivity is small.

13.3.1.4. Soil compaction

Soil compaction may have its greatest effect on SDI system integrity and operation (Section 13.1.3.5.4), but also can have interactions with SDI through the crop response.

Using SDI at a depth of 0.3 m was beneficial in overcoming the effect of cotton root-limiting soil strength (> 2 MPa) on loamy sand in the U. S. Southeastern Coastal Plain (Camp et al., 2001). Cotton lint yields under no tillage with SDI were similar to treatments including shallow tillage even though soil strength was found to be root limiting at 0.15 m for the no-tillage treatment and at the 0.20- to 0.25-m depth with the two shallow-tillage treatments. The researchers concluded that enough applied water moved through the compacted zone into the active rooting zone to maintain adequate crop growth.

Soil compaction can be reduced with SDI systems because there is reduced wetting of the soil surface and because mechanical and human traffic can be confined to zones away from the subsurface driplines (Chase, 1985). Some cultural operations can continue during irrigation without causing adverse compaction. This is particularly beneficial to alfalfa production with SDI (Hutmacher et al., 1992). When surface and near-surface soil conditions are conducive to compaction, however, it is wise to avoid cultural operations during irrigation. When cultural operations are routinely required under such conditions, design dripline length should be decreased and/or longer continuous irrigation events should be used to help alleviate compaction. (Hills et al., 1989b).

13.3.1.5. Managing the soil water budget components

Many potential advantages of SDI depend on the careful management of the various soil water budget components, such as soil water evaporation, transpiration, percolation, and runoff. The balance of most of these components is closely interrelated to the important SDI system design factor of dripline depth, and some of the water budget components have been previously discussed in Section 13.2.2.5. Greater dripline depths can limit evaporation and decrease rainfall runoff, but may cause greater percolation of applied water or reduce beneficial transpiration in shallow-rooted crops. These conditions can reduce the effectiveness of applied water and thus application efficiency. The interactions between the soil water budget components with dripline depth are also closely affected by soil type and crop characteristics. The unsuccessful adoption of SDI in many regions is caused by the improper balancing of these interrelationships or by the lack of understanding of the need for the proper balance.

13.3.1.6. Special or unique soil issues

The inherent characteristic of SDI being located below the soil surface presents some special or unique issues and considerations. Some examples include opportunities for improved weed control, subsurface placement of agrochemical and biological effluent applications, and soil-profile injection of gases.

13.3.1.6.1. Weed control

Herbicide application for general surface weed control is usually not practical through SDI because of the inability to distribute water uniformly to the soil surface layers where most weed seed germination occurs. Herbicides have been applied by SDI systems or released from SDI components to prevent root intrusion into the emitters, but these applications are not for general weed control (See Section 13.1.3.5.2). Weed germination can be less with SDI than with other types of irrigation that wet the soil surface, however, particularly in arid and semiarid climates where there is less precipitation. The amount of weed seed being transported within the field by furrow irrigation or sprinkler irrigation runoff is also reduced with SDI. Reduced weed pressure has been reported with SDI for alfalfa (Bui and Osgood, 1990; Henggeller, 1995a), almond (Edstrom and Schwankl, 1998a and b), cotton (Henggeller, 1995b; Khalilian, et al., 2000), field corn (Lamm and Trooien, 2005), processing tomato (Grattan et al., 1988; Grattan et al., 1990), and sweet corn (Bar-Yosef et al.,1989; Oron et al., 1991).

Harvesting of alfalfa results in growth stress on the plant crown, and this opens the opportunity for a flush of annual weeds when the soil surface is wetted by irrigation. SDI can continue during harvest with less physiological stress on the crown of the plants. In addition, the dry soil surface results in less weed germination. Fewer weeds also results in better quality alfalfa hay that can receive a premium price in some regions.

Weed control with SDI on almond is enhanced by not wetting the soil surface. This helps reduce herbicide applications by up to 66% and mowing costs by 50% (Edstrom and Schwankl, 1998b) resulting in easier harvest operations (tree shaking, windrowing, drying, and sweeping). Four years of research showed no differences in almond yield between SDI and DI. Microsprinkler and DI treatments always required a preharvest foliar herbicide application, but SDI did not.

Weed growth and the resultant nitrogen (N) uptake by the weeds with SDI at a 0.3-m depth was reduced by almost 28% compared with DI for sweet corn production on a loessial soil in Israel (Bar-Yosef et al., 1989). In the arid region of California, weed control with SDI without herbicide application was at least as effective as both furrow and sprinkler irrigation with herbicides (Fig. 13.26). Tomato red fruit yields with SDI were 34% higher than with sprinkler and furrow irrigation when no herbicides were applied (Grattan et al., 1988; Grattan et al., 1990).

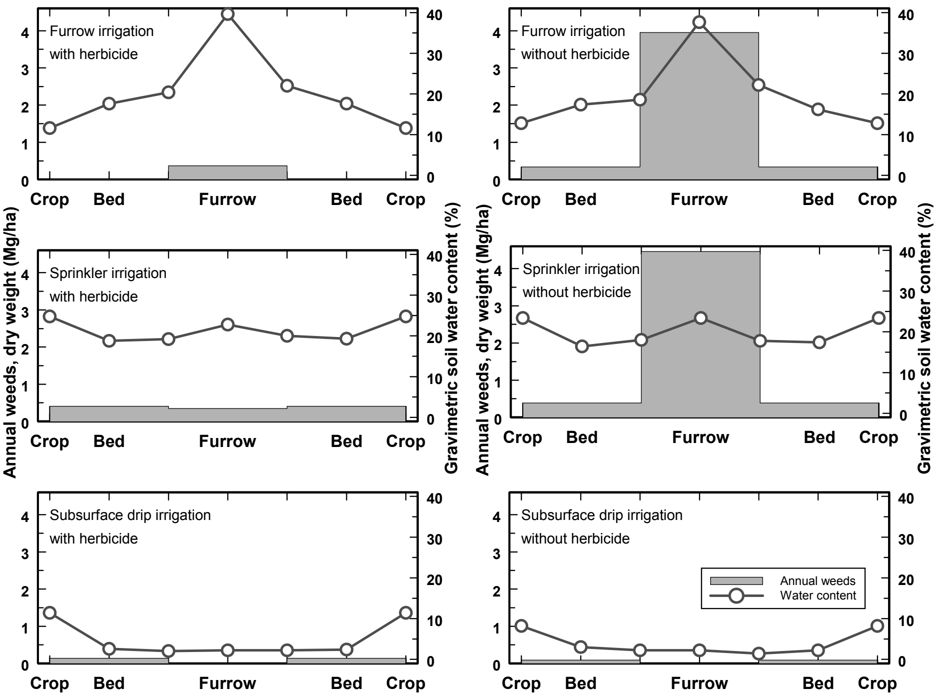

Figure 13.26. Weed control and soil water content in the surface 25 mm of the soil profile in a processing-tomato field as affected by irrigation method and herbicide application. Water contents were measured 24 hours after irrigation. After Grattan et al. (1988).

13.3.1.6.2. Application of insecticides for crop protection

Although there are few herbicides that that are licensed for application through SDI, some systemic insecticides have been used experimentally and were found to be effective (Wildman and Cone, 1986; Royer et al., 1989; Felsot et al., 1998; Wright and Cone, 1999; Felsot et al., 2000; Leib et al., 2000). The feasibility of applying insecticides through SDI to asparagus was demonstrated by Wildman and Cone (1986.) SDI application of disulfoton significantly reduced the number of aphids with protection lasting up to 54 days. There was greater uptake of disulfoton in the second year because of increased root development that resulted in greater chemical efficacy but chemical residues in the asparagus spears exceeded the federal tolerance limits by approximately 500 percent. In another study, Royer et al. (1989) examined SDI insecticide application to bell pepper, celery, and cantaloupe. A more varied response was observed from the SDI application compared with a more stable response for foliar application. Effectiveness of the SDI application was limited to phloem-feeding insects, and was slower in attaining control. However, SDI application was generally less expensive than foliar application. They concluded that SDI could be used for insectigation with careful and wise management.

Imidacloprid is a systemic insecticide that has shown promise with SDI, but its high solubility in water also makes it susceptible to leaching and movement into groundwater. Both furrow irrigation and SDI were investigated for insectigation of imidacloprid to control aphids on hops (Felsot et al., 2000). They concluded that both irrigation systems can work effectively, but the mode of effectiveness was different. Furrow irrigation had long periods between irrigation that allowed greater upward movement and plant uptake, whereas SDI could apply smaller, more frequent applications to a smaller wetted zone, helping to reduce leaching. When applying imidacloprid, all irrigation events need to be carefully matched to the prevailing soil water conditions and anticipated crop evapotranspiration rates (Felsot et al., 1998). Further reduction in potential groundwater contamination and crop carryover can be achieved by waiting until the aphid population reaches an economic threshold (Wright and Cone, 1999).

Although there are environmental risks and high management requirements for applying insecticides through SDI systems, there are other advantages to the environment such as reduced worker exposure to foliar insecticides, reduction of chemical waste from tank cleaning, elimination of insecticide wind drift, and less harm to beneficial insects not susceptible to systemic insecticides (Felsot et al., 1998). SDI and insectigation of systemic herbicides also can be combined with plastic mulch to maximize benefits from all three technologies. Muskmelon yield was increased 250% by application of imidacloprid alone, 400% by plastic mulch alone, and 1000% by the combined use of SDI, plastic mulch, and insectigation (Leib et al., 2000).

13.3.1.6.3. Application of biological effluent

Application of biological effluent is discussed in Chapter 9 and also in Section 13.2.4.2, but additional discussion of the topic is appropriate. The discussion in this Section is not to exhaustively review the subject, but rather to show unique opportunities with SDI. Application of biological effluent through SDI is likely to increase and remain an active area for future research.

Subsurface drip irrigation has two unique characteristics over other methods of irrigation because it can provide a pathogen barrier to crop contamination and also allows biofiltration and treatment of the wastewater within the soil profile. The effectiveness of SDI for biological effluent application depends on the emitter location, plant and root water-uptake characteristics, and the irrigation strategies (Oron et al., 1999b). Two parameters that primarily control this process are the hydraulic loading of the soil and the organic loading of the soil. Improper balance of either parameter will lead to problems such as irrigation runoff, crop contamination, soil clogging, insufficient biological treatment, and/or groundwater contamination. Soil water content is a very important factor in pathogen survival (Oron et al., 2001). Van Ginneken and Oron (2000) developed a model for assessing the human risk of infection on the basis of initial wastewater treatment, irrigation system type, elapsed time between irrigation and crop consumption, and consumer behavior. The model indicates that the interrelationship of all the factors influence the risk of infection. The annual risk of infection with SDI was one and five orders of magnitude smaller than DI and sprinkler irrigation, respectively, for the same initial wastewater treatment. Using SDI for effluent application can allow for less comprehensive initial treatment of the wastewater, a reduction in the amount of elapsed time between irrigation and crop harvest, an increase in food safety, or some combination of the three criteria.

13.3.1.6.4. Soil profile injection of gases

Limited research has been conducted in evaluating the injection of gases into the soil profile with SDI. Gases might be injected for fumigation, aeration, fertilization, or even to modify soil temperature. Aerated water improved growth and yield for zucchini, soybean, and cotton on a heavy clay soil in Australia (Bhattarai et al., 2004). They attributed the greater fruit set and yield in all three crops to enhanced root function due to better aeration. Air injection increased bell pepper numbers by 33% and pepper weight by 39% in a one-year study on a sandy loam soil in California (Goorahoo et al., 2001), but the effect tended to disappear with greater distance from the dripline inlet on these 60 m-long plots. Compressible gas and gaseous water mixture flow and distribution through the SDI system are much different than standard water flow and distribution (e.g., changes in flow characteristics due to viscosity and friction losses; gaseous mixtures changing concentrations along the length of dripline). This may place design and operational limits on the use of gas injection on larger and longer SDI systems. Still, this may be a growing SDI technology if the benefits can be evaluated and demonstrated for more crop and soil types.

13.3.2. Crop Issues

In a review of SDI, Camp (1998) listed 26 different horticultural crops and 12 different agronomic, turf, and forest crops where SDI had been used. General suitability of various crops also was discussed in Section 13.1.3.1. While crop transpiration for a well-watered crop does not vary across irrigation systems, differences can exist in the ability of alternative irrigation systems to provide a consistently well-watered condition that matches plant growth and the economic yield formation needs of the crop. In essence, the extent to which the conditions match a well-watered condition could differ spatially within the crop root profile and also could differ temporally on diel or longer timescales.

13.3.2.1. Crop water uptake and crop growth

The concepts of a controlled wetted soil volume and SDI soil water redistribution patterns were discussed in Section 13.3.1.1. The crop response to SDI soil water redistribution also differs with crop rooting and growth characteristics, weather conditions, and irrigation water quality.

The presence of a consistently and adequately wetted root zone can be especially important for crops that develop yield below the soil surface. Increased soil water availability and reduced soil strength on soils wetted by SDI were contributing factors in higher onion yields in India (Abrol and Dixit, 1972). Potato yield was increased 27% with SDI over sprinkler irrigation while reducing irrigation needs by 29%, provided there were driplines in each crop row (DeTar et al., 1996). Their results indicated that very little water would be wasted using a high frequency, every-row SDI system and that the system could closely match the actual potato transpiration needs. Nutrient availability, mobility, and plant uptake can also be enhanced under the SDI-controlled wetted volume near the center of the crop root zone (Bar-Yosef, 1999). Conversely, when the controlled wetted volume is not matched well to the crop root zone, SDI can be a poor irrigation method. Tomato yields were decreased 30% when using SDI, compared with DI, on a sandy soil in Florida (Clark et al., 1993) where deep percolation was excessive for this shallow-rooted crop.

Crop water uptake and the resulting crop response are also heavily influenced by the SDI design characteristics of dripline and emitter spacing, crop row spacing and orientation, and dripline depth that were previously discussed in Sections 13.2.2.1 and 13.2.2.5. Subsurface drip irrigation can better manage the soil water budget components (Section 13.3.1.5), and there is growing evidence that this improvement can be important in marginal and deficit irrigation management. In an early report of studies with cantaloupe, zucchini, and oranges, Davis and Pugh (1974), concluded that SDI had greater production and higher water use efficiency than DI, furrow, and sprinkler irrigation, particularly when applied irrigation was close to the consumptive use. Marketable yield of tomato was 22% higher with SDI than with furrow irrigation and saved nearly 55% in applied irrigation (Bogle et al., 1989). Subsurface drip irrigation requirements for muskmelons were only 25 and 42% when scheduled at 40 and 20% soil water depletion, respectively, of the furrow irrigation requirement that was scheduled at 40% depletion (Bogle and Hartz, 1986.) There was also a trend towards earlier maturity and increased total and marketable melon yields. Careful management of SDI systems reduced net irrigation needs by nearly 25%, while still maintaining corn yields of 12.5 Mg/ha (Lamm et. al., 1995). The 25% reduction in net irrigation needs was primarily associated with the reduction of in-season drainage, elimination of irrigation runoff, and reduction in soil evaporation, all non-beneficial components of the water balance. Additionally, drier surface soils allow for increased infiltration of seasonal precipitation events that occur in the region (summer pattern rainfall, semiarid climate). Greater cotton lint yields were reported in Texas for SDI than sprinkler irrigation under limited irrigation scenarios, while there was no significant difference in yields for the two systems under full irrigation (Bordovsky and Porter, 2003). Grain sorghum yields were significantly greater with SDI than with sprinkler irrigation under deficit irrigation (< 50% of crop evapotranspiration) in Texas, but greater yields were reported with sprinkler irrigation under full irrigation (Colaizzi et al., 2004). It was suggested that the yield trend reversal at the higher irrigation level may have been caused by deep percolation of water, leaching of nutrients, or by the lack of crop canopy humidification with SDI.

13.3.2.2. Frequency of irrigation

Although it is often assumed that high irrigation frequency is a necessary and desired practice with microirrigation systems, a literature review of SDI (Camp, 1998) indicates that SDI frequency is often only critical for shallow-rooted crops on shallow or sandy soils. In many instances, the effect of SDI frequency will be similar to that for DI, so the reader also is referred to Chapter 12 for further discussion. There can be additional benefits to increased frequency of SDI other than crop yield increases. High-frequency SDI reduced deep percolation and increased use of water from shallow water tables for several crops in California (Ayars et al., 1999). The importance of the water holding capacity of the soil disappears as irrigation frequency increases, resulting in salinity management as the only remaining reason for over-application of water (Rawlins, 1973).

The effect of SDI frequency on yield is even quite variable among vegetable and horticultural crops. Daily or twice weekly SDI events were better than weekly irrigation for onion and bell pepper, but weekly irrigation was as good or better for carrot, cantaloupe, and lettuce (Bucks et al., 1981; Hanson et al., 2003b). There were no yield differences for continuous or pulsed (3 events spaced 4 h apart) daily SDI applications for broccoli, cowpea, green bean, muskmelon, or squash on a loamy sand in South Carolina (Camp et al., 1993). No yield or total evapotranspiration differences were observed in sweet corn with furrow, sprinkler, SDI or automated SDI, but automated, high-frequency SDI had less than 50% of the irrigation requirements of the other methods (Wendt et al., 1977). The number of seasonal irrigation events was 25 for the automated SDI system and 3 to 5 events for the other three methods. Processing-tomato yields were increased 24% by using continuous phosphorus injection and high-frequency SDI scheduled to replace each 1 mm of ET_c from lysimeter measurements compared with less-frequent, 25-mm water applications with DI on a clay loam soil (Phene et al., 1990). Tomato yields were 35% higher with daily SDI than with events every third day on a calcareous soil in Egypt (El-Gindy and El-Araby, 1996). The more frequent irrigation events resulted in wider wetting patterns and may have reduced salinity in the vicinity of the roots. However, Hanson et al. (2003b) found no yield benefit to SDI (0.2 m depth) for multiple irrigation events per day for processing tomato compared with frequencies as low as weekly on a silt loam soil in California. The phosphorous fertilizer in this study was applied preplant, and the nitrogen was applied weekly. These studies show that irrigation frequency can interact with soil characteristics and cultural practices in different ways.

Irrigation frequencies of one to seven days have had very little effect on field corn production, provided soil water was managed within acceptable stress ranges (Caldwell et al., 1994; Camp, et al., 1989; Howell et al., 1997). Irrigation water use efficiency was increased 16% by decreasing the frequency from one to seven days due to better use of precipitation in the semiarid, summer precipitation climate of Kansas (Caldwell et al., 1994). In a later Kansas study on corn with a deficit irrigation capacity of 3.8 mm/d, Lamm and Aiken (2005) found no major effect of SDI frequencies ranging from one to seven days. Irrigation frequency had an effect in only one of the three years of the study, and in that extreme drought year, the less-frequent, seven-day treatment had higher grain yield. The number of kernels/ear was greater for the less-frequent irrigation treatments in this drought year. It was hypothesized that the larger irrigation amount (i.e., 26.7 mm/7 d) for the less-frequent treatment established a larger wetted root zone, allowing for better early season ear and kernel development. Frequency of SDI under deficit irrigation also was not an important factor in cotton production on a silty clay loam in Texas (Enciso-Medina et al., 2003). There were no differences in cotton yield, quality, or gross returns related to SDI frequency, and the researchers concluded that longer periods between irrigation may allow irrigators to use less-expensive, manually operated SDI systems.

13.3.2.3. Crop response to conjunctive water and nutrient management

The combined management of water and nutrients is one of the most significant advantages of SDI. Water and nutrients can be supplied in optimum amounts to the most active part of the crop root zone, with timing appropriate for maximum plant response, while minimizing the potential for nutrient leaching. Fertilizer applications for most crops are most effective when applied at the latest possible date compatible with quick uptake by the plant. The key point is providing the fertilizer in a readily available form in the presence of the crop root system. Subsurface drip irrigation can effectively manage the placement and availability of both soil mobile and immobile nutrients.

Phosphorus fertigation with SDI increased plant nutrient uptake, root growth, or yield of tomato (Phene et al., 1990; Ayars et al., 1999), sweet corn (Bar-Yosef et al., 1989; Martinez-Hernandez, et al., 1991, Phene et al., 1991), cotton (Aloni et al., 2000), cabbage and zucchini (Rubeiz et al., 1989). Application of P through SDI accomplishes more than just placing the P at the center of the crop root zone. Continuous P fertigation allows uptake of this relatively immobile nutrient through mass flow to the plant roots rather than just the roots growing and coming in contact with fixed P within the soil profile.

Tomato yields were significantly increased on a clay loam soil when P and potassium (K) were injected with high frequency SDI, without a concurrent increase in crop water use (Fig. 13.27), thus resulting in higher water use efficiency for SDI (Phene et al., 1990). Rooting and nutrient uptake patterns were deeper with SDI and P fertigation, and similarly petiole P deficiencies occurred very early in the season for SDI when P was not injected (Ayars et al., 1999).

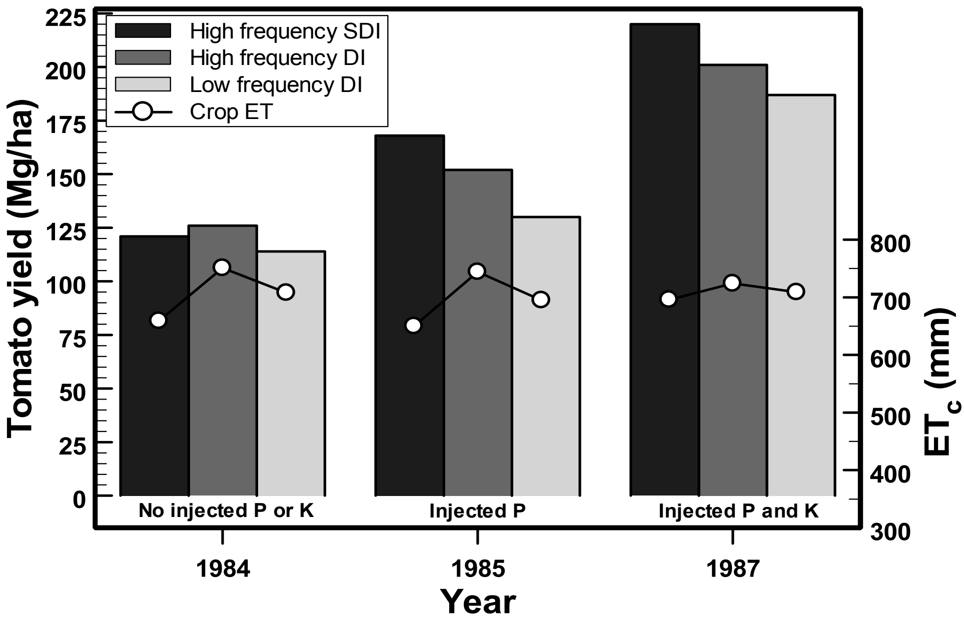

Figure 13.27. Tomato yield and crop ET as affected by irrigation system type and fertigation of macronutrients phosphorus (P) and potassium (K) on a clay loam soil. Data from Phene et al. (1990).

SDI fertigation of P moved the center of the root density to a depth of 0.3 m, compared with a depth of 0.1 m for DI (Martinez-Hernandez et al., 1991), and increased marketable sweet corn ear yield by 12%. Similar results were reported for P fertigation of sweet corn by Phene et al. (1991) who found that DI had the greatest root density in the 0 to 0.3 m depth, whereas SDI had greater root density below 0.3 m. Sweet corn yield increases of 4 to 10% were reported for SDI, compared with DI, for a range of irrigation water P concentrations from 0.04 to 1.29 mol/m^3 (Bar-Yosef et al., 1989). Total biomass P uptake was unaffected by irrigation system type, however, so the increased ear yield response with SDI was due to greater allocation of dry matter to the ear.

Similarly, nitrogen fertigation with SDI can also be beneficial in plant nutrient uptake, root growth or crop yield, and environmental protection. Some forms of N are readily leachable, so SDI can be a good tool for timely applications with precise placement in the crop root zone. Plants are capable of direct uptake of both ammonium- and nitrate-N. Ammonium-N is held on the cation exchange complex and is relatively unleachable, whereas nitrate-N is free to move with the soil water solution. The nitrogen fertilizer solution urea-ammonium nitrate (UAN, 32-0-0) is not only very water soluble for SDI injection (reduced emitter clogging hazard), but also contains approximately 25% nitrate-N, 25% ammonium-N, and 50% urea-N (reduced in the first step to ammonium-N). Subsurface drip irrigation of water containing UAN (32-0-0) supplies both the readily absorbed nitrate-N and the less mobile ammonium-N, which can be absorbed directly by the plant or microbially transformed to nitrate-N. Combined management of irrigation and anticipated rainfall has long been a necessary tool to manage nitrogen fertilization on sandy soils. An untimely rainfall event, coupled with a fully recharged soil profile, can lead to the loss of a significant portion of the soil N.

Corn grain yield, plant nitrogen uptake, and water use efficiency were not affected by the N application method (preplant surface application or in-season SDI fertigation) on a deep silt loam in Kansas (Lamm et al., 2001), but all three factors were influenced by the combined total N amount. The N application method did have an effect on the amount and distribution of total soil N and nitrate–N in the soil profile after harvest. Nearly all of the residual nitrate–N after corn harvest was within the upper 0.3 m of the soil profile for the treatments receiving only preplant–applied N, regardless of irrigation regime (75, 100, and 125% of ET_c). In contrast, the nitrate–N concentrations increased with increasing rates of N injected by the SDI system and migrated deeper into the soil profile with increased irrigation. The results suggest that N applied through an SDI system at a depth of 40 to 45 cm redistributes differently in the soil profile than the surface–applied preplant N banded in the furrow. Potential reductions in nitrogen applications with SDI while maintaining high crop yield has also been suggested for cotton (Camp et al., 1997b; Sorenson et al. 2004).

A best management practice (BMP) for SDI nitrogen fertigation for corn production on deep silt loam soils in Kansas was developed using the criteria of residual ammonium- and nitrate-N levels in the soil profile, grain yield, plant nitrogen uptake, and water use efficiency (Lamm et al., 2004). After four years of continuous, seasonal fertigation treatments (0, 90, 135, 180, 225, or 275 kg/ha.), nitrate-N concentrations in the soil profile increased and moved downward when the fertigation rate exceeded 180 kg/ha (Fig. 13.28). The higher fertigation rates of 225 and 270 kg/ha resulted in soil nitrate concentrations for some depth increments exceeding 10 mg/kg. In contrast, the lower fertigation rates had nitrate-N concentrations less than 3 mg/kg for all depths except the surface 0.15 m, which was still less than 5 mg/kg. The overall BMP included weekly application of nitrogen fertilizer solutions, with the cumulative in-season nitrogen fertigation amount not to exceed 180 kg/ha and the total applied nitrogen (fertigation, preseason applications, starter fertilizer, and naturally occurring amounts in the irrigation water) not to exceed 210 kg/ha. Also, irrigation was to be scheduled to replace approximately 75% of the calculated soil water deficit attributable to evapotranspiration. Corn grain yield, nitrogen uptake, and water use efficiency *(WUE)* all plateaued at the same level of total applied N (180 kg/ha N fertigation rate, with additional 30 kg/ha from starter fertilizer application and amounts naturally occurring in irrigation water), emphasizing that high-yielding corn production also can be efficient in nutrient and water use (Fig. 13.29).

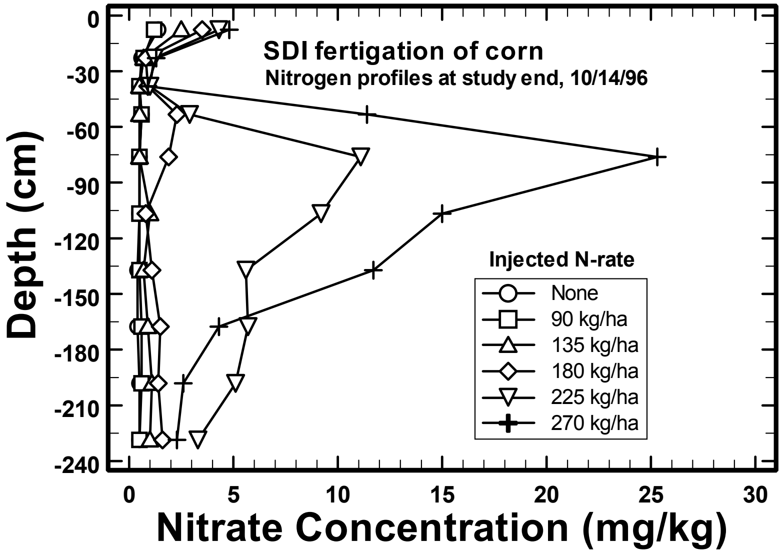

Figure 13.28. Residual nitrate-N concentrations in a deep silt loam soil profile as affected by SDI fertigation (0.45 m depth) at the conclusion (10/14-96) of a four year corn study. After Lamm et al. (2004).

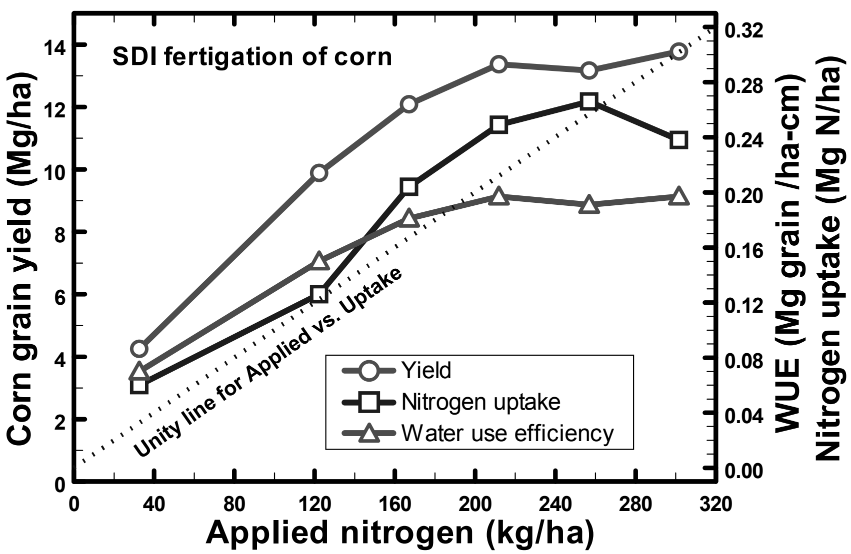

Figure 13.29. Corn grain yield, nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied N. Total applied N exceeded fertigation-applied nitrogen by 35 kg/ha. After Lamm et al. (2004).

Combined SDI and nutrient management schemes have been developed for several fruit and vegetable crops in the southwestern United States, reflecting a growing acceptance of the SDI production system in that region. The crops include watermelon (Pier and Doerge, 1995), cauliflower and broccoli (Thompson et al., 2000 and 2002), collard, mustard, and spinach greens, romaine and leaf lettuce (Thompson and Doerge 1995 a and b, 1996), and citrus (Thompson et al., 2001). The optimum response for many of these crops requires careful management of SDI and applied nitrogen. Higher irrigation water use efficiency and greater broccoli yield occurred at an intermediate irrigation regime (target root zone soil water potential of -7 kPa) under a wide range of nitrogen levels (Fig. 13.30) on a sandy loam soil in Arizona (Thompson et al., 2002).

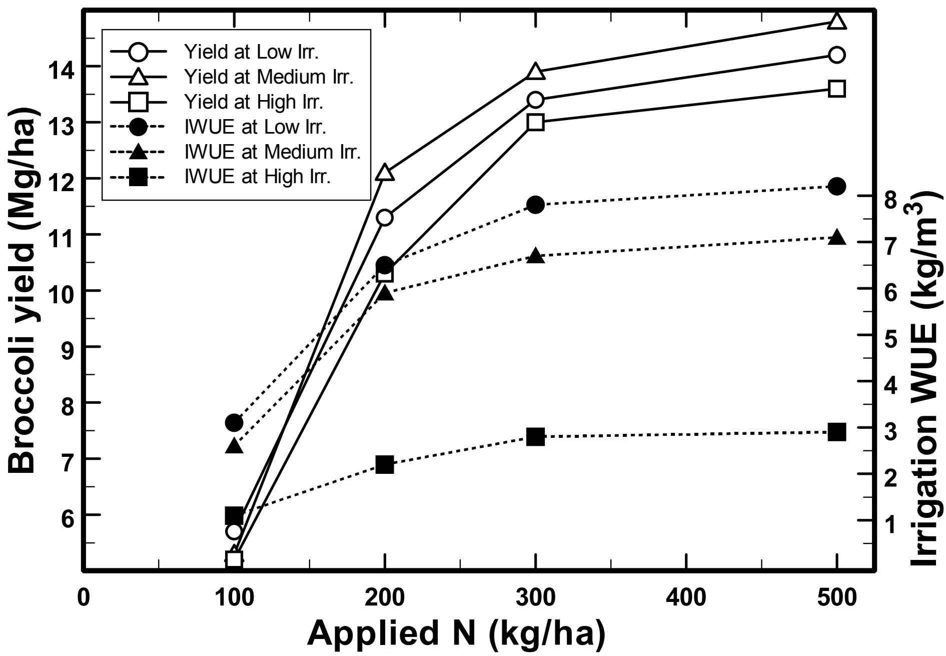

Figure 13.30. Broccoli yield and irrigation water use efficiency (yield/irrigation amount) as affected by SDI fertigation-applied N on a sandy loam soil. Data for 1994 through 1996 study years from Thompson et al. (2002).

13.4. SUMMARY

When compared with other irrigation systems, subsurface drip irrigation (SDI) has advantages and disadvantages that should be carefully considered. There are many design and management similarities to surface drip irrigation (DI), but there are also some unique differences that affect uniformity, operation, and system longevity. Factors that affect SDI uniformity are emitter clogging, root intrusion, root pinching, mechanical and pest damage, soil overburden and compaction, soil hydraulic parameters, and, possibly, system age. A typical SDI system often requires additional components, compared to DI, such as flushlines, additional air/vacuum relief valves, and pressure gauges and a flowmeter for system monitoring. Emitter flowrate and spacing, and dripline diameter, wall thickness, spacing, and depth are all important design criteria for SDI systems. Flushing of SDI driplines is also a key design criterion, and some designers prefer to begin their design with the flushing system. SDI can potentially provide a more consistent soil water and nutrient environment for optimum crop growth, but there can also be challenges in some regions, such as crop establishment, salinity management, soil water redistribution, and application of some agrochemicals. The application of SDI for some of the lower-value grain and fiber crops has been increasing, and this trend is likely to continue.

ACKNOWLEDGMENTS

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LIST OF TERMS AND SYMBOLS

BMP	best management practice
C	Hazen-Williams friction coefficient for pipe, unitless
CV	manufacturer's coefficient of variation, 0 to 100
D_d	dripline inside diameter, mm
D_f	flushline inside diameter, mm
Dv	flushline valve inside diameter, mm
DI	surface drip irrigation
DU_{lq}	lower quartile distribution uniformity, 1 to 100
ES	emitter spacing, cm
E_s	maximum anticipated soil water evaporation rate, mm/d
ET_c	crop evapotranspiration, mm/season or mm/d
EU	design emission uniformity, 1 to 100
F	multiple outlet factor, decimal fraction
FES	fully enclosed subirrigation
HDPE	high-density polyethylene
h_f	friction loss for pipeline in Hazen-Williams equation, m
ID	pipe, tubing or dripline inside diameter, mm
K	potassium
K_v	valve coefficient, 35.7 for branched or 33.4 for unbranched flushlines

K_s	soil saturated hydraulic conductivity, mm/d
L_e	maximum potential soil water evaporation loss, fraction or percent
L_f	length of flushline section, m
LSI	Langelier Saturation Index, unitless number
m	2 E_s/K_s, unitless
n	number of emitters/plant
N	nitrogen
N_d	number of driplines flowing in that branch of flushline
q_{avg}	average emitter flowrate along the dripline, L/h
q_{max}	maximum emitter flowrate along the dripline, L/h
q_{min}	minimum emitter flowrate along the dripline, L/h
q_{var}	emitter flow variation, fraction or percentage
Q_f	cumulative flowrate of all driplines flowing into a flushline section, L/s
Q_v	total flowrate through the flushline valve, L/s
P	phosphorus
PC	pressure-compensating
P_d	total downstream dripline pressure, kPa
PE	polyethylene
P_v	allowable pressure loss through the flush valve assembly, kPa
PVC	polyvinyl chloride
SAR	Sodium absorption ratio
S_d	dripline spacing, m
SDI	subsurface drip irrigation
SDR	standard dimension ratio used in pipe and tubing descriptions
SSVA	site specific variable application
UAN	urea-ammonium nitrate
UC	Christiansen's Uniformity Coefficient, 1 to 100
UV	ultraviolet radiation
V_f	dripline flushing velocity, m/s
WUE	water use efficiency (crop yield/water use), Mg/ha-mm or kg/m^3
z_d	minimum dripline depth, cm
α	inverse of the capillary length (Gardner fitting parameter), cm^{-1}

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

14. BUBBLER IRRIGATION

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"Microirrigation is well suited to regions where strong competition for water exists."

MULUNEH YITAYEW
University of Arizona, Tucson, Arizona, USA

14.1. APPLICATION AND GENERAL SUITABILITY

In bubbler irrigation, water is applied to the soil surface as a little stream, typically from a small diameter tube (1 mm to 13 mm) or a commercially available emitter. Because the application rates generally exceed the soil infiltration rates, small basins or furrows are needed to control the water distribution on the land. Although bubbler application is extensively utilized in landscape irrigation systems, its use in agriculture is currently limited. Two major types of bubbler irrigation systems are available, the low head or gravity (about 10 kPa) and pressurized (50 to 150 kPa) systems. Design procedures for gravity systems have been developed over the last several years and are relatively unique to this type of irrigation. Design of pressurized bubbler systems is similar to the procedures for most microirrigation systems as outlined in Chapter 5. While this chapter covers both bubbler types, the primary focus is on gravity systems.

Two of the first long-term, operating bubbler irrigation systems were established in citrus groves at Tacna, Arizona and Riverside, California (Rawlins, 1977). Water to the systems was supplied from irrigation canals and distributed through thin-wall, corrugated polyethylene pipe to the bubbler tubes. By adjusting the elevations of the tube outlets, the gravity pressure water flow to each tree was equalized. Despite this early experimental success, the bubbler concept has not been widely adopted in agriculture. Perhaps one of the main reasons for the lack of interest is that design criteria and recommended operating procedures have not been readily available (Yitayew et al., 1995).

Bubbler systems are well suited for perennial crops, particularly orchards and vines, because the irrigation system typically includes buried pipes and small earthen basins around the plantings. Bubbler systems can also be adapted to row crops that utilize furrows. The laterals are placed along the furrows after planting and are removed from the field following harvest. Landscapes with level typography or with a gentle, uniform slope are ideal for bubbler systems. A fine soil texture is also preferred. Bubbler systems can readily utilize low-head water supplies, similar to surface irrigation systems. The following sections outline advantages and disadvantages of bubbler systems relative to other types of microirrigation systems.

14.1.1. Advantages and Disadvantages

14.1.1.1. Potential advantages

Compared with other microirrigation systems, bubbler systems have some potential advantages:

- Energy requirements are low – While the annual required depth of water is similar for all microirrigation systems, the energy needed to apply water by gravity flow bubbler systems is typically less than for other systems. Pressures as low as 10 kPa may be adequate for bubblers, whereas pressures of between 100 to 200 kPa are typical for other microirrigation emitter types.
- Maintenance is low – Low-pressure bubbler systems use less equipment, such as filters and pumps, in the control head. Typically, chlorination and acidification are not needed unless poor water quality leads to a buildup of aquatic plants in the system.
- Susceptibility to emitter clogging is low – Compared with other microirrigation systems, both gravity and pressurized bubbler systems are not as susceptible to emitter clogging. Clearances for bubbler emission tubes are relatively large, and particulate matter is able to pass through much easier than it can for other microirrigation emitters.
- Water with higher suspended solids concentration can be used – The water quality for bubbler systems can be of a lower standard with regard to solids content than that typically needed for most microirrigation emitters. Filtration is usually not required.
- Operating costs are low – Although system hardware costs for bubbler systems are similar to those of other microirrigation systems, the operating costs for bubblers are substantially lower because of the lower energy and maintenance requirements.
- Intervals between irrigations are long – Bubbler systems utilize a basin flooding procedure and therefore the depth of water applied over the basin is typically greater than 50 mm. The frequency of irrigations is less than for other microirrigation systems, where depths of application are typically smaller.
- Duration of an irrigation event is short – Because the discharge rates for bubblers are higher than typical drip emitters (e.g., 250 L/h vs. 4 L/h), the application times to obtain a desired depth of water are considerably shorter.
- Accumulated salts are uniformly leached – The individual basins are fully flooded with the bubbler system during each irrigation, and as this uniformly applied water infiltrates into and percolates through the soil, any accumulated salts are carried downward with each irrigation.
- Bubbler basins increase catchment of rainfall – In a desert environment where precipitation is scarce and occurs primarily through infrequent large precipitation events, basins used for bubbler systems are ideal for harvesting intense rainfall and watering individual plants.

14.1.1.2. Potential disadvantages

Some potential disadvantages to bubbler systems are:

- Very few agricultural bubbler systems have been installed or are in operation – Although bubbler irrigation has been investigated periodically over the past 30 years, farmers have not adapted the technology because other irrigation systems are usually more compatible with their topographical conditions and/or cultural practices.
- Design criteria and recommended operating procedures are not well documented – Very few farms utilize bubbler systems. Therefore, the opportunity to document practices is limited. Because alternative microirrigation systems are well established and accepted by the agricultural community, there has been little incentive to pursue a technology with marginal benefits.
- Entrapment of air in the pipe network can lead to blockages – With the relatively low flowrates in gravity bubbler systems and with a natural rise in water temperature, dissolved air can come out of solution and accumulate in non-turbulent regions of the pipe network. Unless appropriate hardware is installed, entrapment of air in the pipe network can lead to air blockages in these systems.
- Farm topography needs to be nearly level – The major disadvantage for gravity bubbler systems is that the farm topography needs to be level or of a gentle, uniform slope. Minor elevation head changes result in relatively major changes in total pressure head.
- Bubblers are not suitable for sandy soils – Fine textured soils with relatively low infiltration rates enhance the rapid spread of water over the entire basin, whereas sandy soils lead to low application efficiencies because of the uneven water distribution water.
- Small earthen basins are typically required around plants – Because bubbler emitters apply relatively high rates of water, basins are needed to hold the water until it has an opportunity to infiltrate. Earthen basins require additional labor to prepare and maintain.
- Cultural practices are more difficult to perform around earthen basins – Because the earthen basins placed around the plants are relatively permanent, weed control and other mechanical operations are restricted to avoid damaging the basins.

14.2. SYSTEM DESIGN AND APPLICATION

14.2.1. Materials and Components

The layout of a bubbler system is similar to that of typical microirrigation systems with emitters, laterals, manifolds, and a control head, as described in Chapter 5. However, some basic differences exist relating to operating pressures and flowrates. System components are generally constructed from polyvinylchloride (PVC), polyethylene (PE), or other plastic compounds.

Bubbler emitters suitable for landscaping are available from a number of companies. These emitters usually incorporate orifices and deflectors of various designs for controlling discharge rates and for directing the flows. Commercial bubblers have been evaluated for use in desert landscapes (Yuan et al., 2001). The bubblers tested incorporated adjustable orifices and discharged water from 0 to 420 L/h for operating pressures up to 140 kPa. The manufacturer's coefficient of variation for the five models tested ranged from 8 to 21%, which is relatively high for microirrigation emitters. ASAE Standard EP405.1 (2000) recommends values less than 11% and suggests that values greater than 15% are unacceptable.

For agricultural applications, bubblers with long-path, small diameter polyethylene tubes have received the most attention. Plastic tubing of 1 to 5 mm diameter is customarily used for pressurized bubbler systems. The discharge rate can be modified by varying the tube length for any given pressure. Larger diameter tubing (typically 6 to 10 mm diameter) is used in gravity bubbler systems where the flowrates are controlled by adjusting the outlet elevations. Emission control is different for gravity and pressurized systems and will be reviewed separately.

14.2.1.1. Gravity system emitters

Emitters for gravity flow bubblers are unique in that they are not designed to dissipate energy, unlike those associated with the other types of microirrigation. Bubbler emitters are essentially delivery tubes for transferring water from irrigation laterals to the plants. Gravity bubbler systems operate at very low pressures (about 10 kPa) where flowrates through the delivery tubes can be altered by adjusting their outlet elevations. Because the operating head of the bubbler system is low (about 1 m head), small changes in elevations throughout the system have a large impact on discharge rates. Additionally, friction losses within the pipes and tubes affect water pressures within the system, and therefore affect discharge rates. Although discharges are usually less than 225 L/h, friction losses in the delivery tubes do affect the flowrates. These losses must be estimated and handled through proper selection of tube diameter. For small diameter, smooth pipes, the Darcy-Weisbach and Blasius equations can be combined to predict friction head loss, h_f (m), accurately in bubbler tubes (Keller and Bliesner, 1990):

$$h_f = \mathrm{K}_{\mathrm{fdw}} \frac{Q^{1.75}}{D^{4.75}} L \tag{14.1}$$

where D is the inside diameter in mm, Q is the flow within tube in L/s, L is the length of tube in m, and $\mathrm{K}_{\mathrm{fdw}} = 7.89\mathrm{x}10^5$ constant for SI units at a water temperature of 20°C.

The head loss gradient (pipe friction loss as a function of length) for a variety of pipe diameters and flows are given in Fig. 14.1. Generally, bubbler laterals are centrally situated between plant rows with delivery tubes placed on both sides of the lateral. Tube lengths can range from less than 1 m in row crops to more than 5 m for orchards.

14.2.1.2. Pressurized system emitters

Pressurized bubbler systems are similar in design to alternative microirrigation systems, and typically operate between 50 kPa and 150 kPa. The emission devices, however, have relatively high discharge rates up to 225 L/h. The lengths of the small diameter emission tubes control the rates in a manner similar to that of capillary tubes in drip irrigation. Uniformity can be achieved by adjusting the tube lengths along the lateral.

Discharge rate as a function of tube length can be derived from fundamental hydraulic principles. Energy conservation within the bubbler tube can be described by the Bernoulli's equation (see Chapter 5), as:

$$\frac{p_1}{\gamma} + z_1 + \frac{V_1^2}{2g} = \frac{p_2}{\gamma} + z_2 + \frac{V_2^2}{2g} + \sum h_f + \sum h_{ml} \tag{14.2}$$

where h_f is the friction head loss in pipes in m; h_{ml} is the minor losses at pipe fittings in m; V_1 and V_2 are the flow velocities of water in the pipe at locations 1 and 2, respectively, in m/s; p_1 and p_2 are the pressures within the pipe at locations 1 and 2, respectively, in kPa; z_1 and z_2 are the elevations of pipe at locations 1 and 2, with respect to a reference datum in m; γ is the specific weight of water, 9790 N/m^3 at 20^{o}C; and g is the gravitational constant, 9.81 m/s^2.

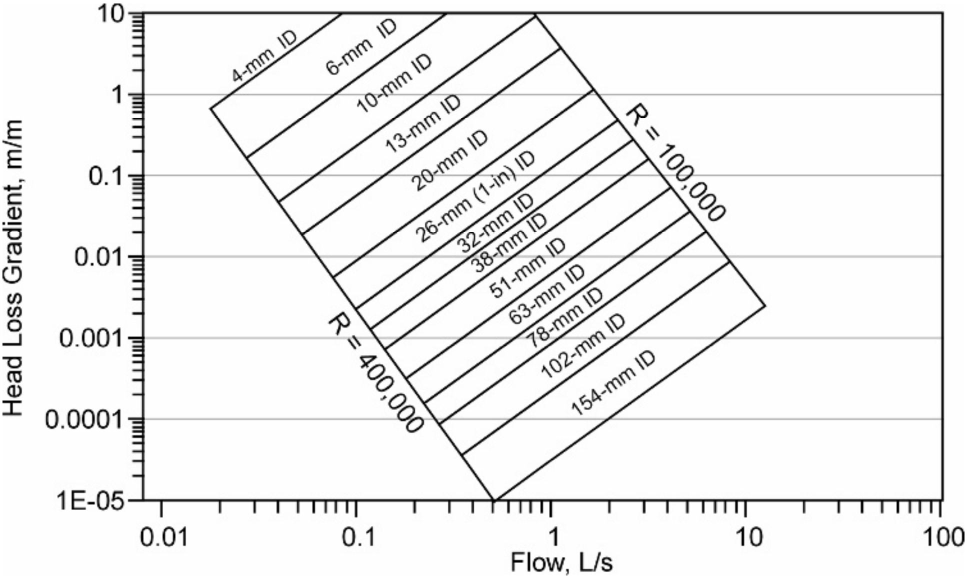

Figure 14.1. Head loss gradient for smooth (PE and PVC) pipe for Reynold's Numbers (R) between 100,000 and 400,000 and for a water temperature of 20^{o}C. Adapted from Reynolds et al. (1995).

When applying Eq. 14.2 to a bubbler tube, points 1 and 2 can be set at the entry and outlet of the tube. Several assumptions can then be made to simplify the equation, as follows: 1) minor losses (h_{ml}) are zero; 2) no elevation change along tube, $z_1 = z_2$; 3) continuity equation applies, $V_1 = V_2$; and 4) $P_2 = 0$, atmospheric pressure.

Based on the preceding assumptions and by defining the head loss, h_f, by Eq. 14.1, the following equation defines the bubbler tube discharge:

$$q_b = K_b \left(\frac{P}{L_b} \right)^{0.57} D^{2.71} \tag{14.3}$$

where q_b is the bubbler tube discharge in L/h, P is the operating pressure in kPa, L_b is the length of bubbler tube in cm, D is the diameter of bubbler tube in mm, and K_b = 5.52, a constant for units of variables as defined.

Eq. 14.3 can then be rearranged to solve for L_b, giving

$$L_b = K_l \left(\frac{D^{4.75}}{q_b^{1.75}} \right) P \qquad (14.4)$$

where K_l = 19.88 is a constant for the variables as defined in Eq. 14.3.

Discharge rates for a variety of tubing diameters and lengths are shown in Fig. 14.2 for an inlet pressure of 10 kPa. By using a computer spreadsheet program, the progressive flowrates in the lateral and respective head losses can be estimated from the distal end. The pressure gradient along a lateral is, therefore known, and the lengths of bubbler tubing can be calculated with Eq. 14.4, so that a uniform discharge can be achieved along the lateral. On level terrain, the lengths of bubbler tubing would decrease with the corresponding pressure reduction from the inlet to the distal end of the lateral. The required lengths of 2 mm (Fig. 14.3) and 3 mm (Fig.14.4) diameter tubings for the desired discharge rates can be obtained according to the inlet pressures.

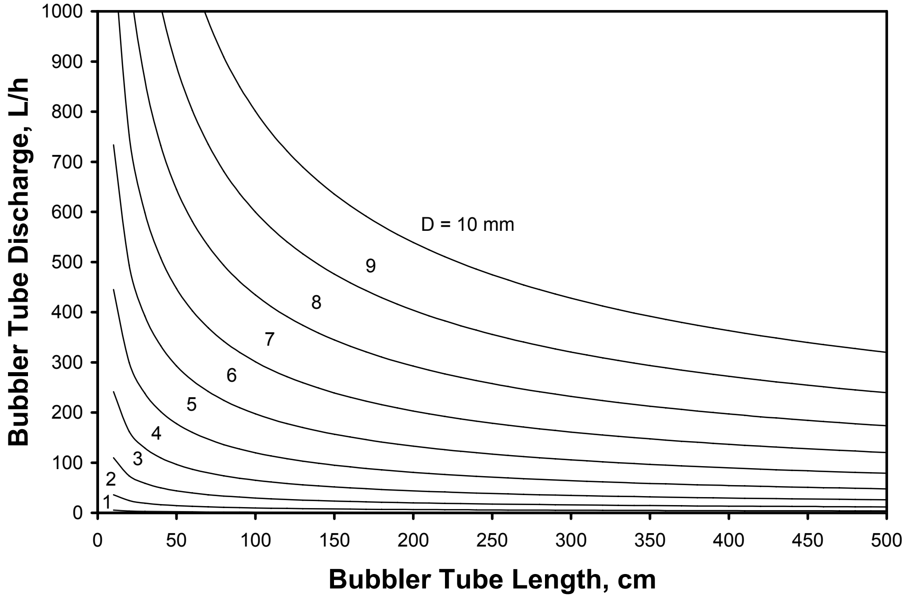

Figure 14.2. Bubbler tube discharge as a function of tube length (10 cm to 500 cm) and diameter, D, (1 mm to 10 mm) at 10 kPa.

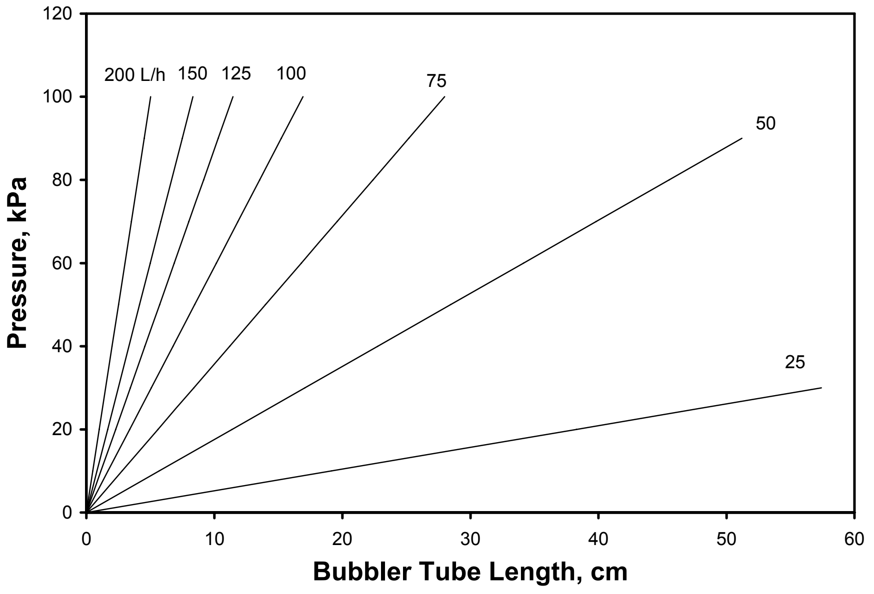

Figure 14.3. Required length of 2-mm tubing for desired discharge rate (L/h) according to the inlet pressure.

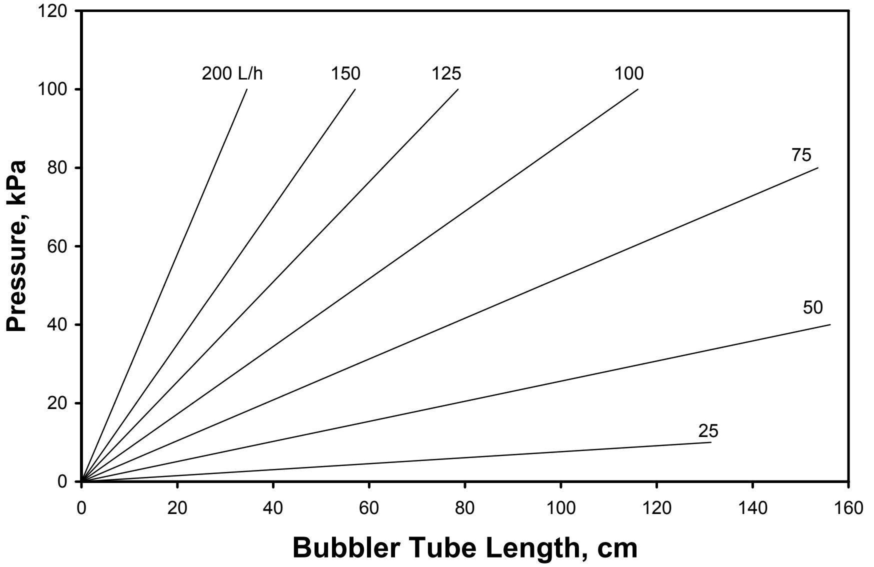

Figure 14.4. Required length of 3-mm tubing for desired discharge rate (L/h) according to the inlet pressure.

14.2.1.3. Laterals and manifolds

Laterals and manifolds for bubbler systems are typically constructed from smooth PVC and/or corrugated PE pipe. Due to the relatively high emission discharge rates, however, the diameters of laterals and manifolds are generally larger and/or their lengths are shorter than those in other microirrigation systems. For typically sized lateral and manifold PVC pipes used in bubbler systems, the Hazen-Williams equation is used for predicting friction head loss, h_f (m), as a function of flowrate, pipe length, and pipe diameter. The following Hazen-Williams equation is very similar to the Darcy-Weisbach derived equation (Eq. 14.1) used for small diameter bubbler tubes:

$$h_f = \mathrm{K}_{\mathrm{fhw}} \frac{Q^{1.85}}{D^{4.87}} L \tag{14.5}$$

where D is the inside pipe diameter in mm, Q is the inlet flowrate in L/s, L is the length of pipe in m, and $\mathrm{K}_{\mathrm{fhw}} = 1.135\text{x}10^6$, a constant for SI units at 20°C.

As described in Chapter 5, the Christiansen reduction coefficient, F, can be applied to Eq. 14.5 to account for head loss in pipes that discharge their flow uniformly along the pipe's length via laterals and manifolds. Reduction coefficients are listed in Tab. 14.1. Depending on the location of the first outlet relative to the lateral's inlet, either F_1, F_2, or F_3 is selected. F_1 is used when the distance from the lateral inlet to the first outlet is S_b. F_2 is used when the first outlet is adjacent to the lateral inlet. F_3 is used when the distance from the lateral inlet to the first outlet is $S_b/2$. With minor modification to Eq. 14.5, taking into account the outlets for the bubbler tubes, the following equation gives the total head loss for a lateral or manifold, with the same notation as described earlier:

$$h_f = \mathrm{K}_{\mathrm{fhw}} F \frac{Q^{1.85}}{D^{4.87}} L \tag{14.6}$$

Because of its relatively low cost, corrugated PE pipe can also replace PVC pipe for low-pressure systems. Friction head loss, however, is greater for the corrugated PE, and the values presented in Fig. 14.1, which were established for smooth pipes, are not applicable. According to Hermsmeier and Willardson (1970), the friction head loss equation for corrugated plastic pipe for a water temperature of 20°C is

$$h_f = \mathrm{K}_{\mathrm{p}} \frac{Q^2}{D^5} L \tag{14.7}$$

where h_f is the friction head loss in m, D is the inside diameter in mm, Q is the flow within pipeline in L/s, L is the length of pipeline in m, and $\mathrm{K}_{\mathrm{p}} = 5.78\text{x}10^6$, a constant for units of variables as defined. The friction loss gradient for corrugated plastic pipe, h_f/L, as calculated in Eq. 14.7, is presented in Fig. 14.5 for pipe diameters between 51 mm and 204 mm and flowrates between 0.2 L/s and 100 L/s. Laterals and manifolds are sized according to the allowable friction loss in the system, by taking into account the reduction coefficient, F, as described in Eq. 14.6 and Tab. 14.1.

Table 14.1. Coefficients of F for plastic pipe. F_1 is used when the distance from the lateral inlet to the first outlet is S_b. F_2 is used when the first outlet is adjacent to the lateral inlet. F_3 is used when the distance from the lateral inlet to the first outlet is $S_b/2$. Adapted from Benami and Ofen (1984).

Number of outlets	F_1	F_2	F_3
5	0.469	0.337	0.410
10	0.415	0.350	0.384
12	0.406	0.352	0.381
15	0.398	0.355	0.377
20	0.389	0.357	0.373
25	0.384	0.358	0.371
30	0.381	0.359	0.370
40	0.376	0.360	0.368
50	0.374	0.361	0.367
100	0.369	0.362	0.366

Selection of pipe size for the manifold is to a large extent an economic decision, which involves balancing friction losses against various economic factors. One common method of pipe size selection is the "percent head loss method," where the allowable friction loss in the manifold is limited to 5 to 20% of the irrigation system's design head, H_d, (Keller and Bliesner, 1990). In practice, both the 5 and 20% conditions are often calculated, and the final decision is based on the calculated results and on additional factors such as price differences, availability, installation, maintenance requirements, and end-user preferences. The allowable friction loss in the manifold, h_{fam}, may then be expressed by the following equation for either 5% or 20% of the irrigation system's design head:

$$h_{fam} = \frac{(5\% \, or \, 20\%)}{100} H_d \tag{14.8}$$

The allowable headloss gradient in the manifold is then expressed as

$$h_f / L = h_{fam} / (F \bullet L_m) \tag{14.9}$$

where L_m is the length of the manifold in m and the remaining variables have been defined.

In addition to friction loss in pipes, the slope of the field is a variable to consider in designing laterals and manifolds. Elevation differences are especially critical to gravity systems because minor changes in elevation head may have a significant effect on pressures within the system.

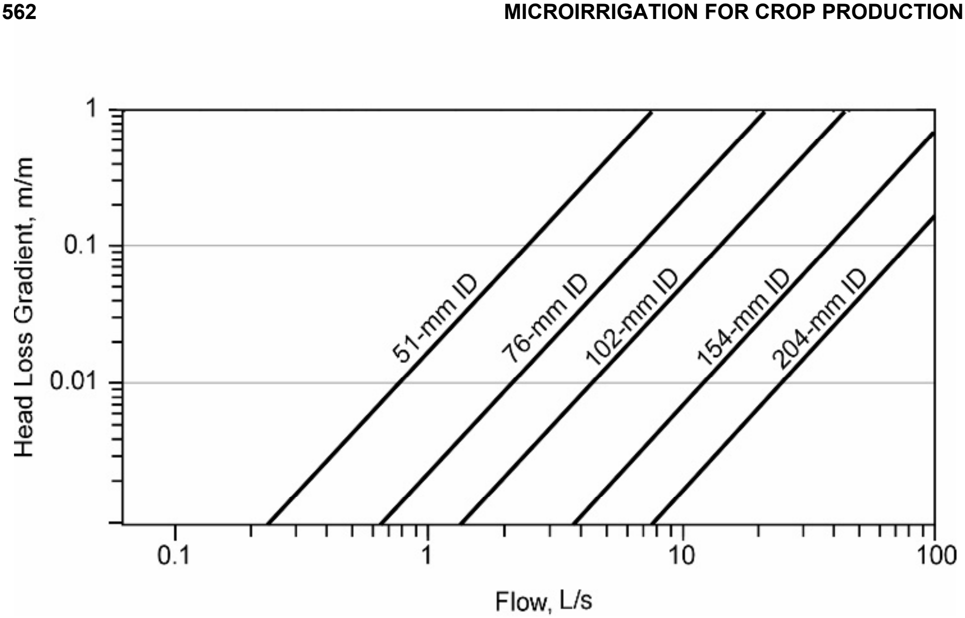

Figure 14.5. Head loss gradient for corrugated PE pipe, water temperature at 20^{o}C. Adapted from Reynolds et al. (1995).

Additional considerations for bubbler systems include equipment in the control head and air release hardware in gravity flow networks. Clogging of bubbler tubes in low-pressure systems is usually not a concern because tube openings are relatively large, 6 mm to 10 mm diameters. Filters are usually not required for such systems. In high-pressure systems that use 1 mm to 4 mm diameter emission tubes, 80 mesh screen filters are recommended. Injection hardware for fertilizers and other chemicals may also be incorporated in bubbler systems.

For gravity bubbler systems, a constant head device is required when the water source (reservoir or canal) is not maintained at a constant elevation. A constant head device (e.g., standpipe and gate valve) can be installed near the water source or elsewhere along the mainline to maintain a constant design head during bubbler operation. For a pressurized system, a pump in the control head is selected based on the desired flowrate and system inlet pressure. The pump should have a high operating efficiency and conform to the general desirable criteria presented in Chapter 5.

Air locks may occur in pipelines of low-pressure gravity systems when air accumulates at the crest of pipe undulations. These air pockets can absorb a significant amount of energy and may partially or entirely block the flow of water. Although air relief valves may be installed throughout the system, a more cost effective procedure is to maintain pipe velocities greater than 0.3 m/s (Reynolds and Yitayew, 1995). At these velocities, water turbulence prevents air accumulation in the pipes. Therefore, emission tubes less than 13 mm in diameter are recommended for these hydraulic conditions to be achieved under low-pressure operation. From empirical data, the following equation can be used to calculate the minimum pipe flowrate to prevent air locks in both types of bubbler systems:

$$Q = K_a D^{2.45} \tag{14.10}$$

where D is the inside diameter of the pipeline in mm, Q is the flow within pipeline in L/s, and K_a is equal to 0.0001, a constant for units of variables as defined (Reynolds and Yitayew 1995).

Once the system is installed, the discharge rate from each bubbler is measured, the tube's outlet elevation is adjusted up or down to attain the desired flow, and the tube is then secured to a stake or other support. This dynamic calibration, described in detail by Rawlins (1977), is a procedure by which errors in friction loss calculations can be evenly distributed along the lateral.

14.2.1.4. System design procedures

The design of pressurized bubbler systems uses procedures that are similar to those identified in Chapter 5 for general microirrigation systems. One major difference between design of bubblers and other microirrigation systems is that the design flowrates are assumed at the beginning of the design because bubbler flows are typically larger than the soil infiltration rates so that water is distributed quickly across the basin. However, for low pressure gravity systems, a different approach is used because the water source and field topography/geometry are critical factors that must be considered initially. Procedures in gravity flow bubbler system design are as follows:

1. Determine field layout.
2. Design constant head device.
3. Identify bubbler tube locations and desired discharge rates.
4. Calculate length and number of manifolds, laterals, and bubbler tubes.
5. Calculate design flowrates for mainline, manifolds, and laterals.
6. Select diameters of mainline, manifolds, laterals, and bubbler tubes.
7. Calculate bubbler tube elevations.
8. Plot piezometric diagram.

14.3. SAMPLE DESIGN—LOW HEAD BUBBLER SYSTEM

A low head bubbler design is given in Example 14.1.

Example 14.1

Design a bubbler system to irrigate a citrus orchard with tree spacings of 6 m x 6 m. The field is level and has dimensions of 120 m x 96 m, as shown in Fig. 14.6. The water source is from a low-head pipeline that discharges water into an irrigation standpipe, located midway along the edge of the field. Water pressure in the pipe maintains the water surface in the standpipe at 1 m above ground level.

For this example, the maximum and minimum bubbler tube elevations, relative to the ground surface, are assumed to be 1 m and 0.3 m, respectively. To minimize lateral friction loss, the first bubbler tube on each lateral will be located one-half emitter spacing from the manifold.

Step 1: Determine field layout.

According to Fig. 14.6, the water source is located at one end of the field, from which a manifold is installed. Laterals extend the entire length of the field from the manifold. The following information is known:

Field length, $L_f = 120$ m
Field width, $W_f = 96$ m
Field slope, $\Delta El_L = \Delta El_W = 0$ (length and width, respectively)

Step 2: Design constant head device.

The standpipe and gate valve assembly will provide a constant water pressure to the system, as follows:

Design head, $H_d = 1.0$ m

Step 3: Identify bubbler tube locations and desired discharge rates.

Given:

Tree spacing, $S_p = 6$ m (plant spacing within row), $S_r = 6$ m (row spacing)
Maximum bubbler tube elevation head, $H_{max} = 1.0$ m
Minimum bubbler tube elevation head, $H_{min} = 0.3$ m

To minimize hardware costs, each lateral serves two rows of trees. The lateral is buried at a depth of 0.5 m, midway between the two rows, as shown in the figure, and bubbler tubes extend on both sides of the trees. These two spacings are defined as:

Bubbler tube spacing, $S_b = S_p = 6$ m
Lateral spacing, $S_l = 2S_r = 12$ m
Depth of lateral, $d_l = 0.5$ m

As is common in bubbler systems, a bubbler discharge rate is assumed and the pipe network is designed accordingly. In this case, the discharge rate is assumed to be:

Design bubbler discharge rate, $q_b = 180$ L/h or 0.05 L/s

Step 4: Calculate length and number of manifolds, laterals, and bubbler tubes.

Length of pipes:

The length of the manifold, L_m, is calculated by dividing the field in half and subtracting two row spacing halves as:

$$L_m = (W_f/2)-(2S_r/2) = 96/2 - (2)(6)/(2) = 42 \text{ m}$$

The length of each lateral, L_l, extends the length of the field, minus one plant spacing half:

$$L_l = L_f - (S_p/2) = 120 - 6/2 = 117 \text{ m}$$

The required total number of laterals, N_l, is one-half the number of plant rows:

$$N_l = (1/2)(W/S_r) = (1/2)(96/6) = 8$$

The length of each bubbler tube, L_b, spans one-half the row spacing, plus the buried depth of the lateral and the tube's elevated height adjacent to the plant:

$$L_b = [(S_r/2) + d_l + H_{max}] = [(6/2) + 0.5 + 1] = 4.5 \text{ m}$$

The required number of bubbler tubes per lateral, N_e, matches the total number of plants served by each lateral:

$$N_e = 2L_f / S_e = 2(120)/6 = 40$$

The total number of trees, N_t, relates to the total number of bubbler tubes:

$$N_t = (N_e)(N_l) = (40)(8) = 320$$

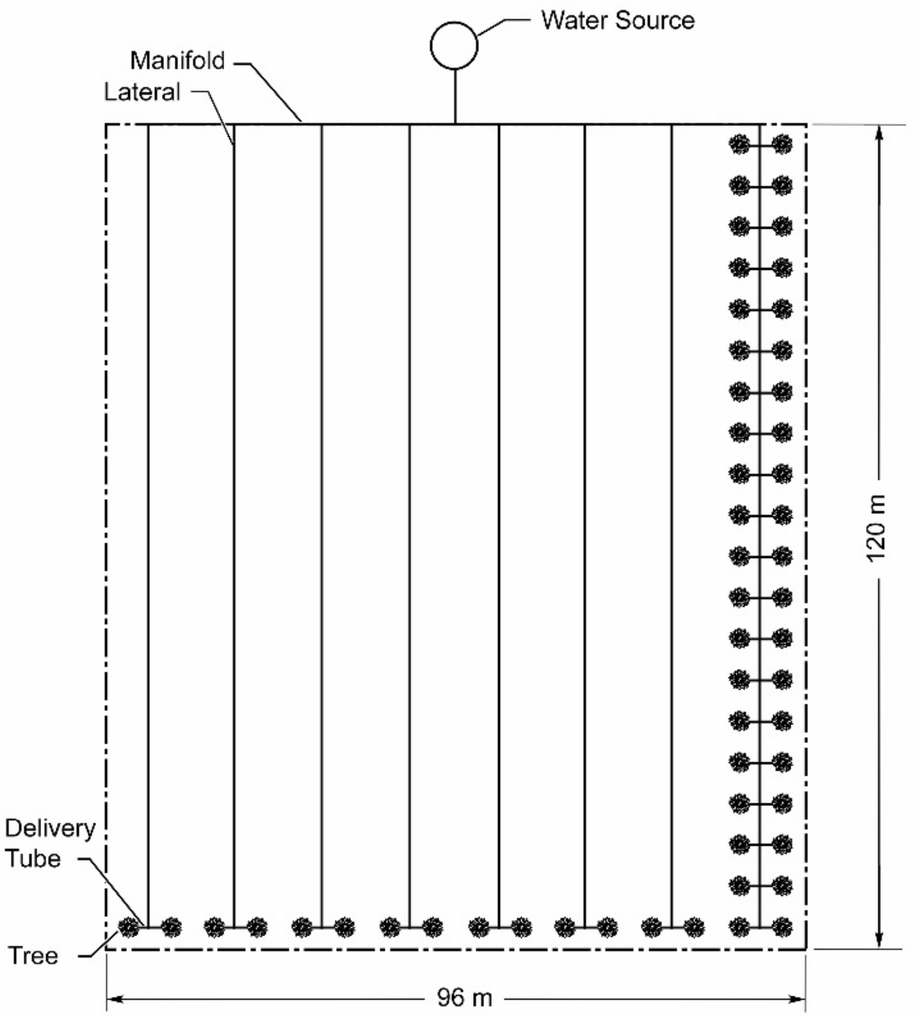

Figure 14.6. Field layout for sample design of a bubbler irrigation system on level terrain. The citrus trees are planted in a square grid with 6 m spacings. The first row of trees begins 3 m from the orchard boundary.

Step 5: Calculate design flowrates into mainline, manifolds, and laterals.

Flowrate into each lateral, Q_l is :

$$Q_l = (q_b)(N_e) = (0.05)(40) = 2.0 \text{ L/s}$$

Flowrate into each manifold, Q_m is:

$$Q_m = (Q_l)(N_l/2) = (2.0)(8/2) = 8.0 \text{ L/s}$$

Flow into mainline, Q is:

$$Q = (q_b)(N_l) = (0.05)(320) = 16.0 \text{ L/s}$$

Step 6: Select diameters of mainline, manifolds, laterals, and bubbler tubes.

Mainline diameter: This particular example does not have a mainline because the source of water in the standpipe is located adjacent to the manifold. If a mainline is required, however, the diameter would be sized to carry the system design capacity flow at a maximum velocity of 0.6 m/s. The design head is then determined by subtracting the mainline friction head loss from the available head.

Manifold diameter: Using the percent head loss method of pipe size selection, as described by Eq. 14.8, the two conditions of allowable head loss in the manifold, h_{fam}, are:

$$h_{fam} = 0.20\,H_d = (0.20)(1.0) = 0.20 \text{ m—(20\% design head) or}$$

$$h_{fam} = 0.05\,H_d = (0.05)(1.0) = 0.05 \text{ m—(5\% design head)}$$

From Tab. 14.1 the Christiansen reduction coefficient, F_1, is 0.41 for four outlets, with the first outlet spaced one-half spacing from the lateral inlet. By substituting the preceding values into Eq. 14.10, the manifold head loss gradients become:

$$h_f/L = h_{fam}/(F)(L_m) = (0.20)/(0.41)(42) = 0.012\text{—(20\% design head) or}$$

$$h_f/L = h_{fam}/(F)(L_m) = (0.05)/(0.41)(42) = 0.003\text{—(5\% design head)}$$

From Fig. 14.5, the manifold head loss gradients with a flow of 8.0 L/s indicate a manifold diameter, D_m:

D_m *= 154-mm, corrugated PE pipe—(20% design head) or*

D_m *= 204-mm, corrugated PE pipe—(5% design head)*

From Fig. 14.1, the manifold head loss gradients with a flow of 8.0 L/s give:

D_m *= 102-mm, PVC pipe—(20% design head) or*

D_m *= 154-mm, PVC pipe—(5% design head)*

Because the cost of 102-mm PVC pipe is approximately the same as the 154-mm corrugated PE pipe, and the cost of 154-mm PVC pipe is approximately the same as the 204-mm corrugated PE pipe, there is no cost advantage in corrugated PE versus PVC. The PVC pipe, however, is preferred because PVC pipe fittings are more readily available and fewer problems are likely with PVC pipe than with corrugated PE pipe. The decision of whether to use 5% or 20% of the design head as the allowable head loss *in the manifold depends on the overall costs of the two systems. One advantage in using 5% of the design head is that the total manifold head loss is small and can be neglected. This would reduce the number of bubbler tube computations by eight-fold because the inlet pressures at all eight laterals will be assumed equal. For this example the 154-mm PVC pipe (5% of the design head) is chosen, simply to reduce the subsequent number of bubbler tube calculations.*

Lateral and bubbler tube diameters: Sizing the diameters of laterals and bubbler tubes is the most critical aspect in bubbler system design. These diameters must be determined because a tradeoff exists between the sizes of the two components.

The allowable head loss for the lateral and bubbler tube assembly, h_{fa}, is based on the difference between the lateral inlet pressure, H_l, and the minimum bubbler tube elevation, H_{min}, and the field slope, ΔEl_L, as follows:

$$h_{fa} = H_l - H_{min} - \Delta El_L$$

For this example the pressure loss in the manifold is negligible, so that $H_l = H_d = 1.0$ m. Additionally, there is no slope in the field and $\Delta El_L = 0$.

$$h_{fa} = 1.0 - 0.3 - 0 = 0.7 \text{ m}$$

It is a reasonable practice when designing bubbler systems for level fields to divide the total allowable head loss equally between the laterals and bubbler tubes. Therefore, when sizing the diameters of laterals and bubbler tubes, the allowable friction head losses in laterals, h_{fal}, and bubbler tubes, h_{fab}, should each be set equal to 50% of h_{fa}.

$$h_{fal} = h_{fab} = 0.5\, h_{fa} = 0.5\,(0.7) = 0.35 \text{ m}$$

The Christiansen reduction coefficient is 0.368 for 40 multiple outlets with one-half spacing for the first outlet (Tab. 14.1). By substituting the above values into Eq. 14.9, the head loss gradients for laterals, $(h_f/L)_l$, and bubbler tubes, $(h_f/L)_b$, are:

$$(h_f/L)_l = h_{fa}/FL_l = 0.35/(0.368)(117) = 0.008$$
$$(h_f/L)_b = 0.35/4.5 = 0.08$$

and the design flowrates are:

$$Q_l = 2.0 \text{ L/s}$$
$$q_b = 180 \text{ L/h } (0.05 \text{ L/s})$$

From Fig. 14.1, the following diameters for laterals, D_l, and bubbler tubes, D_b, are obtained:

$$D_l = 63 \text{ mm}$$
$$D_b = 10 \text{ mm}$$

Step 7: Calculate bubbler tube elevations.
After the lateral and bubbler tube diameters have been determined, the elevations of the bubbler tubes are calculated by computer spreadsheet and tabulated (Tab. 14.2).

Table 14.2. Bubbler tube elevation tabulation for lateral located on field edge of the sample design, as illustrated in Fig. 14.6.

Outlet/ section (I,f) (1)	Flow Qj (L/s) (2)	Section length Lj (m) (3)	Total length (Ll)j (m) (4)	Ground elev. (z)j (m) (5)	Lateral F/loss (hlat)j (m) (6)	Lateral HGL (HGL)j (m) (7)	Tube F/loss (hdh)i (m) (8)	V/Head + Minor losses (m) (9)	Total losses (hl)i (m) (10)	Tube HGL (HGL)i (m) (11)	Tube elev. (z) (m) (12)	Refer datum (y) (m) (13)
0						1.000						0.00
1	2.00	3	3	0.0	0.020	0.980	0.337	0.037	0.394	0.61	0.61	-0.39
2	1.90	6	9	0.0	0.037	0.942	0.337	0.037	0.431	0.57	0.57	-0.43
3	1.80	6	15	0.0	0.034	0.908	0.337	0.037	0.465	0.53	0.53	-0.47
4	1.70	6	21	0.0	0.031	0.877	0.337	0.037	0.496	0.50	0.50	-0.50
5	1.60	6	27	0.0	0.028	0.850	0.337	0.037	0.524	0.48	0.48	-0.52
6	1.50	6	33	0.0	0.025	0.825	0.337	0.037	0.549	0.45	0.45	-0.55
7	1.40	6	39	0.0	0.022	0.803	0.337	0.037	0.571	0.43	0.43	-0.57
8	1.30	6	45	0.0	0.019	0.784	0.337	0.037	0.590	0.41	0.41	-0.59
9	1.20	6	51	0.0	0.017	0.767	0.337	0.037	0.607	0.39	0.39	-0.61
10	1.10	6	57	0.0	0.014	0.752	0.337	0.037	0.621	0.38	0.38	-0.62
11	1.00	6	63	0.0	0.012	0.740	0.337	0.037	0.633	0.37	0.37	-0.63
12	0.90	6	69	0.0	0.010	0.730	0.337	0.037	0.643	0.36	0.36	-0.64
13	0.80	6	75	0.0	0.008	0.722	0.337	0.037	0.651	0.35	0.35	-0.65
14	0.70	6	81	0.0	0.007	0.715	0.337	0.037	0.658	0.34	0.34	-0.66
15	0.60	6	87	0.0	0.005	0.710	0.337	0.037	0.663	0.34	0.34	-0.66
16	0.50	6	93	0.0	0.004	0.707	0.337	0.037	0.667	0.33	0.33	-0.67
17	0.40	6	99	0.0	0.002	0.704	0.337	0.037	0.669	0.33	0.33	-0.67
18	0.30	6	105	0.0	0.001	0.703	0.337	0.037	0.671	0.33	0.33	-0.67
19	0.20	6	111	0.0	0.001	0.702	0.337	0.037	0.671	0.33	0.33	-0.67
20	0.10	6	117	0.0	0.000	0.702	0.337	0.037	0.671	0.33	0.33	-0.67

Chosen lateral diameter = 63 mm; Lateral inlet flow = 2.00 L/s; Bubbler tube diameter = 10 mm; Bubbler tube discharge = 180 L/h (0.05 L/s)

Check of results: *Sum of column (6) = 0.298*

Estimated lateral friction loss, $F(h_f) = (0.36)\ (76900000)\ (117/100)\ (1.6900^{1.75}) / (63^{4.75}) = 0.30$

Summation of column (6) = estimated total lateral head loss —OK.

Check if bubbler tube heights are between 0.3 m and 1.0 m —OK.

Step 8: Plot piezometric diagram.

From column (12) of Tab. 14.2, the bubbler tube elevations are between the maximum and minimum delivery hose elevations. A piezometric diagram for the laterals and the bubbler tubes is constructed from Tab. 14.2 by plotting columns (5), (7), and (11) on the lateral elevation profile, as shown in Fig. 14.7.

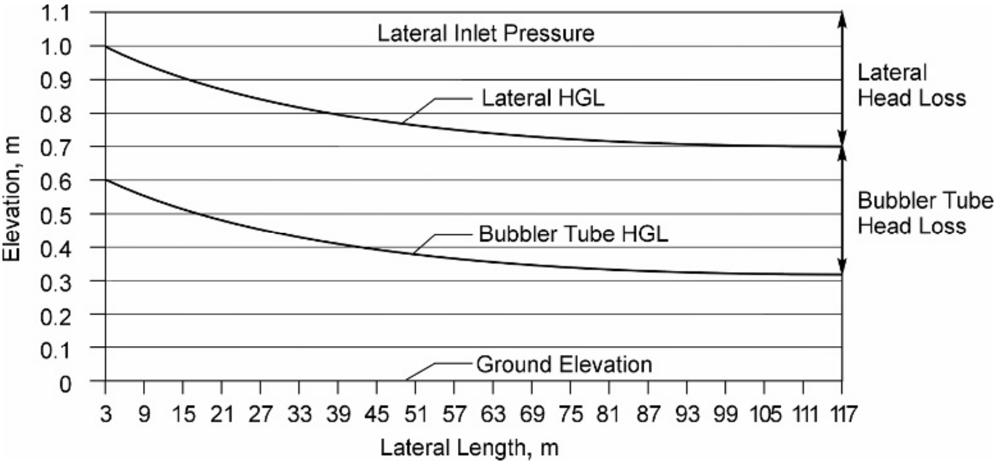

Figure 14.7. Piezometric pressure diagram for the sample design of a bubbler irrigation system on level terrain.

14.4. MANAGEMENT, EVALUATION, AND MAINTENANCE

14.4.1. Soil Issues

Because discharge rates from bubblers typically exceed the infiltration rates of soils, small basins are usually built around the plants to distribute the water uniformly over the root zone. In orchards, basins can be easily adapted to the needs of the growing trees. When young trees are first planted the root volume is small and water demand is low. A small basin around the tree is sufficient. As the trees grow and their roots expand, the basins can be increased in size to supply more water to the entire root area. The key to attaining high efficiency and uniformity is to get the water over the entire basin as rapidly as possible so that the difference in infiltration opportunity time is small for all areas of the basin. As a guide, the flowrate must be large enough to cover the entire basin in approximately 60 to 75% of the time required for the desired amount of water to infiltrate into the soil. The soil texture, which affects the infiltration rate, is a major factor in determining the maximum size of a basin for a given bubbler discharge rate. Thus, infiltration tests should be conducted in the field before the bubbler system is designed.

The irrigation application time does not have to be determined at the beginning of the design, as is required for sprinkler and alternative microirrigation systems, because bubbler flows are larger than the infiltration rates of the soil and greater than the water requirements of the plants. Bubbler systems tend to operate less frequently and for shorter periods of time than sprinkler or alternative microirrigation systems.

The time that water flows into a basin (inflow time) is usually selected to allow the desired irrigation depth/volume to be applied. After determining the anticipated bubbler discharge rate, inflow time can be calculated using Eq. 14.11:

$$T_i = \mathrm{K_t} \frac{(I)(A_B)}{q_b} \tag{14.11}$$

where T_i is the inflow time in h, I is the desired depth of application in mm, A_B is the area of the basin in m^2, q_b is the bubbler tube discharge in L/h, and $\mathrm{K_t} = 0.001$, a constant for units of variables as defined.

With continuous flooding of a basin, downward movement of accumulated salts can be obtained with each irrigation. For those regions where salinity is a concern, the desired depth of application could contain an additional leaching fraction as described by Keller and Bliesner (1990). If a basin is of sufficient size (i.e., larger than the crop canopy size), salinity in the root zone of the plants can be controlled more easily than with other pressurized irrigation systems.

14.4.2. Crops

Bubbler systems are well suited for orchards and vineyards where small earthen basins can be constructed to control the water within the root zone. Because the irrigation supply pipes are usually buried with bubbler tubes emerging at each plant, bubbler systems are better suited for perennial plantings than annual crops. Also, because irrigations are typically less frequent than for other microirrigation methods, deep-rooted and closely spaced plants are most ideal. Some plants suffer when they undergo long periods in water or very wet soil. When the plants are susceptible to injury from wet conditions and when the soil conditions lead to low infiltration rates, a raised bed surrounding the plant trunk within the basin is recommended.

Scheduling for bubbler systems is similar to that used for alternative microirrigation systems, as described in Chapter 3. However, it is important to assess deep percolation because application rates are relatively high for bubbler systems. Uniformity of coverage over the entire basin is critical when calculating the maximum volume of water that can be safely stored in the root zone.

14.4.3. Evaluation and Maintenance

The basic evaluation and maintenance procedures outlined in Chapters 10 and 11 are also applicable to bubbler systems. The openings of bubbler emission tubes are relatively large, however, and clogging is less of a concern than for alternative microirrigation systems. Thus, low- pressure bubbler systems require less support equipment, such as filters, chemical injectors and pumps, in the control head. Chlorination and acidification are usually not required, unless poor water quality causes a buildup of aquatic plants in the system. In such instances, periodic chlorination is recommended.

Maintenance primarily focuses on the physical conditions of the pipe network. Rodent damage to plastic pipes needs to be monitored. Discharge rates from selected bubbler tubes should be monitored annually. The selected tubes should be located at various points throughout the network to include several where the system pressures are the lowest.

As mentioned earlier, water that contains some suspended solids may be used in bubbler systems, but fine particle buildup may occur in the pipelines. Therefore, at the beginning of each new irrigation season, the pipes should be flushed. A flushing velocity of about 1.5 m/s is recommended. If this is not possible due to the hydraulic characteristics of the system, then velocities approaching 1.5 m/s can be achieved by closing some of the laterals to redirect the flow through a smaller number of laterals.

Reliable basins around the plants are critical to the efficiency and operation of bubbler systems. Any damage to the perimeter dikes caused by tractor implements, erosion, animals, or other physical causes should be immediately repaired. Typically, the distal ends of bubbler tubes are secured to stakes, so that their elevations are accurately fixed. Routine inspection of these assemblies is important. For example, an increase in pressure head within the tube, due to detachment from an elevated to a lower position on a stake can lead to a substantial increase in discharge rate (see Eq. 14.3).

LIST OF TERMS AND SYMBOLS

A_B	Area of bubbler basin, m^2
d_l	Depth that lateral is buried , m
D	Inside diameter of pipe or bubbler tube, mm
D_b	Inside diameter of bubbler tube, mm
D_l	Inside diameter of lateral, mm
D_m	Inside diameter of manifold, mm
F	Christiansen reduction coefficient, decimal
g	Gravitational constant, 9.81 m/s^2
h_f	Friction head loss in pipe or bubbler tube, m
h_{fa}	Allowable head loss for the lateral and bubbler tube assembly, m
h_{fab}	Allowable friction head loss in bubbler tube, m
h_{fal}	Allowable friction head loss in lateral, m
h_{fam}	Allowable friction head loss in manifold, m
h_{ml}	Minor friction losses by pipe fittings, m
H_d	Design head for system, m
H_{max}	Maximum bubbler tube elevation head, m

H_{min}	Minimum bubbler tube elevation head, m
I	Desired depth of application, mm
K_a	Friction constant, 0.0001 for SI units at a water temperature of 20^{o}C
K_b	Friction constant, 5.52 for SI units at a water temperature of 20^{o}C
K_{fdw}	Friction constant, 7.89 x 10^5 for SI units at a water temperature of 20^{o}C
K_{fhw}	Friction constant, 1.135 x 10^6 for SI units at a water temperature of 20^{o}C
K_l	Friction constant, 19.88 for SI units at a water temperature of 20^{o}C.
K_p	Friction constant, 5.78 x 10^6 for SI units at a water temperature of 20^{o}C
K_t	Time constant, 0.0001 for SI units
L	Length of pipe, m
L_b	Length of bubbler tube, m
L_f	Length of field, m
L_l	Length of lateral, m
L_m	Length of manifold, m
N_e	Number of bubbler tubes per lateral
N_l	Total number of laterals
N_t	Total number of trees
P	Pressure, kPa
p_1 and p_2	Pressures within a pipe at locations 1 and 2, kPa
q_b	Bubbler tube discharge rate, L/h or L/s
Q	Flowrate in pipe, L/s
Q_l	Flowrate into a lateral, L/s
Q_m	Flowrate into a manifold, L/s
S_b	Spacing of bubbler tubes along lateral, m
S_l	Spacing of laterals, m
S_p	Spacing of plants along lateral, m
S_r	Spacing of plant rows, m
T_I	Basin inflow time, h
V_1 and V_2	Flow velocities of water in a pipe at locations 1 and 2, m/s
W_f	Width of field, m
z_1 and z_2	Elevations of pipe at locations 1 and 2, m
ΔEl_L , ΔEl_W	Field slope in length (L) and width (W) directions, decimal
γ	Specific weight of water, 9790 N/m^3 with a water temperature of 20^{o}C

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Microirrigation for Crop Production
F.R. Lamm, J.E. Ayars and F.S. Nakayama (Editors)

15. MICROSPRINKLER IRRIGATION

BRIAN J. BOMAN
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"Hasty design results in years of headaches."

15.1. APPLICATION AND SUITABILITY OF MICROSPRINKLERS

Microsprinkler systems are primarily used to irrigate tree and vine crops. The system designs are similar to other microirrigation systems, but microsprinkler systems generally tend to require a higher flowrate per unit area. Typically microsprinkler installations have one 40 to75 L/h flowrate emitter per tree. The most common (spray) emitters have slotted caps or deflector plates that distribute water in distinct streams. Other designs (spinners) have a moving part that rotates to disperse the water stream more uniformly over the wetted diameter.

Installed costs for microsprinkler systems in the United States range from $2000 to $3000/ha or more and represent a considerable long-term debt for the orchard or vineyard operator. Therefore, during the design stage, long-term maintenance costs should be included in the economic analysis. The emitter selection process should consider uniformity as well as other factors such as cost, wind effects, system constraints, maintenance, and soil type so that the best emitter for a particular field condition is selected. Wetting patterns of emitters should be compatible with the soils, tree spacing, and rooting pattern of the trees. Consideration should be given to the water requirements of mature plants. Higher density plantings with smaller trees will require less water per tree than more widely spaced plantings. Larger wetting patterns may be more desirable for the more widely spaced trees. In all cases, designers should ensure that the tree water requirement can be met with reasonable run times with minimal movement of nutrients and water below the root zone.

Microsprinkler systems should be capable of applying the maximum crop water need plus any application inefficiency. The emitters should have a coverage area sufficient to allow this volume of water to be stored in the soil without causing unintentional deep percolation. Emitters should also have a sufficient application rate in the wetted area so that the required run times are compatible with the power unit and labor availability. High application rates can lead to leaching of nutrients and pesticides. By adjusting spray diameter, irrigation duration, and emitter flowrate, systems can be managed to meet tree water needs while minimizing overirrigation and chemical leaching. Experience has shown that factors such as application uniformity, clogging potential, wetting patterns, and ease of maintenance, are important to consider when designing, installing, operating, and maintaining microsprinkler systems.

Regardless of the design employed, it is essential that proper system filtration, flushing, chlorination, and operational procedures be followed to minimize maintenance problems. Users should verify system performance by field testing to ensure actual operation meets design standards. When repairing broken or missing emitters, original equipment should be replaced with emitters with similar flow characteristics to maintain emission uniformity within the system.

15.1.1. Advantages of Microsprinkler Systems

Microsprinkler systems have some distinct advantages over other irrigation methods including:

- Water savings - Microsprinkler systems use less water than overhead or surface irrigation methods due to their higher application efficiencies.
- Freeze protection - Microsprinklers are often the preferred microirrigation method for tree crops because they provide a greater degree of freeze protection than drip systems. Also the accumulated weight of ice associated with overhead sprinklers used for freeze protection can cause extensive tree damage.
- Frequent applications - The ability to maintain adequate soil water levels by applying small amounts of water at frequent intervals during critical growth stages is beneficial for several tree crops. Microsprinkler systems can often be economically designed for automatic operation to include features such as real-time ET based scheduling or incorporate sensors to start and/or stop irrigations.
- Wetted area - Microsprinklers are often preferred over drip systems in areas with coarse textured soils where lateral movement of soil water is limited. The larger wetting patterns of microsprinklers cover a higher percentage of the rooting area and these systems require less management effort than drip systems.
- Chemigation - Microsprinklers provide an economical method of applying fertilizer, nematicides, pesticides, and other agricultural chemicals on a timely basis.
- Reduced evaporation - Microsprinkler systems on tree crops can significantly lower annual water applications compared with flood or sprinkler irrigation, mainly due to higher application efficiencies without application to non-productive areas. These water savings are especially evident in a young orchard when trees are small and have limited root zones.
- Weed control - The reduced wetted area of microsprinklers compared with flood and overhead sprinklers often results in the additional benefit of less weed growth.
- Cost - Microsprinkler systems have a considerably lower initial cost than permanent solid set sprinkler systems for widely spaced tree crops. In addition, energy costs for microsprinkler systems are less than for overhead sprinklers due to lower pressures.
- Flexibility - Although microsprinkler systems require higher flowrates/area than drip systems, the run time required to apply an equivalent amount of water is less. This can be important for multi-zone systems when irrigation must be interrupted for other cultural practices such as pesticide application, mowing, and harvesting.

15.1.2. Disadvantages of Microsprinkler Systems

Microsprinklers have some distinct disadvantages compared with other methods including:

- Management level - Microirrigation systems require a higher level of management expertise than other irrigation methods due to frequent operation, low application rates, small orifices, and wetting patterns that cover only a fraction of the root zone.
- Maintenance - Microsprinkler systems require more maintenance than conventional overhead sprinkler or surface irrigation systems. In addition, microsprinkler stake assemblies are prone to be damaged or be moved during normal orchard cultural operations such as mowing, pesticide application, and harvesting.
- Frequent operation – Irrigation for microsprinkler systems must be scheduled more frequently than overhead sprinkler or surface irrigation systems because the microsprinklers wet only a fraction of the root zone. Automation may be required to utilize labor efficiently and still meet crop water demands where irrigation durations are relatively short and multiple irrigations per day are needed.
- Discharge into air - Because microsprinklers discharge water streams into the air, the application losses are usually greater than drip irrigation systems. In areas using high-salinity irrigation water, trees may be salt-damaged from wind-blown water that contact the trunks, leaves, and flowers.
- Cost - Microsprinkler systems have higher initial costs than comparable drip systems because the discharge rate per unit area of the emitters is greater. As a result, pumps, filters, and the piping network must have greater capacities.

15.2. MATERIALS AND COMPONENTS

15.2.1. Materials Used in Systems

Important considerations for selecting equipment in microirrigation are the ability of the material to withstand mechanical stresses, tolerate temperature extremes, solar radiation, and chemical damage. Mechanical stress can be caused by earth load, thermal expansion and contraction, and impacts to the component. Internal conditions from water pressure, water acidity or alkalinity, water hammer, or vacuum may also impose mechanical stresses.

Dvir (1997) discusses many of the numerous combinations of metals, composites, plastics, ceramics, and elastomers available for fabricating microsprinkler components. The materials must be able to withstand the mechanical and environmental stresses and also be compatible with each other in order to avoid internal corrosion or galvanic effects. The important factors in component that must be considered in selection are their pressure rating, temperature range, chemical resistance, and cost.

The design working pressure is the most important factor for selecting materials for the distribution system. Typically, pipelines and control devices should be able to withstand twice the normal operating pressure. For example, if the maximum normal operating pressure is 300 kPa, all components should be able to withstand a surge of 600 kPa.

The ambient air and water temperatures should also be considered in the selection of construction materials. High temperatures may decrease the strength of plastics. In situations where components may be exposed to high temperatures (such as around pump stations), special high-temperature resistant plastics or steel should be used instead of polyvinyl chloride (PVC). Under freezing conditions, materials should be selected that will not fracture as easily as cast iron. Plastics resistant to UV radiation should be used where UV intensity is high. Elastomers are normally less influenced by UV radiation, and metals are usually unaffected.

Chemical resistance of the component is an important consideration because microirrigation systems are usually exposed to many types of agricultural chemicals, fertilizers, and line cleaners. Consequently, unpredictable combinations of corrosive compounds may travel through the system. Acidic conditions will cause corrosion of most metals of which aluminum and zinc are the most sensitive. Cast iron, carbon steel, and copper alloys are less sensitive, but for prolonged exposure to acidic conditions, a resistant material such as 316 stainless steel should be considered. High pH (alkaline) conditions may be harmful to aluminum, zinc, and titanium. Most other metals, plastics, and elastomers are unaffected by alkaline conditions.

Ions in water increase electrical conductivity that can accelerate corrosion. Cations such as calcium (Ca^{2+}), potassium (K^+), and sodium (Na^+) have almost no effect on most metals and plastics, whereas ammonium (NH_4^+) may be corrosive to some plastics and elastomers. Anions such as sulfides and sulfates are much more harmful to both metals and plastics.

Solid particles such as sand in the water stream can cause severe erosion of metal and plastic components. Erosion of surfaces can also result from cavitation. Cast iron, mild steel, and copper alloys can be coated with hard metals or ceramics to make them more resistant to cavitation. Plastics and elastomers are more resilient to cavitation erosion. However, they are more susceptible to abrasive damage from high-velocity solids.

15.2.1.1. Ferrous materials

Cast iron is generally used in most flowmeters and valves that are larger than 76 mm. Cast iron is also used for other large components to reduce cost. Under high-pressure applications and severe working conditions, ductile cast iron, cast alloy, or other special metals are used.

Cast iron has good resistance to corrosive conditions without any special protection. Coating the bodies with protective paints such as epoxy resins is a common practice. However, under normal operating conditions, unprotected cast iron parts normally do not corrode to a degree that impairs their performance. When cast iron is in direct contact with cathodic materials such as copper, corrosion can occur. Corroded parts should be periodically replaced to prevent malfunction.

Components constructed from steel plate normally have low corrosion resistance. Therefore, these components must be specially coated or galvanized on both the inner and outer surfaces. In spite of this protection, serious corrosion may occur to the component if copper or copper alloy parts contact the steel. Welded parts are especially prone to corrosion. Periodic inspection and re-coating are necessary to ensure long-term reliable operation.

15.2.1.2. Non-ferrous metals

Bodies of valves smaller than 50 mm and other small components are often constructed from cast bronze. Cast bronze is also used for bodies of larger valves designed for high pressure and for various parts of valve and meter mechanisms. Brass is used for machined parts such as shafts and spindles. Brass inserts are used for bearings and threaded connections in cast iron bodies to reduce friction and corrosion.

Special copper alloys are used for extremely corrosive and erosive conditions. They are also used for applications that have high velocity. Cast aluminum is typically only used in components that are portable or where weight is a serious consideration.

15.2.1.3. Plastics

Plastic components are fabricated from a wide array of polymers that have different useful properties. Plastic materials are less resistant to stress than metals and tend to lose strength under pressure and elevated temperatures. They are used for smaller valves and as parts for many devices such as flowmeter impellers, low-friction bushings, and components that are not subjected to mechanical stress.

Bodies of smaller valves are typically made of glass-reinforced polyester, polyacetal, and polycarbonate. Small mechanisms may be made of an acetal resin such as Delrin, and where low friction components are required, Teflon linings may be applied. Nylon, Teflon, and polyacrylic glass-fiber reinforced materials are used for flexible small-diameter tubing and joints. Filtering elements use acetal, polycarbonate resins, thermoplastic polyester, or high density polyethylene. To protect metal bodies and components against corrosion, plastic linings and epoxy resins are often used. Valve vanes are coated with nylon or Teflon to reduce friction.

15.2.1.4. Elastomers

Elastomer materials used for gaskets and seals must be able to withstand physical, chemical, biological and temperature stresses. Natural or synthetic rubber has proven to be the most suitable material for gaskets and seals in irrigation systems. Rubber performs adequately for resilience, flexibility and wear. However, rubber materials are prone to degradation by microorganisms, especially when in long contact with wet soil. Neoprene reinforced with nylon is generally suitable for flange gaskets. When corrosive materials are present, other hydrocarbon acrylonitrile elastomers such as Buna N, neoprene, Viton, or EPDM rubber should be used.

15.2.2. Microsprinkler Emitters

15.2.2.1. Emitter hydraulic characteristics

Microirrigation emitter flowrates have different responses to pressure variations. The response of a specific emitter depends on its design and construction. The relationship between the emitter operating pressure and flowrate is given by the following equation:

$$Q = K_d P^x \tag{15.1}$$

where Q is the flowrate; P is the pressure at the emitter; K_d is the emitter flow coefficient, which is constant for a given emitter and is dependent on the units of Q and P; and x is the emitter exponent.

The emitter exponent is a measure of flowrate sensitivity to pressure changes. The value of x is usually between 0 and 1. The larger the x value the more sensitive the emitter is to pressure variation (Tab. 15.1). A value of 1.0 means that for each 10% change in pressure there is a corresponding 10% change in flowrate. In contrast, an x value of 0 means that the emitter flowrate does not change as pressure changes. The emitter exponent is generally about 0.5 for labyrinth-type and orifice control emitters, x is less than 0.5 for pressure compensating emitters, and x is greater than 0.5 for long flow path or microtube emitters.

Table 15.1. Flow change rate (in percent) for emitters with various pressure-discharge coefficients. Adapted from Burt and Styles (1994).

Pressure change	Emitter exponent *(x)*				
	0.4	0.5	0.6	0.7	0.8
10%	3.9	4.8	5.9	6.9	7.9
20%	7.6	9.5	11.6	13.6	15.7
30%	11.1	14.0	17.1	20.2	23.3
40%	14.4	18.3	22.3	26.6	30.9
50%	17.6	22.5	27.5	32.8	38.3

The emitter exponent can be calculated from measured flowrates at various pressures using the following relationship or is provided from manufacturer's specifications,

$$x = \frac{\log\left(\frac{Q_1}{Q_2}\right)}{\log\left(\frac{P_1}{P_2}\right)} \tag{15.2}$$

where Q_1 is the flowrate at pressure P_1; Q_2 is the flowrate at pressure P_2; and x is the emitter exponent. The discharge coefficient, K_d is then determined by rearranging Eq. 15.1.

Example 15.1.

Determine the emitter discharge coefficient and the emitter exponent for the green base (1.27 mm orifice) emitter in Tab. 15.2

At P_1 = 103 kPa, Q_1 = 49 L/h, and

at P_2 = 138 kPa, Q_2 = 56 L/h

The emitter exponent is calculated using Eq. 15.2 as:

$$x = \frac{\log\left(\frac{49}{56}\right)}{\log\left(\frac{103}{138}\right)} = 0.46$$

The discharge coefficient is calculated by rearranging Equation 15.1 and using Q_1, P_1, and the computed x value:

$$K_d = \frac{Q}{P^x} = \frac{49}{103^{0.46}} = 5.8$$

(K_d is valid only for Q expressed in L/h and with P measured in kPa)

15.2.3. Emitter Manufacturing Variation

In addition to variation in flow due to pressure, variation in flow between emitters due to manufacturing also occurs. No two emitters can be identically manufactured; some variation will exist from emitter to emitter. The manufacturing coefficient of variation C_{vm} is defined as:

$$C_{vm} = \frac{S_{dm}}{q_{avg}} \tag{15.3}$$

where S_{dm} is the standard deviation of emitter flowrate for new emitters operated at the same pressure; and q_{avg} is the mean flowrate.

A C_{vm} of 0.10 implies that 68% of all flowrates is within plus or minus 10% of the mean flowrate. The design of the emitter, the material used in its construction, and the precision with which it is manufactured determines the variation for any particular emitter. With recent improvements in manufacturing processes, most emitters have C_{vm} values less than 0.10. Pressure compensating drip emitters generally tend to have somewhat higher C_{vm} than labyrinth path emitters. C_{vm} values of 0.05 or less are considered excellent, 0.05 to 0.10 are good, 0.10 to 0.15 are marginal, and greater than 0.15 are unacceptable (ASAE, EP405.1, 1999). Independent laboratory data are available for emitters of most manufacturers (e.g., Center for Irrigation Technology, California State University-Fresno, 5370 N. Chestnut Ave., Fresno, CA 93740-0018. Web address: http://cati.csufresno.edu/cit).

15.2.4. Emitter Types

Microsprinkler emitters are available with a wide range of flowrates, coverage pattern, and operating pressure ranges. Manufacturers are continually improving and/or introducing new microsprinkler models to satisfy the market demands. However, all of the commonly used emitters can be classified into three categories based on their method of operation: orifice control, vortex control, or pressure compensating.

15.2.4.1. Orifice control emitters

The most common microsprinklers are orifice control emitters where the flowrate at any given pressure is governed primarily by the orifice diameter (Fig. 15.1). Orifice control emitters are turbulent flow devices where the flowrate is regulated by dissipating energy by friction of water against the walls of the passages and between the fluid particles themselves. Turbulent flow emitters have shorter flow paths and larger diameter passages than the laminar flow devices. Thus, flow velocities are greater and the potential for clogging is less than for the laminar flow devices. Flowrates are less sensitive to pressure (emitter exponent is about 0.5) and less sensitive to water temperature than the laminar flow devices.

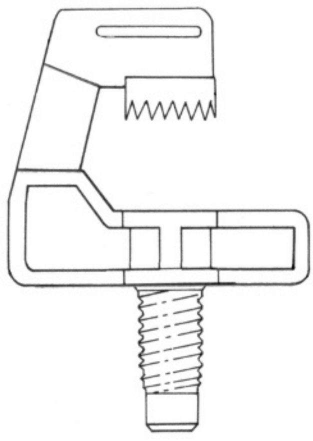

Figure 15.1. Orifice control (turbulent flow) microsprinkler emitter. Courtesy of Maxijet, Inc.

With orifice control emitters, orifice diameter at the base of the emitter determines the flowrate. The top of the emitter determines the pattern and diameter of spread. Numerous types are available from various manufacturers. As pressure increases, water is thrown farther from the emitter resulting in an increased effective coverage area (Tab. 15.2). However, the diameter typically increases more than the flow, so the application rate (expressed in depth per hour) normally decreases as the wetted pattern increases.

15.2.4.2. Vortex control emitters

Vortex control emitters (Fig. 15.2) are less sensitive to pressure variations than laminar or turbulent flow emitters (emitter exponent is about 0.4). In vortex emitters, water is forced to form a vortex or whirlpool at the center of the emitter. As the water rotates centrifugal force pushes it towards the outer edge of the vortex. This action causes a pressure drop in the center, where the orifice is located. The result is a reduction in the energy of water at the discharge point resulting in a controlled flowrate. Emitter flowrate is controlled by vortex design and orifice diameter.

Table 15.2. Effects of pressure on discharge rate and average application depth for typical orifice control emitters with 360^{o} patterns. Different manufacturers have different flow, diameter, and coverage characteristics for the same color emitters. Therefore, it is important to verify the emitter performance when replacing emitters with a different brand.

Emitter base color	Orifice diameter (mm)	Operating pressure (kPa)	Discharge rate (L/h)	Coverage diameter (m)	Coverage area (m^2)	Application rate (mm/h)
Blue	1.02	69	30	2.5	4.9	6.2
		103	34	2.9	6.6	5.2
		138	38	3.4	9.2	4.1
		172	43	4.1	12.9	3.3
Green	1.27	69	40	3.4	8.8	4.5
		103	49	3.8	11.6	4.2
		138	56	4.4	15.3	3.7
		172	62	4.9	19.1	3.3
Red	1.52	69	60	3.7	11.0	5.5
		103	74	4.5	16.2	4.6
		138	87	5.5	23.4	3.7
		172	98	5.9	27.2	3.6

15.2.4.3. Pressure compensating emitters

Pressure compensating emitters (Fig. 15.3) use excess inlet pressure to modify the shape, length, or diameter of the flow path to control the flowrate. Generally, a diaphragm made of an elastic material deforms to control the flowrate. As the pressure increases, the diaphragm restricts the passage diameter. Pressure compensating emitters are designed to discharge at a fairly constant rate over a wide range of pressures where the emitter exponent is usually less than 0.1.

A major shortcoming of pressure compensating emitters is the changes in elasticity of the diaphragm over time. As a result, the flow and pressure compensation characteristics can change. In addition, diaphragms will often retain some moisture when the pressure is off. The moisture may allow microbial growth within the emitter and emitter clogging may occur. Another problem can result from the invasion of ants seeking a food source. Ants may feed on organic material in the emitter and destroy the diaphragm. Additionally, when the system is pressurized, ants and their body parts may clog the emitter.

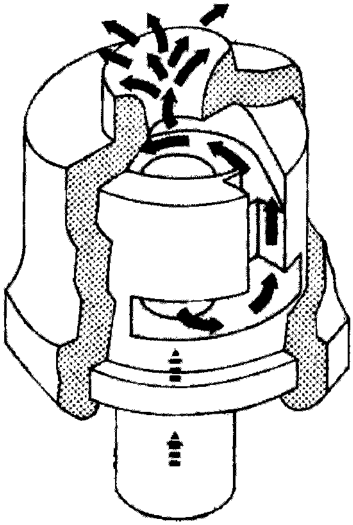

Figure 15.2. Vortex control microsprinkler emitter. Courtesy of Plastro Irrigation, Inc.

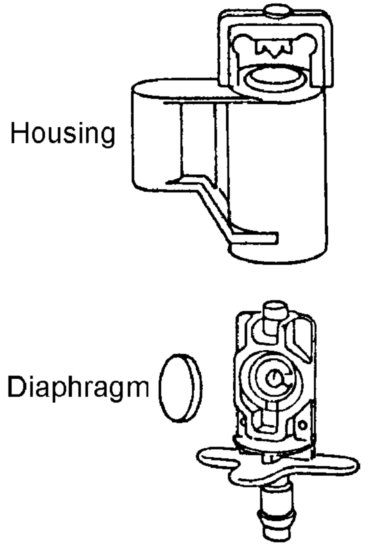

Figure 15.3. Components of pressure compensating microsprinkler emitter. Courtesy of Netafim Irrigation, Inc.

15.2.5. Emitter Wetting Patterns

Wetting patterns of microsprinklers are important for sandy soils or where root zones are shallow. Boman (1989a) determined distribution patterns of several microirrigation spinner and spray emitters under no-wind conditions. Spinner-type emitters had much higher application uniformities than the spray-type emitters. Both types of emitters had higher uniformity when the pressure was 138 kPa and higher than 103 kPa. Spinners had most of the wetted area receiving near-average application depths, with nearly continuous wetting throughout the pattern (Fig. 15.4a). Spray-type emitters are characterized by wetted spokes radiating from the emitter (Fig. 15.4b). The spray-type emitters typically had 50 to 75% of the area within the coverage diameter receiving little or no wetting.

Application rates at the end of the radials for spray emitters can be quite high (the solid black areas in Fig. 15.4b represent catch cans receiving more than six times the average application). For example, an emitter with a 57 L/h flow and 4.6 m diameter pattern will have an average application rate of 3.6 mm per hour. If the pattern for the emitter were similar to that in Fig. 15.4b, the darkest areas would receive over 85 mm during a 4 h irrigation, whereas the areas with dots would remain dry unless wind distorted the pattern. In very sandy soils where lateral redistribution of applied water is limited, these types of emitters may be unacceptable. Under these conditions, consideration should be given to selecting emitters that have more uniform wetting in order to minimize nutrient leaching losses and to provide a sufficiently large volume of soil that is wetted so soil water stress does not occur.

With tree crops, emitters that wet a higher percentage of the under-tree area are often preferred over emitters that wet a smaller area. However, larger pattern emitters need a corresponding flowrate to make it possible to manage them effectively. When the average flowrate per unit wetted area decreases to less than 2 mm per hour, water application requires very long run times to move the water into the mid and lower root zone with microsprinklers. Typically, potential for wind drift, evaporation, and wetting of non-productive areas increases as the wetted diameter increases. In high density plantings, it is normally most effective to provide each tree with a smaller pattern emitter than to install larger pattern emitters on every other tree. The wetting pattern from larger pattern emitters is often distorted by interference from tree trunks and low branches, resulting in shadows in the coverage pattern. The smaller wetting patterns provide more inter-tree wetting with more efficient water applications.

15.2.6. Stake Assemblies

Emitters are normally attached to stake assemblies that raise the emitter about 0.2 m above the ground (Fig. 15.5). The elevated position of the emitters provides a larger wetting pattern, and allows water to be dispersed over low-lying weeds and grass. The stake assemblies usually have 4 mm nominal inside diameter (I.D.) tubing made of vinyl or polyethylene (PE). Vinyl tubing generally has greater wall thickness than PE tubing, thus it has higher friction loss per unit length. Microtubing (spaghetti tubing) commonly has an outside diameter (OD) of about 6.4 mm, with an I.D. of 3.6 mm for vinyl and 4.1 mm for polyethylene. The length of microtubing used on a stake assembly depends on grower preference, but typically is 0.6 to 1.2 m long.

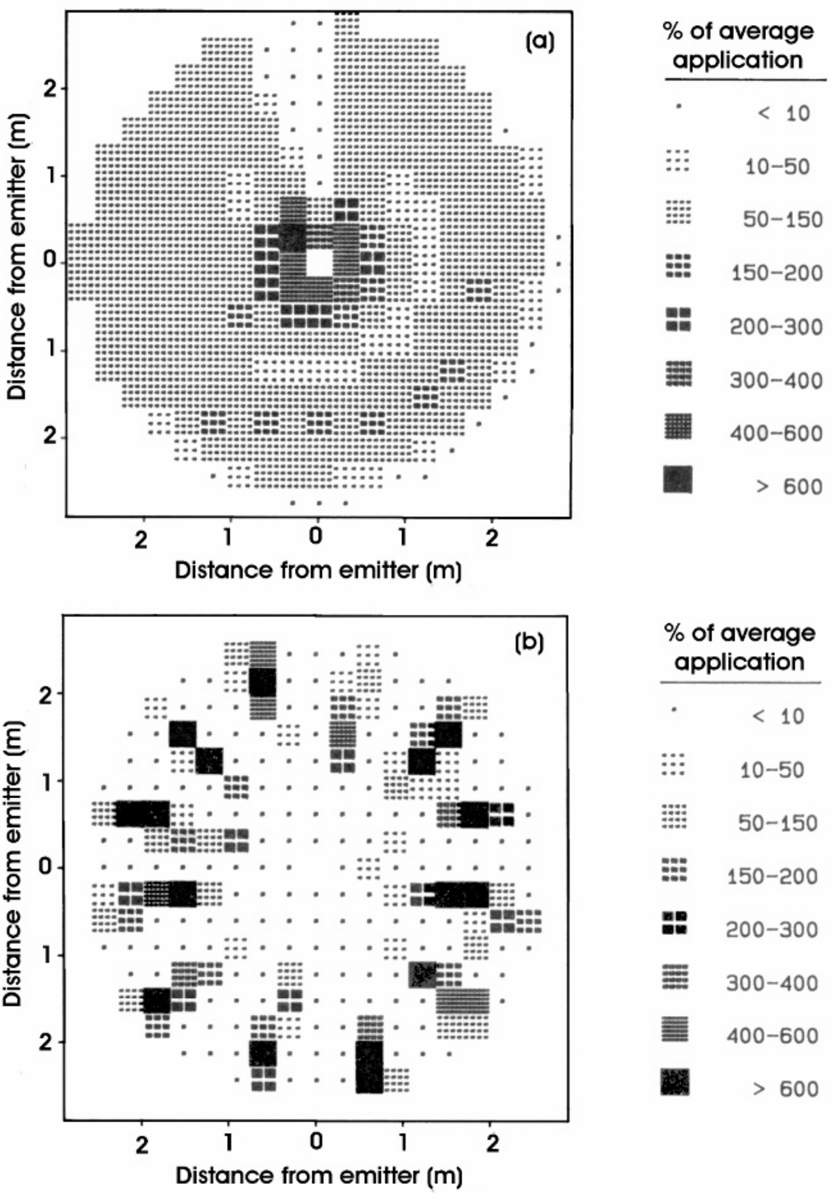

Figure 15.4. Catch distribution patterns of 1.02 mm diameter, orifice-control, emitters operated at 138 kPa for 6 h for spinner-type (a) and spray-type (b) designs. Adapted from Boman (1989a).

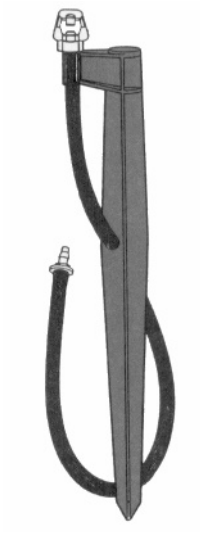

Figure 15.5. Microsprinkler stake assembly. Courtesy of Maxijet, Inc.

Microtubing is connected to the polyethylene lateral tubing with barbed or threaded connectors (Fig. 15.6). Experience has shown that the barbed by barbed connections generally are more durable in the field than other types of connections. Threaded connectors typically have thinner walls and are therefore more prone to breakage. Failure of the connectors is most commonly due to impact on the stake assembly or tubing during harvesting operations.

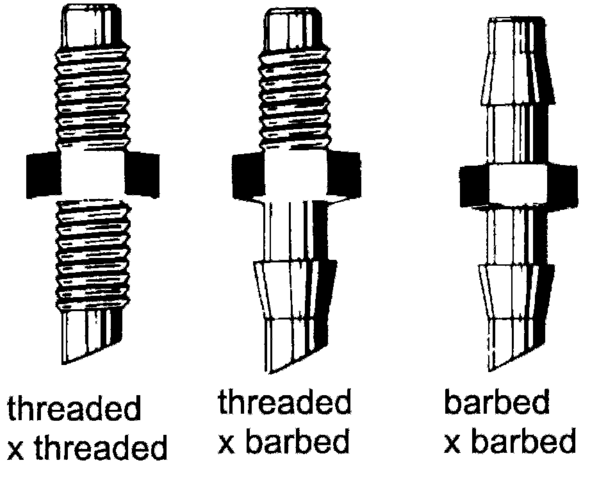

Figure 15.6. Typical microtubing to lateral tubing connectors. Courtesy of Maxijet, Inc.

Field measurements of emitter flowrates usually indicate application rates that are less than the manufacturer's specified rates for a particular pressure in the lateral lines. The reduced flow is often caused by pressure losses in the stake assembly. Manufacturers usually base their specifications for flow and pattern area on pressure at the emitter. In practice, pressure is typically measured in the lateral, and the standard 4 mm diameter microtubing used in most assemblies can result in pressure losses significant enough to decrease flowrates.

Boman (1989b) showed that flowrates in 1.22 mm orifice diameter emitters (66 L/h manufacturer specified flowrate) with 4 mm diameter microtubing were reduced 12% compared with 6 mm tubing. Flow was reduced nearly 40% (from 121 L/h to 75 L/h) when 10 mm microtubing was replaced with 4 mm tubing on assemblies with 2.03 mm orifices (121 L/h manufacturer specified flowrate). Boman (1991) further reported that pressure drops in stake assemblies could significantly reduce the available operating pressure. At flowrates of about 38 L/h and a system pressure of 172 kPa, pressure losses in stake assemblies with 4-mm tubing were nearly 20 kPa (Fig. 15.7). Once the flowrates reached 120 L/h, over 50% of the system pressure was lost in the stake assembly.

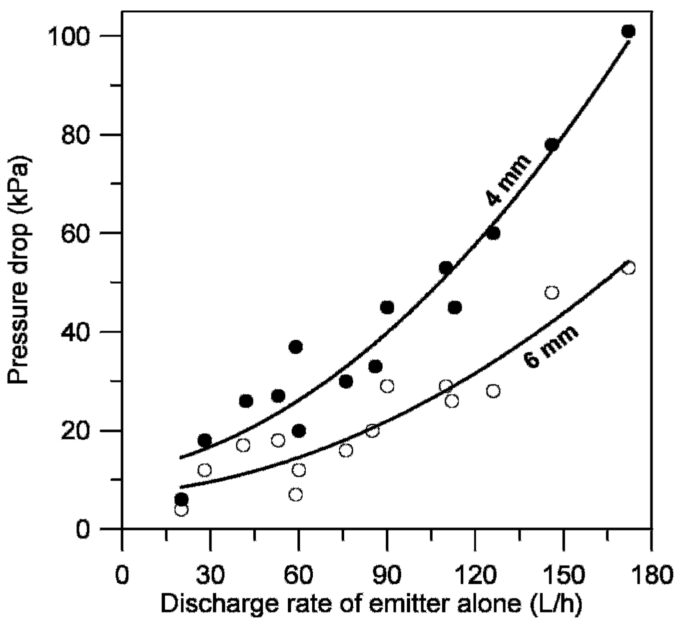

Figure 15.7. Calculated pressure drop in stake assembly for emitters with 4-mm and 6-mm microtubing for a given flowrate for emitters directly connected to lateral tubing. Adapted from Boman (1991).

The amount of head loss in the barbed connector can be significant, depending on the flowrate of the emitter and the connector inside diameter. For instance, the pressure loss in a 4.4 mm barbed by barbed connector is about 7 kPa at a flowrate of 57 L/h. Friction losses in the adapter can be estimated by Eq. 15.4 (provided by Bowsmith, Inc.).

$$H_{fa} = 0.119\left(\frac{Q^2}{D^4}\right) \tag{15.4}$$

where H_{fa} is the friction loss in the adapter (kPa); Q the flowrate of emitter (L/h); and D the inside diameter of coupling (mm).

In addition to the lateral tubing connection, pressure losses will occur in the microtubing caused by friction. Overall friction losses in the lateral tubing and connector typically are in the range of 15 to 40 kPa for emitters with flows in the range of 60 to 80 L/h. Friction losses in the microtubing can be calculated by Eq. 15.5 (provided by Bowsmith, Inc.).

$$H_{fs} = 4.82\left(\frac{Q^{1.75}}{D^{4.77}}\right) \tag{15.5}$$

where H_{fs} is the friction loss in the microtubing (kPa per meter of length); Q the flowrate of emitter (L/h); and D the inside diameter of the microtubing (mm).

The combined effects of the barbed adapter and friction losses in the microtubing are given in Fig. 15.8 for 3.6 mm I.D. vinyl tubing and Fig. 15.9 for 4.0 mm polyethylene tubing. Note that at flowrates of about 60 L/h and higher, the pressure in 3.6 mm I.D. lateral tubing must be 10 to 28% higher (depending on tubing length) than that at the base of the emitter to maintain the specified flowrate. When the emitter flow increases to 91 L/h, the lateral pressure must be 20 to 50% higher to account for pressure losses in the barb and microtubing.

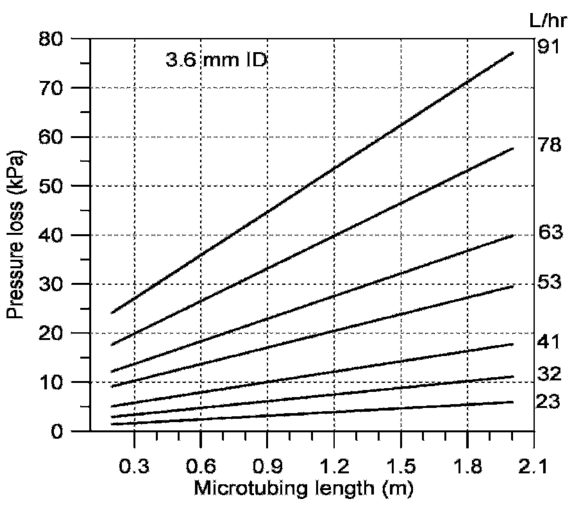

Figure 15.8. Combined losses from barbed adapter and microtubing for 23-91 L/h emitters operated at 138 kPa (at emitter base) for various lengths of 3.6 mm I.D. vinyl tubing. Courtesy of Bowsmith, Inc.

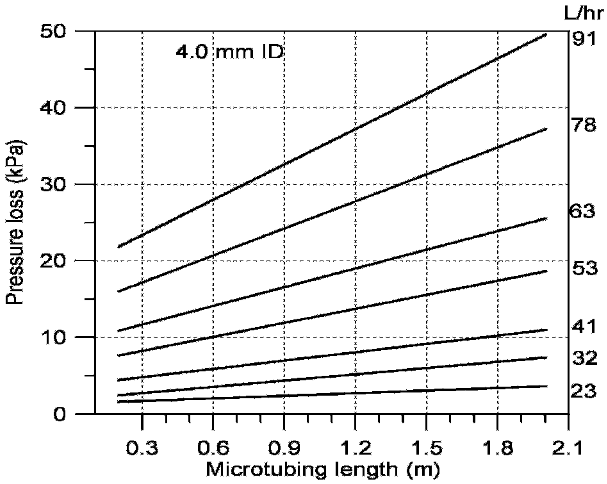

Figure 15.9. Combined losses from barbed adapter and microtubing for 23-91 L/h emitters operated at 138 kPa (at emitter base) for various lengths of 4.0 mm I.D. polyethylene tubing. Courtesy of Bowsmith, Inc.

Microsprinkler system designs should be based on the actual installed emitter flows. Specifications given for emitters often do not account for pressure losses in the stake assemblies. Improper design flowrates may result in inefficient system designs in terms of both cost and performance. Systems designed to provide continuous operation in all zones in order to satisfy peak demands may result in unwanted crop stress when the design flowrate cannot be delivered.

15.2.7. Lateral Tubing

Because microsprinkler systems are generally installed on perennial tree or vine crops, the lateral tubing must be durable enough to last many years. Tubing with various combinations of inside and outside diameters and wall thickness are available. For economic reasons, tubing is typically limited to nominal diameters of 14, 19, and 25 mm, and in some cases, 32 mm (Tab. 15.3). The most frequently used tubing sizes 19 mm (which comes in 305 m rolls) and 25 mm (which comes in 201 m rolls).

Splices in tubing are normally made with barbed insert fittings and stainless steel clamps to secure the tubing on the fitting. When compression fittings are used, it is recommended that those specified by the tubing manufacturer be used. Compression fittings may fit the tubing, but failure might result in the field after the tubing is exposed to pressure changes, heat, expansion, contraction, and weathering. The ends of lateral tubing may be terminated with an insert by male adapter with a threaded cap or by folding the flexible polyethylene tubing over and securing the fold with a ring.

Table 15.3. Typical friction loss characteristics *(H_f)* for Bowsmith, Inc. polyethylene lateral tubing. (H_f = pressure loss in m per 100 m of tubing calculated using the Hazen-Williams formula with C=140). Shaded areas represent velocities over 1.5 m/s that should be used only with caution and with proper restraints.

Mfg's ID No.:	700P50		3/4"-50		1"-45		1530P75	
Nominal size:	13 mm (1/2 in.)		19 mm (3/4 in.)		25 mm (1 in.)		32 mm (1-1/4 in.)	
Tube ID, mm:	15.0		20.8		26.8		34.5	
Tube OD, mm	17.8		23.7		30.4		38.9	
Thickness, mm:	1.4		1.5		1.8		2.2	
Flowrate L/min	Velocity m/s	H_f m/100m	Velocity m/s	H_f m/100m	Velocity m/s	H_f m/100m	Velocity m/s	H_f m/100m
3.8	0.4	1.5	0.2	0.3	0.1	0.1		
7.6	0.5	3.1	0.4	1.1	0.2	0.3		
11	1.1	11.1	0.5	2.3	0.3	0.6	0.2	0.2
15	1.4	19.0	0.7	3.9	0.4	1.1	0.3	0.3
19	1.8	28.7	0.9	5.8	0.5	1.7	0.3	0.5
23	2.1	40.2	1.1	8.2	0.7	2.4	0.4	0.7
26	2.5	53.5	1.3	10.9	0.8	3.1	0.5	0.9
30	2.8	68.5	1.5	14.0	0.9	4.0	0.5	1.2
34			1.6	17.4	1.0	5.0	0.6	1.5
38			1.8	21.1	1.1	6.1	0.7	1.8
45			2.2	29.6	1.3	8.5	0.8	2.5
61			2.6	39.4	1.5	11.3	0.9	3.3
61			2.9	50.4	1.8	14.5	1.1	4.3
68					2.0	18.0	1.2	5.3
76					2.2	21.9	1.3	6.4
83					2.4	26.1	1.5	7.7
91					2.6	30.7	1.7	9.0
98					2.8	35.6	1.7	10.4
106					3.1	40.8	1.9	12.0
114					3.3	46.4	2.0	13.6

15.3. LATERAL AND MANIFOLD DESIGN

The water distribution network for microsprinkler systems generally consists of a mainline, submains or manifolds, lateral lines, and emitters. Submains are often used to divide groups of laterals into zones that can be independently controlled. These zones may combine areas of similar tree age or variety. In addition, they may be based on factors such as soil types, topography, and elevation changes. The following discussion is intended to illustrate points to consider in the design and does not substitute for a thorough design analysis. The reader is referred to Chapter 5 for a more thorough discussion of microirrigation system design.

15.3.1. Head Losses in Lateral Lines

As water flows through the lateral tubing, friction between the wall of the tubing and the water molecules results in a gradual, but not uniform reduction in the pressure within the lateral line. The magnitude of pressure loss in a lateral line depends on flowrate, pipe diameter, roughness coefficient, elevation changes, and lateral length. In level laterals, friction loss is greatest at the beginning of the lateral. Approximately 50% of the pressure reduction occurs in the first 25% of the lateral's length, and about 75% of the pressure loss in the first 40% of the lateral. In a level lateral, the average emitter flow occurs at about 40% of the distance from the lateral inlet.

When a lateral line is placed upslope, emitter flowrate decreases due to the combined influence of elevation and friction loss. Where topography allows, running the lateral line downslope can produce the most uniform flow because friction loss and elevation factors cancel each other to some degree.

Lateral length may have a large impact on uniform application. In general, flowrates are less uniform with long than short lateral length. It is very important to recognize the hydraulic limits of irrigation lateral lines to efficiently deliver water. Lateral lengths too long for a given pipe diameter and emitter flowrate are the main sources of nonuniformity in microirrigation systems. When this occurs, not only will friction losses increase and average emitter flow will decrease, but system uniformity and efficiency will also be lowered.

15.3.2. Pressure Variation

The system pressure variation can be calculated by rearranging the standard orifice equation as

$$\frac{P_{min}}{P_{avg}} = \left(\frac{q_{min}}{q_{avg}}\right)^{\frac{1}{x}} \tag{15.6}$$

where P_{avg} is the average system pressure; P_{min} the minimum pressure in system; q_{avg} the average emitter flow; q_{min} the minimum emitter flow due to pressure variations in system; and x the emitter pressure-discharge exponent.

The amount of pressure variation allowable in the design is governed by the design emission uniformity (EU) of the new system and the hydraulic characteristics of the emitters. EU can be calculated as (ASAE EP405.1, 1999.):

$$EU = 100\left(1 - \frac{1.27C_{vm}}{\sqrt{n}}\right)\frac{q_{min}}{q_{avg}} \tag{15.7}$$

where n is the number of emitters per tree and C_{vm} the coefficient of manufacturing variation for emitters. The allowable pressure difference (ΔP) between emitters throughout the system can be calculated by

$$\Delta P = 2.5\ (P_{avg} - P_{min}) \tag{15.8}$$

where P_{avg} is the average system pressure (kPa) and P_{min} the minimum pressure in the system (kPa). The multiplier can vary from about 2 to 3, depending on elevation differences and whether pressure regulators are used on each lateral. A multiplier of 2.5 is recommended by Burt and Styles (1994) for most applications.

The ΔP will be consumed by elevation changes along laterals, friction losses in the tubing and stake assemblies, and within pressure regulators if they are used. In zones with constant downslope in the direction of the lateral, it is often possible to offset friction loss with elevation change. In undulating terrain, it is difficult to balance friction losses with elevation changes. The allowable friction loss along a lateral is equal to:

$$P_a = \Delta P - P_{elev} - P_{reg} \tag{15.9}$$

where P_a is the allowable friction loss (kPa); P_{elev} the pressure change resulting from elevation differences along lateral (kPa); and P_{reg} the pressure regulator variation (kPa). Pressure regulator variation is calculated by multiplying the pressure regulator variability by the average operating pressure (e.g., for a 5% regulator and 150 kPa operating pressure, the regulator variation would be 150 kPa x 5% = 7.5 kPa).

15.3.3. Lateral Design

The design of laterals involves selecting the proper size of tubing for a given lateral length that can deliver the required amount of water to the plants within an acceptable range of uniformity. Typically, tree spacing is based on factors such as tree geometry and tree size at maturity. Row length is often fixed by land shape or factors such as harvesting considerations or drainage facilities. Therefore, lateral design often consists of incorporating layouts for different tubing sizes and determining the most economical alternative. The maximum number of trees that can be serviced by a single lateral needs to be assessed to determine the most economical design. The assessment is based on the specific lateral diameter for a given flow condition, ground slope, and flow characteristics of the emitter. The information required for lateral design includes ground slope, tree spacing, row length, number of emitters per tree, emitter pressure/flow relationships, and desired uniformity.

To assist in design, most tubing manufacturers provide tables or charts to determine pressure loss for various emitter flowrates (Tabs.15.4 and 15.5, and Fig. 15.10). The tables usually require interpolating from table values to the specific conditions of the design. The figures require calculating the specific flow gradient for the lateral. The flow gradient is the flowrate from a unit length of tubing (L/min-m). Flow gradient may be calculated by dividing the total lateral line flowrate by the total lateral length, or dividing the average emitter flowrate by the average emitter spacing. Each flow gradient curve applies to a specific diameter of tubing. For a given flow gradient, the curves will provide total friction loss in the lateral as a function of lateral length.

Table 15.4. Maximum number of microsprinkler emitters and maximum lateral lengths for 18-mm lateral tubing diameter with ±5% or ±10% allowable flow variation (for level ground: based on Bowsmith (20.8 mm I.D.) tubing (¾”-50 tubing).

Allowable flow variation	Flow rate (L/h)	Spacing on lateral (m)									
		2.3		3.0		3.8		4.6		5.3	
		No.	Length (m)	No.	Length (m)	No.	Length (m)	No.	Length (m)	No.	Length (m)
±5%	30	44	103	40	123	37	142	35	160	33	176
	38	39	89	35	107	32	123	30	139	28	153
	45	34	80	31	95	28	110	27	123	25	136
	53	31	72	28	87	26	100	24	112	23	123
	61	28	66	26	80	24	91	22	103	21	113
	68	26	61	24	74	22	85	20	95	19	105
	76	25	57	22	69	20	80	19	89	18	98
±10%	30	57	132	52	159	48	183	45	206	42	227
	38	50	115	45	138	41	159	39	179	36	197
	45	44	102	40	123	37	141	34	159	32	175
	53	40	93	36	111	33	128	31	144	29	159
	61	37	85	33	102	30	118	28	132	27	146
	68	34	79	31	95	28	109	26	123	25	135
	76	32	74	29	89	26	102	25	115	23	127

In any installation, there are tradeoffs that need to be economically analyzed to determine the optimum design. Many computer software programs are available to assist the designer with the hydraulic and economic analysis related to pipe sizing, friction loss calculations, and energy requirements for various alternatives. Designers should become thoroughly familiar with the various software packages available and utilize those systems best suited for their needs.

Table 15.5. Maximum number of microsprinkler emitters and maximum lateral lengths for 25-mm lateral tubing diameter with ±5% or ±10% allowable flow variation (for level ground: based on Bowsmith (26.8 mm I.D.) tubing (1”-45 tubing).

Allowable flow variation	Flow rate (L/h)	Spacing on lateral (m) 2.3		3.0		3.8		4.6		5.3	
		No.	Length (m)	No.	Length (m)	No.	Length (m)	No.	Length (m)	No.	Length (m)
±5%	30	70	160	63	192	58	222	54	249	51	275
	38	60	139	54	167	50	192	47	216	44	238
	45	54	124	48	149	44	171	42	192	39	212
	53	49	112	44	135	40	155	38	174	36	192
	61	45	103	40	124	37	143	35	160	33	177
	68	41	96	37	115	34	132	32	149	30	164
	76	39	89	35	107	32	124	30	139	28	153
±10%	30	90	206	81	247	74	285	70	321	66	354
	38	78	179	70	215	64	247	60	278	57	307
	45	69	159	62	191	57	220	54	247	51	273
	53	63	144	56	173	52	200	49	224	46	247
	61	58	133	52	159	48	183	45	206	42	227
	68	53	123	48	148	44	170	41	191	39	211
	76	50	115	45	138	41	159	39	179	36	197

As pipe diameters increase, the cost per meter of the pipe (especially in sizes larger than 200 mm) becomes substantially greater, and the cost of fittings increases even more dramatically. Therefore, it is generally advantageous to minimize the lengths of the largest pipe sizes needed in the system. Pipe and fitting costs need to be balanced against the increased trenching and installation costs of smaller diameter piping.

Usually, submains and laterals are arranged to divide the main flow in two directions, thereby reducing the flow in any one section and decreasing the overall cost by using smaller pipe sizes. From a maintenance standpoint, it is desirable to have all of the laterals terminating on a roadway. Because clogging frequently occurs at the downstream end of laterals, inspection and maintenance, such as flushing, is easier when the laterals terminate at a readily accessible location. Additionally, in mature orchards, trees canopies often grow together, further restricting worker movement from row to row for the flushing operation.

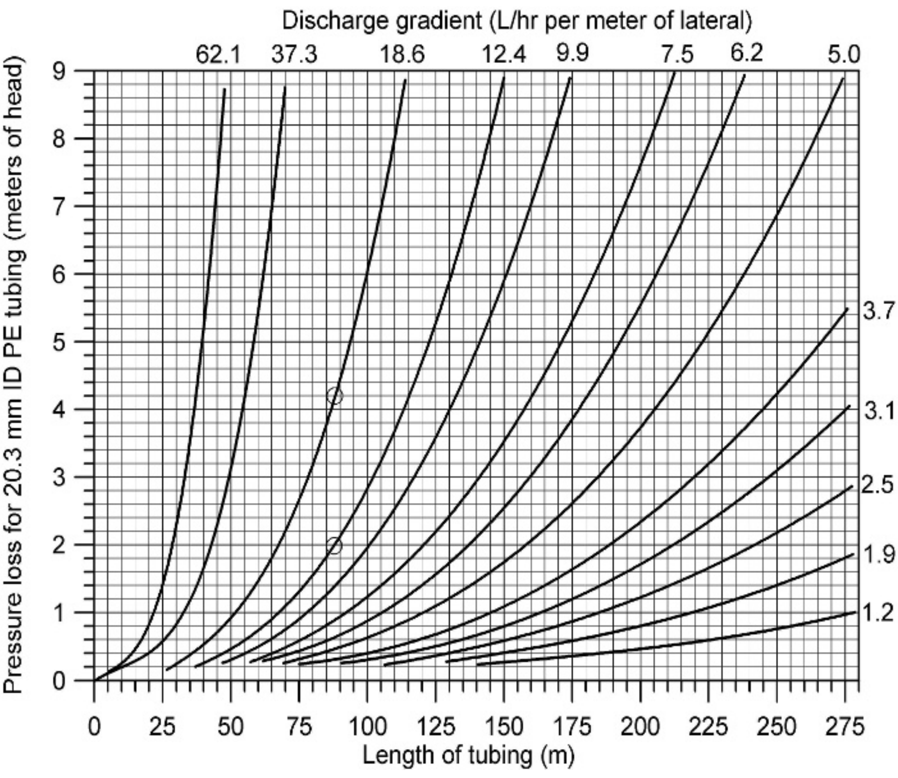

Figure 15.10. Friction loss for 20.3-mm I.D. polyethylene tubing based on flow gradient (L/h-m of tubing) and lateral length. Adapted from Boswell, (1990).

Example 15.2.

A 16 ha (gross area) orchard is planted with 4 m in-row tree spacing by 7 m between-row spacing. The overall area is 400 m x 400 m, with allowances for roads and machinery access around the perimeter reducing the planted area to 54 rows that are each 364 m long. Rows have 92 trees, and each tree will be watered by a single microsprinkler on a stake assembly. Larger diameter orifices are preferred for maintenance and freeze protection considerations. In addition, past experience has shown that wetting 40-80% of the area is most advantageous. Trees are planted on a sandy soil, with peak ET requirements of 7 mm/day. Water supply is from a canal that runs along one side of the property perpendicular to the tree rows. The pump station will be powered by a diesel engine, with about 3 m of lift from the canal to the pump. The land has no significant overall slope throughout the block, but there are several swales and undulations that are ±1 m of the average elevation. Lateral tubing is available in nominal sizes of 14, 19, and 25 mm. The emitters available are those listed in Tab. 15.2.

Emitter Selection

Because freeze protection is desired, the system must have the capacity to apply water to all trees at once with a minimum flow of 19 m^3/ha-h (see section 15.4.3.). Since the system will not be zoned, run times to apply irrigation are not constrained. The surface area allocated to each tree in a 4 x 7 setting is 28 m^2 (357 trees/ha), with the preferred emitter having wetted areas of 11.2 m^2 to 22.4 m^2 (40-80%). From Tab. 15.2, the color-coded emitters and operating pressures that meet this requirement are as follows:

Base	*Pressure*	*Area (m^2)*	*L/h*	*m^3/ha-h*
Blue	*172*	*12.9*	*43*	*15.4*
Green	*103*	*11.6*	*49*	*17.5*
Green	***138***	***15.3***	***56***	***20.0***
Green	*172*	*19.1*	*62*	*22.1*
Red	*103*	*16.2*	*74*	*26.4*

It is apparent that the green base emitter (1.27 mm orifice) is the best choice to meet wetted area and freeze protection requirements. The blue base emitter at 172 kPa meets the wetted area requirements, but does not meet the freeze protection required flowrate. The red base emitter would work at 103 kPa, but experience has shown less clogging problems when systems are operated at higher pressures. At higher pressures, friction and elevation have less impact on EU than at lower pressure (i.e., 20 kPa of friction loss in a system with an average of 100 kPa operating pressure is a 20% loss, where the same 20 kPa loss in a system operating at 175 kPa average pressure is an 11% loss). In addition, red base emitters would require about 30% higher flowrate in the system, and thus, increasing the costs of components such as pump station, mains, submains, and laterals.

Therefore, the green base emitters operating at 138 kPa are initially selected for the orchard. The emitters will wet about 55% of the area allocated to each tree and meet freeze protection requirements. Overall, the system will need to deliver 54 rows x 92 trees/row x 56 L/h-tree = 278.2 m^3/h = 4,636 L/min = 0.077 m^3/s of water to the orchard.

The daily run time at 100% efficiency to meet the peak ET rate of 7 mm/day will be:

7 ha-mm/day = 70,000 L/ha-day = 70 m^3/ha-day requirement
Unit area flow: 56 L/h x 357 trees/ha = 20.0 m^3/h
Run time = 70 m^3/ha-day requirement / 20.0 m^3/ha-h flow = 3.5 h/day

Applications during calm, humid night applications may have high application efficiencies (90%+) and run times may be in the range of 3.9 hours (3.5 h/day divided by 90% efficiency). During hot, dry, windy conditions, efficiencies may be significantly less. If the application efficiency is reduced to 75%, run times may be increased to 4.6 h (3.5 h/day divided by 75% efficiency).

Allowable Pressure Variation

The ratio of the minimum to average flowrates resulting from pressure variation in the system can be calculated by rearranging the terms in Eq. 15.7. For the parameters of EU = 0.90, C_{vm} = 0.03, and n =1, the ratio of minimum to average flowrate is:

$$\frac{q_{min}}{q_{avg}} = \frac{EU \bullet \sqrt{n}}{1-(1.27 \bullet C_{vm})} = \frac{0.90 \bullet \sqrt{1}}{1-(1.27 \bullet 0.03)} = 0.936$$

The pressure variation allowable in the system can be calculated from Eq. 15.6 with q_{avg} / q_{min} = 0.936 and x for green base emitter = 0.46 (see Example 15.1).

$$\frac{P_{min}}{P_{avg}} = (0.936)^{\frac{1}{0.46}} = 0.866$$

Rearranging, P_{min} = 0.866 x P_{avg} and with the average system pressure being be set at 138 kPa for freeze protection, maintenance, and wetting pattern objectives, P_{min} = 0.866 x 138 kPa = 119.5 kPa

ΔP = 2.5 x (138 kPa - 119.5 kPa) = 46.3 kPa *from Eq. 15.8*

P_a = 46.3 kPa - (1 m · 9.81 kPa/m) = 36.5 kPa *from Eq. 15.9*

Lateral Tubing Layout

In order to minimize the cost of the main and submains, the pump station will be located between the 27th and 28th rows at the edge of the planting. A number of configurations for the layout are possible, but they have been reduced to those depicted in Figs. 15.11 and 15.12.

Option 1 (Fig. 15.11): Each submain will serve 27 rows, and each lateral will serve 46 trees in each direction. The flowrate from the submain into each lateral will average 42.9 L/min (46 trees x 56 L/h-tree). The flowrate into each submain from the mainline will need to be 2318 L/min (42.9 L/min-lateral x 54 laterals). Total flow into the mainline must be 4636 L/min. From Tab. 15.4, the conditions of 56 L/h emitter flow at a spacing of 4 m is not included. Interpolating from the table, a maximum of 25 emitters is allowable with the 18-mm tubing for a ±5% flow variation for conditions of 56 L/h at 4-m spacing. Because each row will have 46 trees in this option, the 18-mm tubing is not acceptable for this design.

The same process is repeated for the 25-mm tubing. By interpolating from Tab. 15.5, a maximum of about 38 emitters is allowable with the 25-mm tubing for a ±5% flow variation for conditions of 56 L/h at 4 m spacing. Therefore, the 25 mm tubing is also unacceptable. In some areas, larger tubing may be available. However, the significantly higher cost per meter(about 40% more for 32-mm than 25- mm tubing) and the shorter coil lengths requiring more couplings makes larger tubing a less attractive alternative.

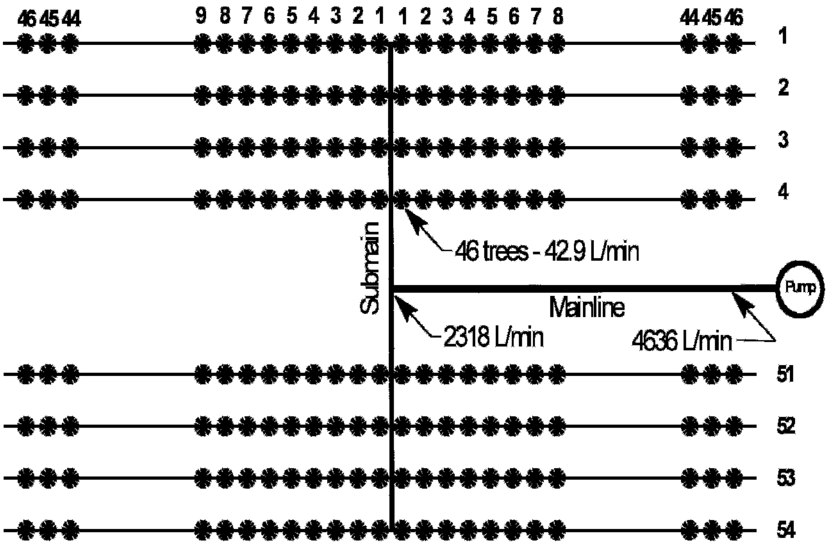

Figure 15.11. Layout of main, submain, and laterals for design option 1.

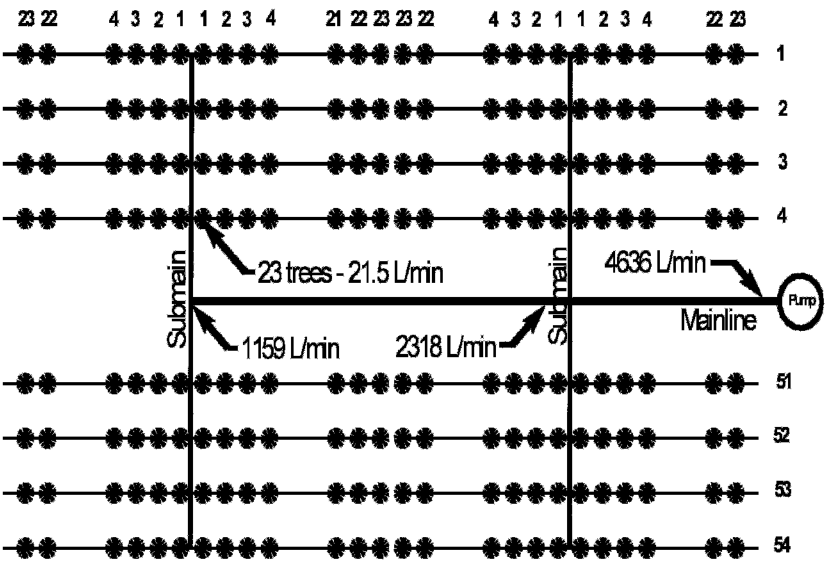

Figure 15.12. Layout of main, submain, and laterals for design option 2.

Option 2 (Fig. 15.12): *There will be 4 submains, each serving 27 laterals that have 23 trees in each direction. The flowrate from submains into each lateral will average 21.5 L/min (23 trees x 56 L/h-tree). The flowrate into each submain from the mainline must be 1159 L/min in each direction (21.5 L/min-lateral x 54 laterals). Total flow into the mainline must be 4636 L/min. From the preceding calculations above, a maximum of 25 emitters was found to be allowable with the 18-mm tubing for a ±5% flow variation for conditions of 56 L/h at 4-m spacing. Therefore, 18-mm tubing is acceptable for this design.*

Alternately, the flow gradient method can be used to select tubing size and determine friction losses in the lateral. To use Fig. 15.10, the lateral length and the flow gradient must be known. The flow gradient for this system would be 56 L/h per 4 m of tubing or 14.0 L/h-m. Laterals would be 88 m long (22 trees x 4 m spacing). From Fig. 15.10, the closest lines are for flow gradients of 12.4 and 18.6 L/h-m. For a length of 88 m, a flow gradient of 12.4 L/h-m has a friction loss of 2.0 m and at 18.6 L/h-m, the loss is 4.2 m (circled on Fig. 15.10). By interpolation, the friction loss for a flow gradient of 14.0 L/h-m would be about 2.6 m or 25.5 kPa (2.6 m x 9.81 kPa/m). Therefore, the design should be adequate because the allowable pressure variation for a EU of 0.90 was calculated as 36.5 kPa.

Pressure Regulators
In this example, there was no need for pressure regulators due to the level terrain. In many cases, this situation does not exist, and the design process must be adjusted. To select the proper pressure regulator, the lateral inlet pressure and flowrate need to be known. These values are then matched with the specifications for various models to determine the most acceptable choice because there is rarely an exact match. Keep in mind that there will be some pressure losses in the regulator itself. This loss should be added to that calculated for the laterals to determine the appropriate regulator.

15.4. UNIQUE MANAGEMENT CONSIDERATIONS

15.4.1. Young Trees

During the first few years of an orchard, trees cover only a small portion of the total area. Often, growers will utilize microsprinklers with either part-circle deflectors (90°, 120°, or 180°) or top hats that confine the flow to a small area (typically 0.9-1.2 m diameter) around the tree (Fig. 15.13). The small area wetted by the emitter requires special attention. Application rates per unit area from these assemblies can be quite high. For example, a 50 L/h emitter with a young tree deflector confining the flow to an area 0.9 m in diameter will have an effective application rate of about 80 L/h. The time required to apply a depth of water equivalent to 20 mm depth would only be 15 min.

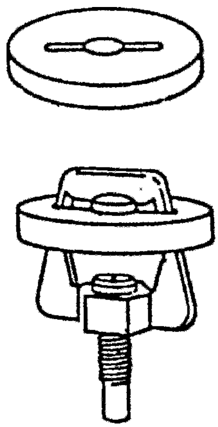

Figure 15.13. A 360° emitter with 'top hat' downspray for young trees. Courtesy of Maxijet, Inc.

In a lysimeter study of young trees, it was demonstrated that the small wetted diameter of these types of microsprinklers could cause nitrogen leaching on sandy soils (Boman, 1993). Nitrate leaching occurred on many occasions during fertigation events even though fertigation and flushing cycles were completed in less than 30 min with 38 L/h emitters. In a typical orchard situation, materials injected at the pump station may take 30 min or more to reach the most distant trees. Therefore, the fertigation/flush cycle time in large systems needs to be 1 h or more. The possibility of leaching soluble nutrients is greatest on sandy soils with small-diameter wetting patterns when application rates exceed 20 mm/h.

15.4.2. Application Volumes

Water use rates and irrigation requirements are usually presented in terms of depth. In practice, decisions on run times are normally made based on a volume per tree applied. Converting the depths to per-tree volumes is required to manage microirrigation systems that water only a portion of the ground surface. Detailed conversion from irrigation depth to irrigation volume requires knowledge of tree planting density and tree size and health. ET rates expressed as depths can be converted to volume by:

$$Q_{vol} = ET \bullet A \tag{15.10}$$

where Q_{vol} is the irrigation volume in L/tree-day, ET is the tree water use in mm/day, and A is the area represented by each tree in m^2.

The conversion should only be used as a starting point with the actual water estimates based on the size and condition of trees in each zone. The water use per tree for mature trees in high density plantings will be less than that in low density plantings due to smaller tree size.

The optimum interval between irrigation events depends on the design of the irrigation system, time of year, and soil characteristics, as well as tree size and condition. Evapotranspiration rates of trees are highly dependant on climatic conditions. Higher evaporation and transpiration rates occur on clear, dry, windy, sunny summer days than on cool, damp, overcast autumn days. Therefore, irrigation frequency must be adjusted throughout the year.

During the critical flowering and early fruit formation periods, it is desirable to limit water stress. To minimize water stress during these periods, it is recommended to limit extraction of soil water to no greater than 1/3 of available water before irrigation. During less critical stages, soil water depletion can be higher (e.g., 50%) without serious effects on yield or quality on several types of tree and vine varieties.

The amount of water needed by an orchard is highly dependent on size and health of the trees. Young trees may require only a few liters per day, whereas mature trees may need over 200 L/day. As the soil dries during extended dry periods, it is important to supply irrigation water at the appropriate frequency and volume to minimize stress to the trees. With proper irrigation, most of the water used by the trees will come from the soil volume wetted by the irrigation system. The amount of water that is available in this wetted volume depends on the soil texture and organic content. Typical microsprinklers wet a circle of 3.5 to 5.0 m in diameter. The water available within the area wetted by the microsprinkler can be calculated based on soil water holding capacity, root zone depth, and the area that is managed as presented in the following example.

Example 15.3.

Estimate the irrigation interval for mature fruit trees planted at a 4 x 7 m spacing in a fine sand soil with a total available water content (TAW) of 0.06 cm/cm and a managed root zone of 1.0 m. Assume that the average daily evapotranspiration is 6 mm/d occurring during the critical bloom period when soil water depletion should be limited to less than 1/3 available water. Each tree has a single microsprinkler that discharges 40 L/h and wets a circle 4.5 m in diameter. At each irrigation, the soil is filled to field capacity (FC). Calculate the water use per tree, assuming the 6 mm application is equally distributed among trees.

ET/tree = 6 mm/day x 1 m/1000 mm x 4 m x 7 m = 0.168 m^3/day = 168 L/tree-day

Total available water (TAW) = 0.06 cm/cm x 100 cm = 6.0 cm = 0.06 m

Volume of water = area x depth of water in root zone
= 3.14/4 x (4.5 m)^2 x 0.06 m = 0.95 m^3 = 950 L

Amount of water available between FC and 1/3 depletion of TAW =
950 L x 0.33 = 314 L

The irrigation interval would be: 314 L available / 168 L/day = 1.9 days

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When these calculations are repeated for other diameters using the same rooting depth and available water, it is apparent that small wetted diameters require more frequent irrigations to adequately replace water extracted by the trees.

15.4.3. Freeze Protection

Various types of irrigation have been used for frost and freeze protection for many years. Microsprinkler irrigation has been shown to be effective in providing good protection for young trees and partial protection of mature trees (Fig. 15.14). In one study, the lower leaves in the direct water spray zone stayed above freezing and were as much as 7.8° C warmer than dry leaves in nonirrigated plots (Parsons et al., 1981). Other work showed that microsprinklers maintained trunk temperatures near -1.1° C when the minimum air temperature reached -9.4° C in a freeze with winds exceeding 32 km/h (Davies et al., 1984). However, improper use of water can increase evaporative cooling or ice loading and can cause greater damage than when no water is used.

Figure 15.14. Microsprinkler used for freeze protection on young citrus tree.

The energy released when the irrigation water decreases from its initial temperature to 0° C contributes sensible heat during a freeze event. When temperatures drop below freezing, the latent heat of fusion is released when the water freezes. As long as enough water is continuously applied to a plant, the heat generated when water freezes can keep the plant at or near 0° C. At least 6 to 9 mm/h is generally required for cold protection. At very low temperatures, low humidity, or high winds, more water must be applied to get adequate protection.

Microsprinklers can also raise the dew point or frost point temperature in the orchard. When the temperature drops to the frost point, heat is released as the water vapor is converted to ice crystals. When the air temperature reaches the dew point temperature, the rate of cooling slows down because heat is released as the water vapor in the air condenses. It has been suggested that microsprinklers can provide some protection above the spray zone because moist air rises and condenses higher up in the canopy. Depending on the dew point temperature, microsprinklers can sometimes create fog on cold nights. Fog is beneficial for frost protection and when the fog is sufficiently dense and the droplets are of the proper size, the rate of cooling can be slowed because fog can act like a blanket and reduce the rate of radiation loss. This phenomenon is similar to clouds, which consist of water droplets that act like a blanket and slow radiation loss.

If the water application rate is high enough up the trunk of a young tree, the tree will be protected by the ice formation. However, at the edge and outside of the iced zone, temperatures will not be maintained at 0^{o} C, and those tree parts will probably be damaged or killed. Therefore, usually the tops of young trees or branches outside the iced zone are severely damaged after a freeze.

Microsprinklers can provide some protection to leaves and stems, particularly on the lower and inner part of the canopy. A dense canopy tends to retain heat from the soil and provide better protection than a thin canopy. Damage will frequently be seen on the outer and upper parts of the tree after severe freezes. Because the fruit is more sensitive to cold temperatures than leaves or stems, microsprinklers generally do not protect the fruit. At higher volumes, microsprinklers will help protect fruit a little better than no irrigation, but in most cases microsprinkler irrigation protects only the tree not the fruit.

The microsprinklers must be close enough to the young tree so that water sprays directly on the trunk and lower part of the tree. Emitters that produce a 90^{o} or 180^{o} pattern concentrate the water on the young tree and provide better protection than 360^{o} patterns. If the microsprinkler is too far away from the young tree, wind can blow the water away. If the water freezes before it hits the tree, milky white ice can form on the tree. Protection under milky ice is usually not as good as under clear ice. It is best to put the microsprinkler on the upwind side of the tree, 0.4 to 0.7 m from the trunk. Emitters on the downwind side of young trees have caused significantly more damage than no irrigation (Parsons et al., 1985).

While microsprinklers perform best for protecting young trees, they also can provide partial protection of mature trees. The greatest benefit has been observed in calm frosts, but other examples of improved recovery of mature trees have been observed where microsprinklers have been used in windy freezes. In a relatively calm frost, microsprinklers benefited trees over 4 m tall. Tree recovery and leaf canopy density 3 months after a freeze were better where microsprinklers were operated in an orchard than where they were not operated (Oswalt and Parsons, 1981). High-flow emitters provide more protection than low-flow emitters. In general, the higher the volume of water provided by microsprinklers, the more effective the cold protection. Approximately 19 m^3/ha-h is needed to provide reasonable protection. An application rate of 28 m^3/ha-h or more can provide even more cold protection (Parsons, 1984).

15.5. EVALUATION OF MICROSPRINKLER SYSTEMS

15.5.1. Uniformity

Uniformity is an indicator of how equal or unequal the application rates are from each individual emitter. A low coefficient of uniformity indicates that the application rates from the emitters are significantly different, whereas a high coefficient of uniformity indicates that the application rates from the delivery devices are very similar. The coefficient of uniformity does not indicate the distribution of applied water within the root zone. Several factors reduce uniformity in microsprinkler systems:

- Inadequate selection of pipe diameter and/or emitter type and flow.
- Emitter clogging.
- Changes in properties of emitters with time.
- Changes in system components such as pump efficiency or pressure regulation.
- Wind conditions that significantly affect the operation of the system.

15.5.2. Irrigation System Efficiency

Water application efficiency is the ratio of the quantity of water effectively applied into the crop root zone to the quantity delivered to the field. To attain high levels of efficiency, uniform flow throughout the system is required. Low efficiency in microsprinkler systems is usually due to a combination of the following factors:

- Poor soil water distribution pattern in relation to root distribution.
- Losses due to deep percolation.
- Losses due to evaporation from the soil surface.
- Wind drift and evaporation from emitter spray.

A more thorough discussion of efficiency and uniformity as they relate to design, operation, and maintenance of microirrigation systems is presented in Chapter 10.

15.5.3. Wetting Pattern

Evaluating pattern uniformity for spinner-emitters is much easier than for spray-emitters due to the distribution of water relative to the emitter. To evaluate spinners, catch cans should be placed at intervals of 0.3 to 0.4 m in two or more radial legs from the emitter. The cans can be of any size, but all should be of the same height and diameter. The system should be run for at least 1 h. The volume of water collected in each can should be measured with a graduated cylinder. As a general rule, at least 50% of the catch cans should receive near-average application depths.

Evaluating distribution uniformity for spray-type emitters with catch cans is more difficult due to the elongated, alternating, wet and dry surface patterns around the head. This petal pattern makes it difficult to place the cans directly under the spray jet or in the petal pattern itself. In addition, interpretation of any catch can data may not truly reflect subsoil water redistribution. Visual observations of soil wetting patterns from each radial leg should be used for evaluation of spray-type emitters. The ideal distribution resembles a petal pattern along each radial. The more uniform each radial leg is in creating a petal pattern, the more uniform will be the soil wetting.

A soil probe can be used to measure the horizontal and vertical distribution of applied water relative to the tree's root zone. In sandy soils, the soil should be probed 2 to 4 h after the irrigation. In most situations, trees should have at least 40% of their potential rooting zone wetted (i.e., with 4 x 7 ft. tree spacing (28 m^2), at least 11.2 m^2 should be watered). The soil probe will also provide information on the depth of water movement. Excessive water movement below the crop's root zone may result in leaching of fertilizers, water-logged conditions, and/or waste of water.

15.5.4. Effects of Wear

A thorough discussion of maintenance required to maintain efficient and economical microirrigation systems is presented in Chapter 11. Microsprinkler emitters are durable and should last many years in the field. However, wear on emitter orifices over long periods of operation can significantly increase microsprinkler flowrates and wetting patterns, especially if the irrigation water contains sand. Boman and Parsons (1993) examined several combinations of flow control method, base size, and operating pressures to determine their effects on long-term microsprinkler flowrates. Flow control methods were by orifice control (OC), vortex control (VC), and by pressure compensation (PC). Emitters with nominal flows of 38 L/h and 57 L/h with the three flow control methods were operated at 138 and 206 kPa for 2,000 h. Initially, emitter flows were individually measured from 20 emitters, and then repeated after 500, 1,000, and 2,000 hours. OC and VC emitters had increases in flowrates of 8 to11% after 2,000 h operation. After 500 h of operation, 57 L/h PC emitters had flow reductions of about 7% when operated at 138 kPa and 18% when operated at 207 kPa. These reductions in flowrate resulted from changes in the properties of the diaphragm. After 2,000 h of operation, the flowrate of the PC emitters was about 8% less than the initial values.

Microsprinkler systems must be designed to account for effects of wear on system components. Pumps, filters, and other system components should be designed with extra flow capacity of 10 to 15% to accommodate for wear on emitter orifices. The amount of increase in emitter flowrates over time depends on several factors such as operating pressure, materials used in emitter manufacturing, water source, filtration, and length of use. If the water contains sand or abrasive grit, the wear problem can be greatly accelerated.

LIST OF TERMS AND SYMBOLS

A	area represented by each tree, m^2
C_{vm}	manufacturing coefficient of variation, decimal
D	inside diameter of pipe or coupling, mm
EU	design emission uniformity in percent
ET	water use, mm/day
H_f	friction loss in m per 100 m of tubing, kPa
H_{fa}	friction loss in adapter, kPa
H_{fs}	friction loss in the microtubing, kPa per meter of length
$I.D.$	inside diameter, mm
K_d	emitter flow coefficient
n	number of emitters per tree
OD	outside diameter, mm

P	pressure, kPa
P_a	allowable pressure loss, kPa
P_{avg}	average system pressure, kPa
P_{elev}	pressure change resulting from elevation differences along lateral, kPa
P_{min}	minimum pressure in system, kPa
P_{reg}	pressure regular variation, kPa
Q	flowrate of emitter, L/h
Q_1	flowrate at pressure P_1 ,L/h
q_{avg}	average emitter flow, L/h
q_{min}	minimum emitter flow due to pressure variations in system, L/h
Q_{vol}	irrigation volume, L/tree-day
S_{dm}	standard deviation of emitter flowrate for new emitters
x	emitter exponent
ΔP	allowable pressure difference, kPa

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