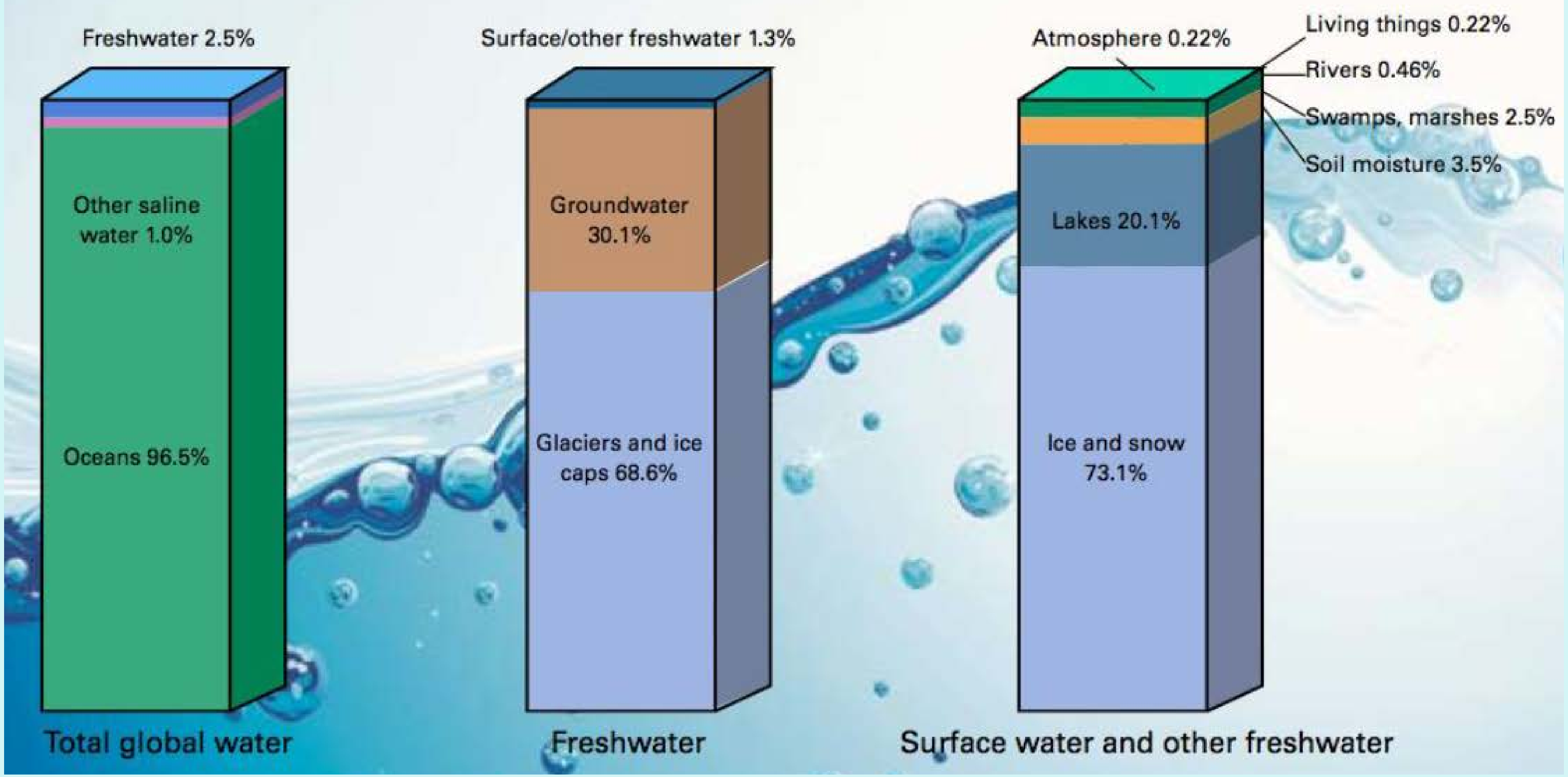
Chapter 4: Groundwater Conservation

Distribution of Earth's Water

- ✓Water is an essential resource for humans and for natural ecosystems.
- ✓Only a small percentage is available as freshwater



Source: Shildermanov, 1991

Groundwater Conservation

- The water budget is the **balance** between the water that **reaches the ground** as precipitation and the water that **leaves the ground** as evaporation, runoff and consumption.
- If the amount of precipitation of a region is greater than the evaporation and consumption added together, then that region has a **positive water balance**, or surplus.
- If the amount of precipitation is less than the usage and evaporation, then the region has a **negative water balance**, or deficit.

Factors controlling the water budget of a region

- The water budget of a region is influenced by many natural factors and human activities.

Some of the natural factors are:

- ✓ Climate condition
- ✓ Soil characteristics
- ✓ Type of vegetation
- ✓ Geology or type of underlying rock, etc

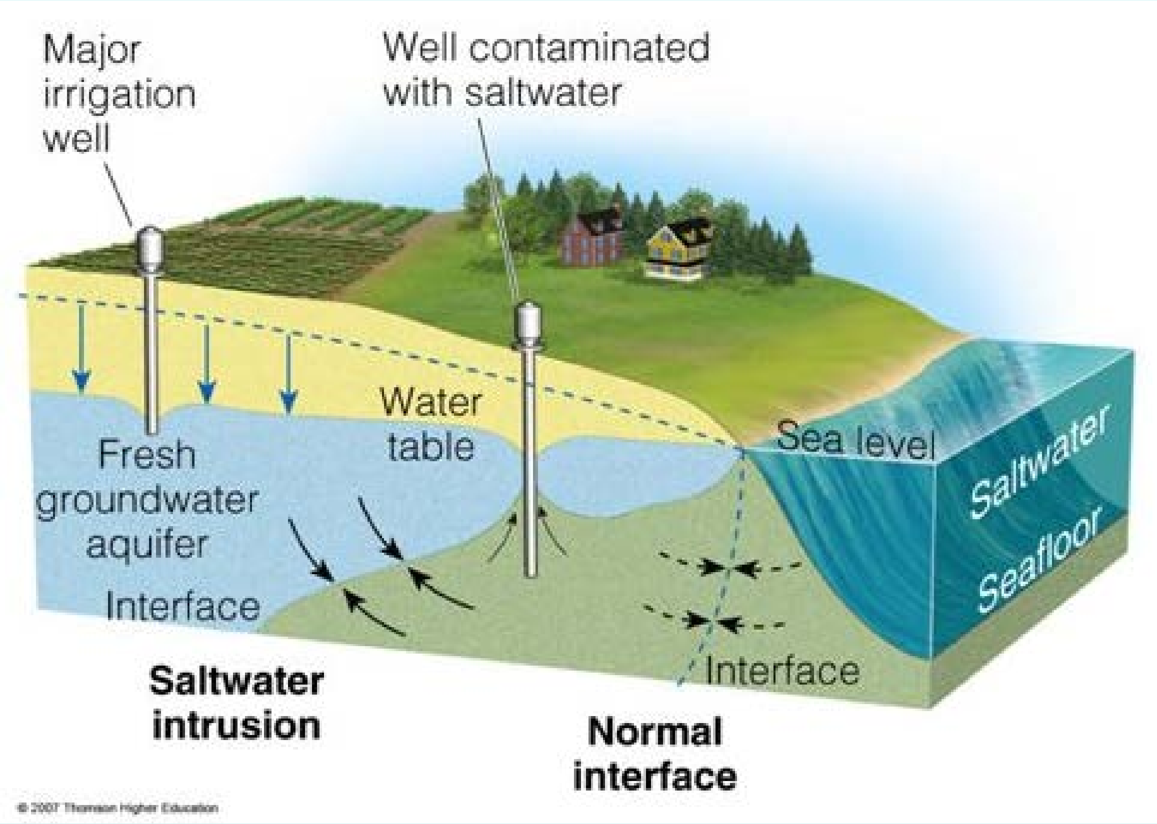
- About 30.1% of the earth's freshwater is in the form of groundwater.
- It is a very valuable resource and it is in a great demand
    - It should be conserved.

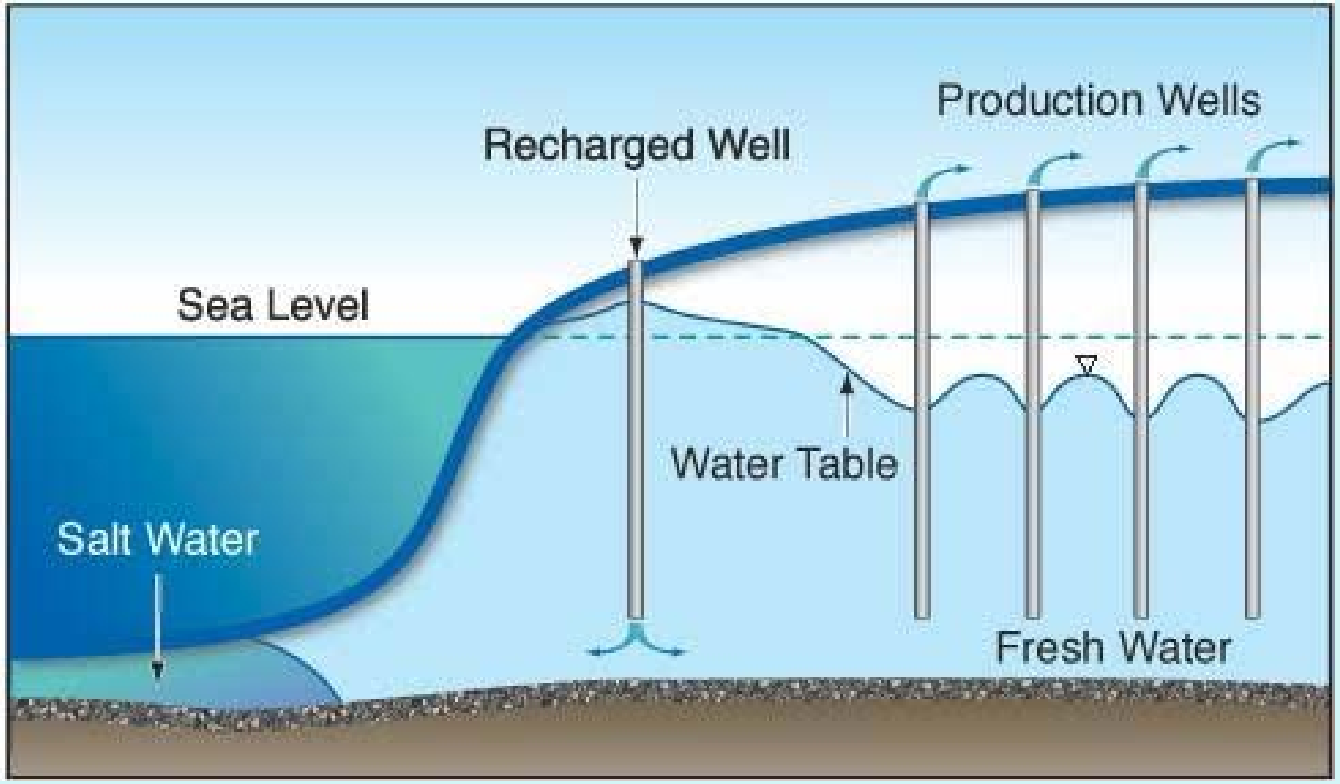
Groundwater Conservation

- The most common threats to groundwater are:
  - Overuse
  - Pollution

- If we take out more water than the aquifer can naturally recharge each year, then the consequences are **dramatic** and in many cases **irreversible**.
- Wells can dry and human communities might have no water
- In coastal areas over-pumping might replace fresh water by salt water
- By removing the water, the rocks become more compact, and the surface of the ground sinks. This phenomena is called subsidence.

Effects of Groundwater Over-pumping



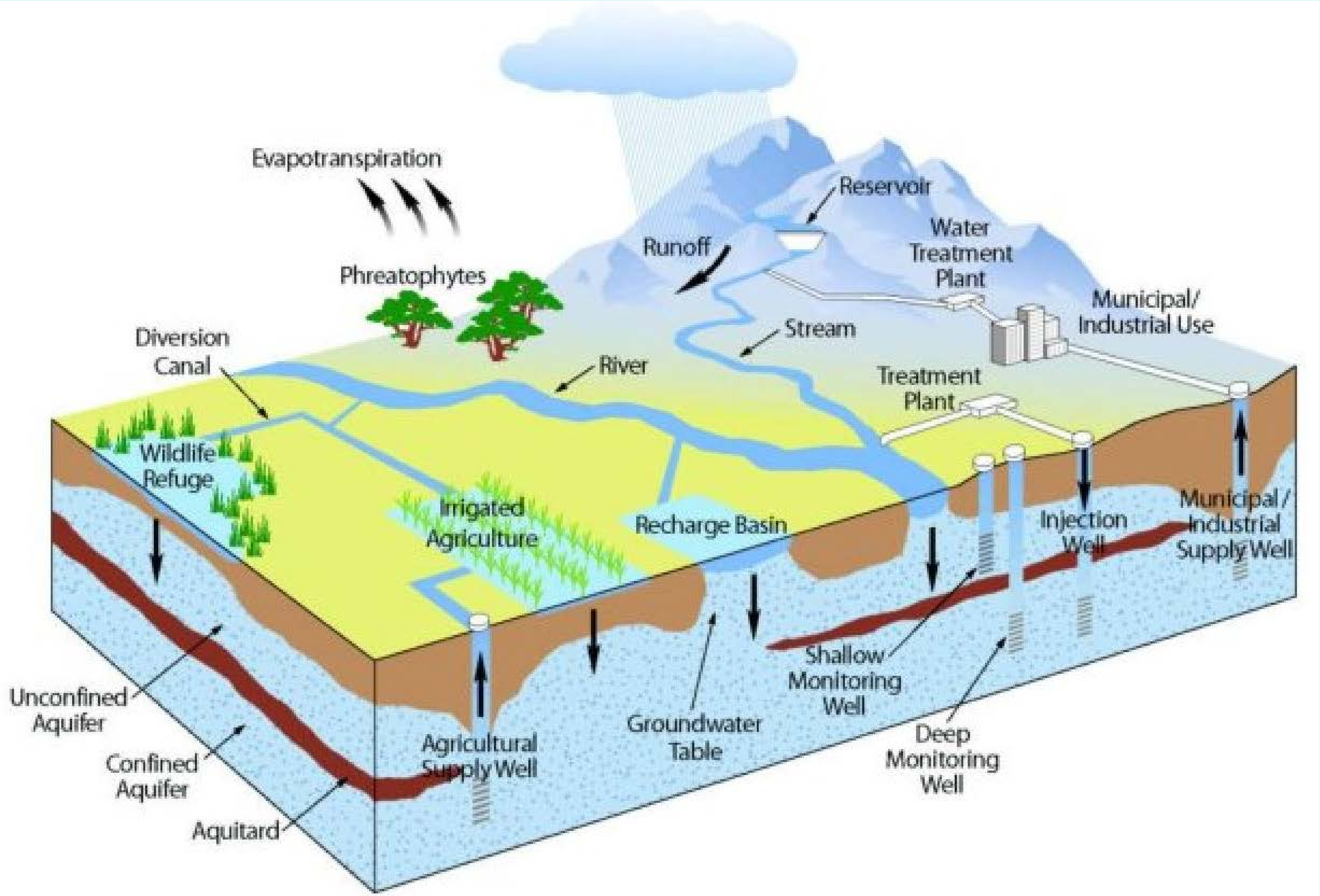


- Contaminate fresh water aquifers with salinity.

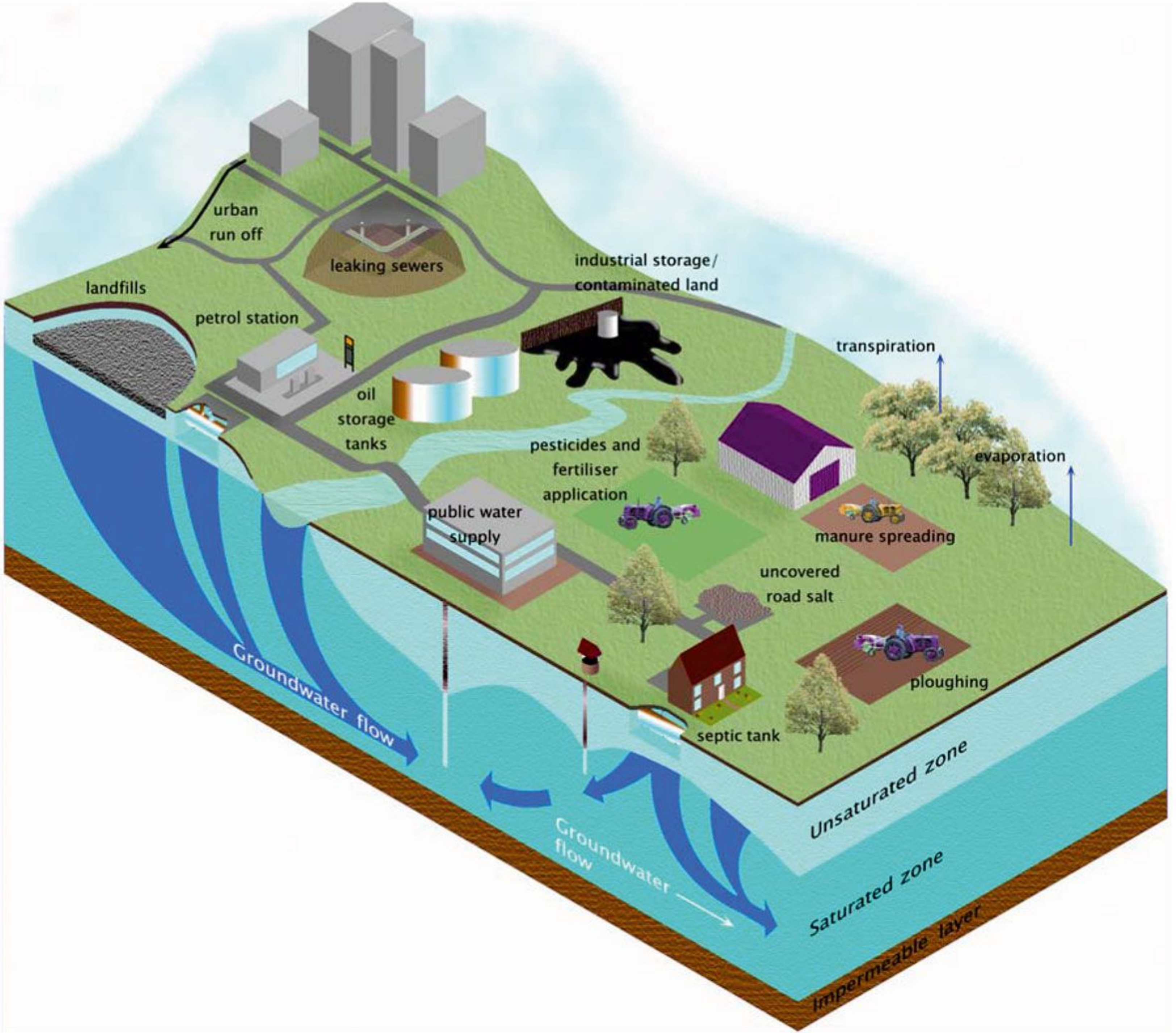
Groundwater Conservation

- By removing water from the subsoil the ground becomes more compacted.
- This is an unwanted phenomenon for two main reasons:
  - Once the porosity of the rocks is lost, the aquifer can not be recharged.
  - Secondly, if the ground loses some of its porosity, it reduces its volume, and sinks.

- Groundwater is recharged by rain seeping down through the soil.
- Virtually any harmful chemical that is disposed at the surface of the ground will reach the groundwater.


Evapotranspiration
Reservoir
Runoff
Water Treatment Plant
Phreatophytes
Municipal/ Industrial Use
Diversion Canal
Stream
River
Treatment Plant
Wildlife Refuge
Irrigated Agriculture
Recharge Basin
Injection Well
Municipal / Industrial Supply Well
Shallow Monitoring Well
Unconfined Aquifer
Groundwater Table
Deep Monitoring Well
Agricultural Supply Well
Confined Aquifer
Aquitard

Groundwater Conservation



Conservation of Groundwater-common tips

- Dispose of chemical properly
- Take used motor oil to a recycling center
- Limit the amount of fertilizer used on plants
- Reducing water losses through (run full loads of dishes and laundry, check for leaky faucets and have them fixed, water plants only when necessary)

- Reducing the use of pesticide and fertilizers
- Using environmental friendly chemicals in agriculture
- The used household water is pumped back into the ground through wells
- Water is also pumped into ponds and allowed to seep back into the ground
- More awareness programmers through out the world

Conservation of Groundwater

- Groundwater quality aspects mainly concern the chemical and microbial composition of the groundwater as well as the physical properties and their alteration.
- If groundwater is used for drinking water supply, it has to meet the quality requirements for food.
- Degradation of groundwater quality can be caused by various factors, e.g.:

  - ✓ the infiltration of polluted surface water,
  - ✓ the infiltration of sewage from sewers or other sanitary systems,
  - ✓ the inappropriate use of fertilizers and pesticides in agriculture (e.g. the widespread pollution by nitrates and pesticides),

Conservation of Groundwater

- ✓ the leachate from polluted sites (e.g. waste disposal sites and landfills with inappropriate liner systems),
- ✓ the inappropriate transportation, storage, and application of substances hazardous to groundwater (e.g. spillage from traffic accidents, or leakage from storage facilities of mineral oil or chlorinated hydrocarbons, or accidents occurring in deposits of radioactive waste),
- ✓ the **deposition** of air-borne pollutants on the **ground surface** and their subsequent **infiltration into the subsurface**,
- ✓ the **intrusion of salt water** in coastal aquifers, caused by an **overexploitation** of groundwater,
- ✓ the **salinization of aquifers** due to agricultural activities,

Conservation of Groundwater

- ✓ thermal influence on groundwater (**heating or cooling**), and the subsequent **alteration** of the **physical, chemical** and **biological properties** of groundwater,
- ✓ the **mixing** of groundwater of **differing origins**, which may alter the physical, chemical and biological properties of groundwater,
- ✓ any **unfavorable alteration** of physical, chemical and biological properties in the aquifer.

- The most important impacts on groundwater are (a) **overexploitation** of aquifers and (b) release of **pollutants**.
- Therefore, groundwater systems often play an important role in **environmental impact** studies.

Conservation of Groundwater

- The protection of groundwater resources represents an indispensable measure for a **sustainable use**.
- A prerequisite is the **investigation of the groundwater flow** and the **transport** and
  - the **fate of dissolved substances**,
    - ✓ of non-aqueous-phase liquids, as well as colloidal particles in the subsurface.

- Moreover, aspects of **water quality** are strongly related to groundwater flow, since the **advective motion** represents the main process for the migration of dissolved substances and of heat in groundwater.

Conservation of Groundwater

- Considering all the technical, legal, social and financial difficulties, which arise or which could arise from remediating contaminated aquifers,
    - ✓ it is obvious that the timely protection of the groundwater environment is preferable.
- National regulations define the framework for the protection of groundwater environments and especially of drinking water wells and springs.
- On the one hand there are existing or planned activities (land use, etc.),
    - which represent hazards or risks for particular groundwater environments, and
    - on the other hand, the aquifers exhibit a certain degree of vulnerability to a wide range of threats like chemical or biological pollution.

Conservation of Groundwater

Accordingly, the principal steps towards the protection of groundwater environments are:

- the evaluation of the existing and planned use of groundwater,
- the characterization of the site,
- the assessment of the existing and potential groundwater contamination or contamination risks,
- the evaluation and implementation of the groundwater protection measures.

Groundwater

- Groundwater resource development is based on the concept of **groundwater yield**,
  - difficult to meet a set of hydrologic, social, and economic objectives and
  - may be defined as the balance between the benefits of maximum **allowed extraction rates** and undesired changes by **pumping** and pollution.

- In this concept **groundwater recharge** is one important component, which is mostly determined under special steady-state initial and boundary conditions;
  - however, groundwater development may change these conditions throughout the **recharge–discharge** regime with time.

Groundwater Conservation

- The development **of sustainable groundwater management** strategies cannot refer to single numbers but needs **an integrated concept** within a specific timeframe.

The management of groundwater resources involves the following subjects:

- ✓ Determination of the range of groundwater recharge with appropriate methods,
- ✓ Manipulation of groundwater recharge according to local needs and possibilities,
- ✓ Protection of the recharge pathways to safeguard natural attenuation,
- ✓ Monitoring aquifer exploitation,
- ✓ The development of special control (early warning) systems to recognize, assess, and prevent groundwater degradation in time.

Groundwater Conservation

- Groundwater recharge in humid temperate and tropical climates accounts for more than 10% and
  - ✓in arid (dry-land) areas for less than 5% of the precipitation;
  - ✓in semi-arid and cold climates the values lie in between these numbers.

The **precision in determining groundwater recharge** depends significantly on

- The conceptual model, based on which **percolation** has been evaluated,
- The precision in determining the **source** (precipitation, snowmelt, dew formation, and infiltration) and **loss functions** (evapotranspiration, overland-flow, interflow),
- The **time span**, to which groundwater recharge refers to.

Groundwater Conservation

- In contrast to infiltration, percolation is a rather **slow process** and both change with boundary conditions mostly in a non-linear way:
  - ✓ therefore, only average values of groundwater recharge result from most studies.
- Nowadays, however, there is also a strong interest to obtain **short-term information** on
  - infiltration, discharge, and the storage of subsurface water for agriculture and irrigation planning as well as
    - for early-warning systems to improve flood control.
- **Long-term** information on the **water balance** refers mostly to precipitation and discharge measurements on a catchment scale;
  - this needs a minimum of 10 years of observation (tropical) to more than 25 years (arid dry land) climates.

Groundwater Conservation

- Such long-term observations
  - smoothen the short-term variability of precipitation and evapotranspiration, which govern the input function of discharge and
  - reduce errors related to **delayed responses** of the **subsurface system** in connection with water storage and release and **slow percolation** velocities.

- In developed countries, such long-term observations on discharge and groundwater level fluctuation exist continuously since the end of the 19th and beginning of the 20th century and are still operating.

Groundwater Conservation

- In many developing countries and areas with a small population, such measurements mostly started in the second half of the 20th century;
  - however, these observations often stopped after some years or decades, because of logistic problems.

- For the last 60 years, artificial and environmental tracer techniques have been developed since the 1940s using chlorides and environmental isotopes or
  - ✓ analyzing in rivers the hydraulic or environmental tracer response to storm events.

Groundwater Conservation

Groundwater recharge on continents has an **uneven horizontal** and **vertical distribution**;

- Horizontally, it depends
  - ✓on climate and weather trajectories,
  - ✓transformations of precipitation and air humidity at the interface atmosphere/biosphere
  - ✓topographic factors and lithology,
  - ✓hydraulic interfaces in the effective root zone;

- Vertically, it depends on the **depth-related sequence** of hydraulic parameters and the **thickness of aquifer systems**.

Groundwater Conservation

- In all climate zones, old (>100 years) and fossil groundwater (>10,000 years) are **more abundant** than the presently recharged groundwater (<100 years old);
  - these old (historic) and fossil groundwater **should not be wasted**, in order to keep operational a buffer system for **variable natural**, **man-made recharge**, the many **ecological functions** of water and emergency situations.

- Groundwater recharge can be **manipulated**
  - ✓ by selecting an appropriate vegetation cover,
  - ✓ by forced gradient river-infiltration and
  - ✓ by artificial recharge through basins, ponds, artificial lakes, and wells.

Groundwater Conservation

- Both the quality and the quantity of the recharged waters are significantly influenced by
  - the plant cover and land use,
    - especially by irrigation practice, urbanization, industrialization, and
      - in more recent times also by the import of blue water from distant areas.

Groundwater recharge occurs in all climate zones, albeit at different rates;

✓ In desert regions there is **little groundwater recharge** (<5 mm/a), which occurs very **irregularly**,

✓ In semi-arid regions it is <50 mm/a and undergoes **large annual fluctuations**,

✓ In humid tropical regions <100 mm and again varies **considerable by years**,

✓ In humid temperate regions groundwater recharge is up to 300 mm/a.

Groundwater Conservation

- Groundwater flows in aquifer systems, having particular hydraulic properties.
- In unconsolidated aquifers, the hydraulic conductivity and porosity generally decrease with depth;
  - statistically, hydraulic conductivities of fissured rocks also decrease with depth.
- Therefore, groundwater recharge **cannot be distributed equally among all aquifers**

As a golden rule in water management, the availability of water resources for human beings and ecosystems **should not exceed the excess water** (P-ET) in the continental water cycle, draining to oceans;

- in the special case of groundwater exploitation for water supply, it **should not exceed the average groundwater recharge**

Groundwater Conservation

- All continuous water use in **excess of groundwater recharge** or **unproductive groundwater losses** are called *water mining* or *overexploitation* and leads on a long run of time to
  - ✓ a regional water table decline,
  - ✓ ecological, soil fertility, hygienic and
  - ✓ soil/rock mechanic problems.

To avoid groundwater mining, which is often met in **dry-lands and urbanized areas**, the following options exist:

- ✓ Store surface run-off,
- ✓ Enhance groundwater recharge by forced infiltration,
- ✓ Transfer water over long distances to water scarce areas,
- ✓ Desalinate ocean or brackish water, or
- ✓ Recycle treated gray water.

Groundwater Conservation

- River discharge on continents does not always reflect the amount of present, average groundwater recharge;
  - in most arid and some semi-arid areas, it often includes a transient component,
    - dating back to groundwater recharge from historic (100 < t < 10 000 years) or
    - geologic times (>10,000 years).

- Because only **renewable water resources** contribute on a long run of time to **sustainability** of health and life in ecosystems,
  - it is important to determine the **present and past recharge** with high precision as well as on different scales and
    - to asses these results with observed discharges of catchments.

Groundwater Conservation

- There is a **delay time** in the sub-surface flow time before re-appearing at the surface.
- This delay time smoothens yearly variations of the intensity of groundwater recharge because of variations in precipitation and,
  - to a minor extent, also to evapotranspiration;
    - this makes groundwater more **continuously available for exploitation** than the collection and surface storage of rainfall, provided wells are appropriate positioned, constructed, and managed.

- The delayed run-off of groundwater recharge enhances natural attenuation processes in the subsurface and thus contributes significantly to **subsurface water quality**.

Groundwater Conservation

- Surface runoff offers easy access to contaminants; it has an abundant biomass and bioactivity of all animal and plant sizes;

- However, in rivers, mean residence times are short and dilution is not strong.
- In contrast, groundwater and percolation water have
  - ✓ low biomasses and bioactivities by habitat reasons (small pore and fissure sizes),
  - ✓ low water contents and flow velocities and
  - ✓ hence, low potential nutrient exchange between water and biofilms.

Mechanism and Processes of Recharge

- The groundwater recharge flux is the residuum of the infiltration flux
  - after accounting for water storage,
  - losses by evapotranspiration and of
  - inter-flow in the percolation zone;
    - it enters groundwater through the capillary fringe and the groundwater table.

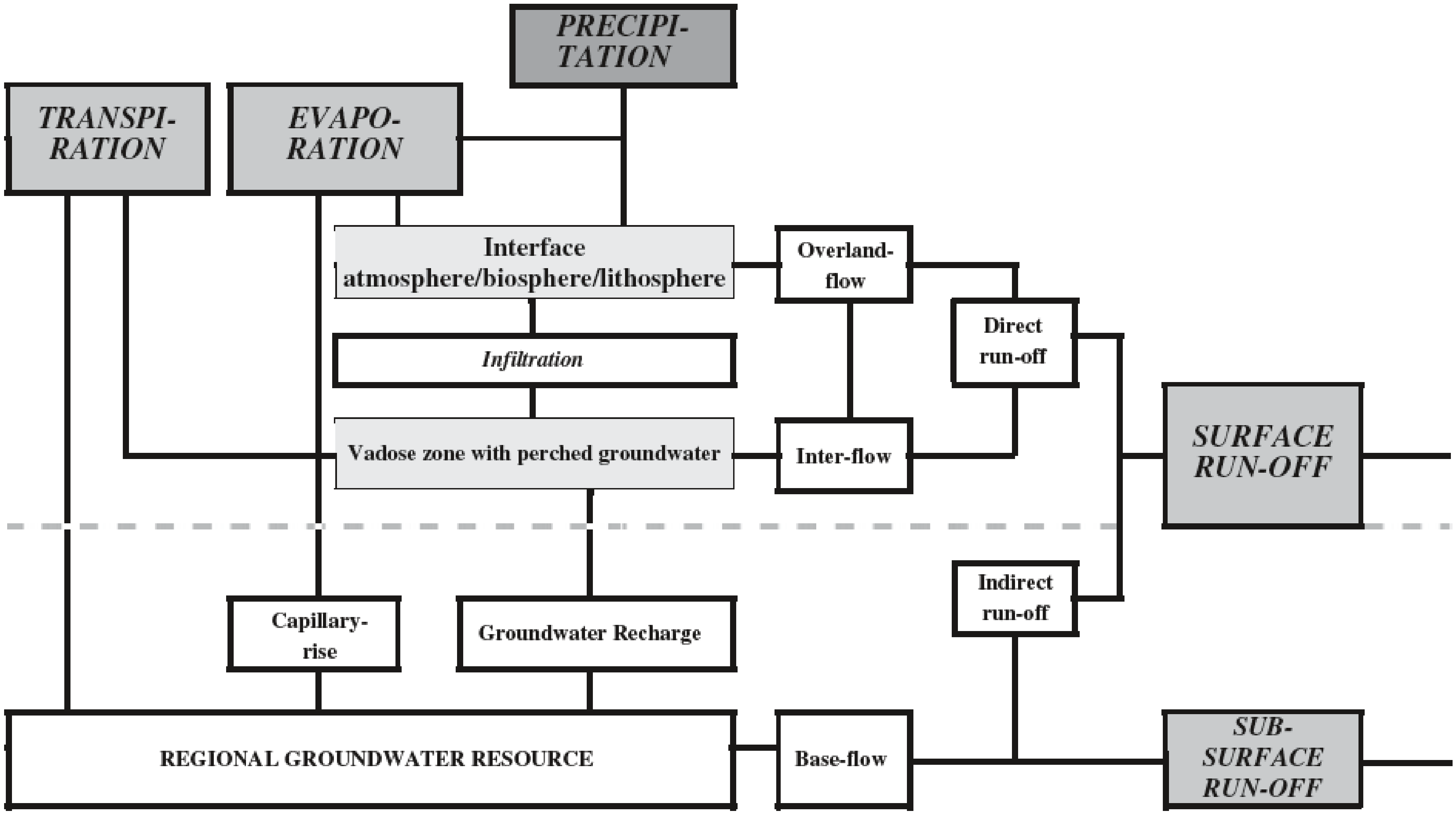
- Precipitation, run-off, and evaporation are the main characteristics of the water cycle all over the world; on continents transpiration, surface and subsurface runoff as well as storage appear as additional elements.

Mechanism and Processes of Recharge

- The transformation from the **input** (precipitation) to the **output** quantities (evapotranspiration, overland-flow, inter-flow, and groundwater recharge) on continents is schematically shown in Figure.

- This scheme is a simplification of reality, because it **represents only main processes** and neglects all interferences, which modify real fluxes.

Mechanism and Processes of Recharge



Mechanism and Processes of Recharge

- Precipitation has an uneven global distribution,
  - ✓ depending on wind systems,
  - ✓ transporting water vapor up and down through the atmosphere, and
  - ✓ regional factors such as mountains, heating and cooling areas, influencing condensation of water vapor.

- High precipitation rates on continents occur only in humid temperate and tropical zones; in all other warm and cold climates precipitation is scarce.
- There exists a relation between precipitation and run-off; however, the explicit focus of run-off generation to precipitation was an oversimplification.

Mechanism and Processes of Recharge

- Many factors redistribute precipitation before hitting runoff; among these
  - ✓kind, duration and intensity of precipitation,
  - ✓pre-event climate,
  - ✓land use,
  - ✓types of sediments and soils, and topography play important roles.

The surface discharge in a river comprises the sum-total of various discharge components; under natural conditions the river runoff consists of one or all of the following

- ✓ Groundwater runoff discharging into the river, also called base-flow,
- ✓ Inter-flow,
- ✓ Overland-flow.

Mechanism and Processes of Recharge

- Rivers discharge surface water and according to existing differences in water level elevations between the river and groundwater table,
  - surface water either infiltrates into the subsurface or groundwater exfiltrates to the surface water.

Unidirectional infiltration from rivers into the subsurface occurs

- ✓ in the upper reach of mountain-rivers,
- ✓ in wadis,
- ✓ in areas with a steep slope of the river course,
- ✓ from artificial lakes, and
- ✓ unlined canals.

Such infiltration recharges groundwater either permanently or for a limited period of time through the unsaturated zone.

Mechanism and Processes of Recharge

- In contrast, surface water stands in direct groundwater contact in areas with
  - ✓low relief energy and
  - ✓in the low reach of rivers.

- When surface and groundwater are in direct contact,
  - more than 45% of surface discharge originates from indirect (groundwater) and
  - less than 55% from direct run-off;
- under these boundary conditions, river-infiltration and river exfiltration is linearly related to water level differences between both media.

Mechanism and Processes of Recharge

- This allows increasing groundwater recharge through
  - forced river-infiltration by creating a hydraulic gradient from the river to an unconfined groundwater level.

- River-infiltration into the subsurface occurs according to the width of the river water surface, the water depth in the channel center, and the hydraulic gradient from the river to the aquifer.

Artificial Recharge

- Many human activities result in artificial groundwater recharge;
  - ✓ from the very beginning of agriculture terracing of hills,
  - ✓ later irrigation contributes to enhanced recharge;
  - ✓ all kind of water storage on dam sites and the construction of unlined canals leak water to the subsurface and in many urban areas groundwater recharge intensifies by forced infiltration or by leakages from urban water distribution and collector systems.
- From urban areas, losses of 5% to more than 50% from water supply and waste water collector systems and of 10–20% from septic tanks are known.
- In irrigation areas, losses of up to 15–20% of applied irrigation (return water) or about 10 mm/day have been reported.

Artificial Recharge

All these recharges are classified as incidental artificial recharge.

In contrast, forced recharge happens through

- ✓ injection wells,
- ✓ infiltration basins, charged by floods or harvested rains,
- ✓ water ponding, and
- ✓ abstraction of river water through groundwater wells;

- These measures aim
  - ✓ to extend natural groundwater recharge and
  - ✓ to meliorate groundwater quality.

Artificial Recharge

Three important aspects in artificial groundwater recharge are quantities, the quality of water sources, and the hydraulic properties of the sink area.

- ✓Quantities are responsible for a continuous recharge supply and need an optimal reservoir design;
- ✓Qualities are of interest if dealing with the chemical compatibility of surface and groundwater or with the long-term efficiency of basin or well installations.

Especially, suspended matter has often a disastrous influence on well clogging, which is difficult to clean up, and can be minimized in infiltration basins by selecting graded sand/gravel packs to keep clogging close to the surface of the infiltration interface and, hence, to be easily removable.

Artificial Recharge

- Best subsurface reservoirs for artificial groundwater recharge are unconsolidated sediments with hydraulic conductivities in the range 10–2m/s to 10–5m/s and a high storage coefficient.
- These bulk hydraulic data also stand for efficient groundwater exploitation.

- A special form of artificial recharge is water ponding or rain harvesting.
- This method applies often in arid (dry-land) areas, guarantees a vegetation cover in restricted areas, and even provides some groundwater recharge.
- A sporadic rain in an arid area produces primarily direct discharge, which can be stored in a pond or depression of limited extent, where it evaporates and infiltrates.

Artificial Recharge

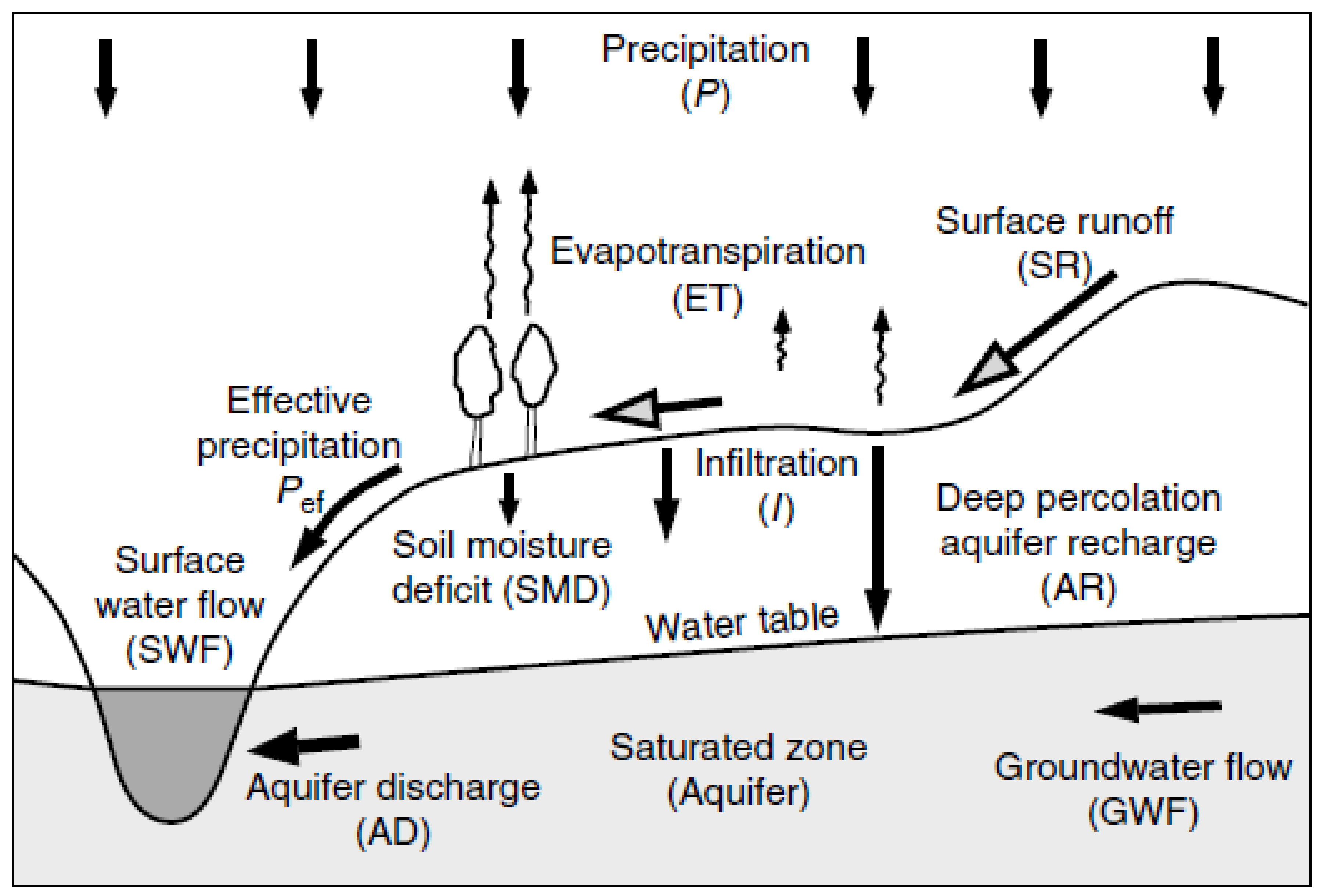


Figure: Key elements of the rainfall–runoff–recharge process.

Artificial Recharge

Depending on the aim of investigation, groundwater recharge studies contribute to develop long- or short-term strategies on water use.

- In a first step, it must be clarified to which extent the studied hydro-geologic system discharges under steady-state respectively transient hydraulic conditions;
  - both conditions occur naturally world wide,
    - because of the always existing global changes in climates, vegetation, and discharge levels, which became accelerated through human activities since the beginning of the industrial age.

- In a second step, the scale to which results on groundwater recharge refer has to be considered, to enable a representative assessment of results.

Artificial Recharge

- Finally, it should be kept in mind that virgin conditions may significantly differ from managed conditions,
  - because groundwater recharge is not a fixed number, but may vary with the boundary conditions of the recharged system.

- Long-term recharge estimates allow to developing appropriate exploration and exploitation strategies for water scarce and water excess periods of time.
- Short-term information on groundwater recharge is needed, to better assess the impact of floods and accidental spills on groundwater resources and to optimize irrigation.

Artificial Recharge

There are six general approaches to estimate groundwater recharge:

- Mass balance methods,
- Mixing methods,
- Hydraulic approaches,
- Flux measurements,
- Methods that are based on outflow analysis, and
- Turn-over-methods.

- All these methods experienced in the past modifications according to the available investigation tools, the local or regional climate, plant cover, and hydro-geologic conditions.

Artificial Recharge

- Most common are meteorological mass balance studies, issuing bulk information on run-off, but mostly not on groundwater recharge.
- Methods of outflow analysis as well as hydraulic approaches that are based on numerical modeling of groundwater flow deliver approximate results on groundwater recharge.

- The results of all these studies always refer to the catchment scale and depend on
  - observations of precipitation,
  - the energy balance, land use, river discharge and groundwater level fluctuations, and
  - must be based on a reliable conceptual hydro-geologic model.

Artificial Recharge

- In contrast, lysimeter mass balance studies, soil hydraulic, and tracer-based turnover-methods always provide small-scale and instantaneous information,
  - referring to local singularities, giving to groundwater recharge an often unknown weighing factor.
- Hence, both large- and small-scale methods inform about bulk respectively distinguished recharge;
  - bulk information have to be tested if they refer to a Reference Elementary Volume (REV) of dedicated or mixed boundary conditions and small-scale results often hardly refer to any REV.
  - Links between both types of results are transfer functions, which are, however, mostly missing.

Artificial Recharge

The above-mentioned methods are frequently applied in humid climates and suffer in arid to semi-arid areas from restrictions, because

- input data for mass balances (meteorological) vary too much in time and space and are mostly not adequately known over a long run of time and in the large scale of the dry-land,
- intrinsic hydraulic parameters, the boundary conditions of aquifer systems, and fit parameters such as groundwater level fluctuations often suffer from non-precision and are often not representative for the entire catchment,
- infiltration in arid (dry-land) and tropical climates is more punctual than areal, and
- much out-flowing groundwater in dry-lands is old and therefore does not correlate with present meteorological data sets.