Manual of Water Supply Practices

M21

Groundwater

Fourth Edition

American Water Works Association

Contents

Chapter 1

The Occurrence and Behavior of Groundwater

More than half of the people served with public water supplies in the United States and Canada obtain their water supplies from groundwater. Nearly 80 percent of all utilities, and most of the smaller systems, derive their source water from groundwater, but groundwater is not visible from the surface and the understanding of its behavior and occurrence by the public is limited. This chapter is intended to provide a general overview of the following:

- the hydrologic cycle
- general groundwater concepts
- major conditions that impact groundwater
- climate impacts on groundwater
- sustainability of groundwater

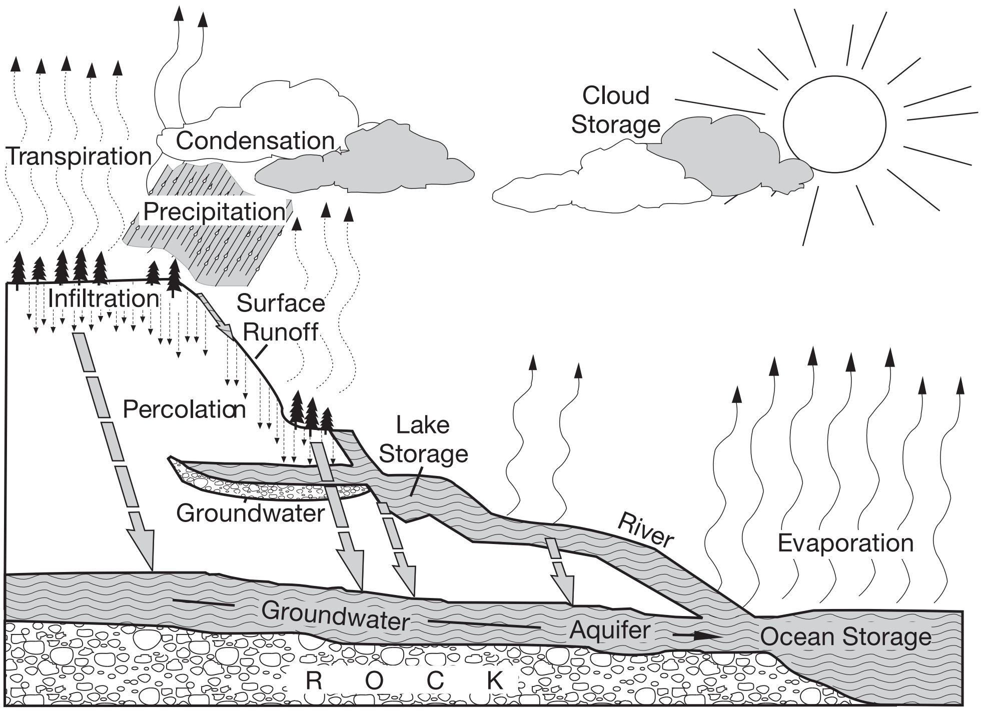
Because groundwater and surface water resources are closely related, any event that occurs aboveground can impact an underground water supply, a fact often not understood by the public and some regulatory agencies. As a result, water purveyors that derive their water sources from groundwater need to monitor surface events, such as rainfall, spills, development, and drought to determine the potential impact on their water systems, as discussed throughout this manual. In addition, the sustainability of many groundwater supplies is in question. If these groundwater supplies do not recharge, several things can occur: land subsidence in areas with friable or unconsolidated materials, potential diminishment or loss of a natural resource, and long-term negative impacts on a sustainable local economy. Reilly et al. (2009) have identified that the overuse of groundwater supplies may be particularly problematic in parts of the western United States and along the eastern seaboard, but this may be symptomatic of the overuse of groundwater in general. Climate impacts on groundwater are addressed in this chapter as well.

HYDROLOGIC CYCLE

Of the total water found on earth, 97.3 percent is saltwater in the oceans. Of the remaining water, over two thirds exists as ice in the polar caps. The rest, or 0.61 percent of all water, is fresh water in lakes, rivers, streams, and groundwater. Seventy-five percent is groundwater. That means that while there is a lot of water out there, getting to a sustainable supply may be of issue.

The constant movement of water above, on, and below the earth's surface is defined as the hydrologic cycle as depicted in Figure 1-1. The hydrologic cycle is the main concept used in the development and management of water supplies. The components of the hydrologic cycle are

- evapotranspiration (ET)
- precipitation
- surface water and runoff
- groundwater



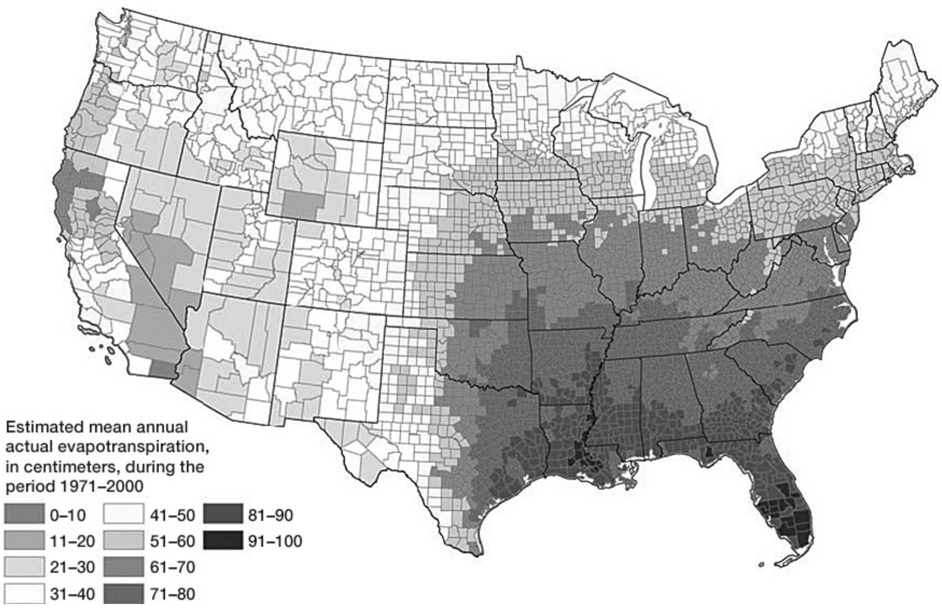
Source: US National Weather Service 1998

Figure 1-1 Hydrologic cycle

Evaporation and Transpiration

Although the hydrologic cycle is continuous and has neither a beginning nor an end, evaporation and transpiration will be discussed first in this manual. These two processes are commonly combined and referred to as *evapotranspiration* (ET). ET is the process of water vapor entering the atmosphere both through water that evaporates from open water bodies and water that transpires from vegetation or other sources. ET rates vary, depending largely on the amount of solar radiation, the latitude of the catchment area, the amount of heat, water surface area, and vegetative cover. Areas close to the equator tend to have higher ET rates. Figure 1-2 is a map of ET rates in the United States (similar mapping may be available for Canada and Mexico). In subtropical areas during the wet season or during summer months in northern latitudes, large bodies of water, including wetlands and estuarine areas, have high evaporation rates. This rising moisture forms clouds that condense and return the water to the land surface or oceans in the form of precipitation. The highest evaporation rates are associated with shallow, open water bodies. Water as much as 4 ft below the surface may be subject to evaporation to some degree.

To grow, plants must continually absorb water through their roots and circulate it up through their leaves. Water vapor evaporates from the plant through transpiration during photosynthesis. For plants that grow in swampy environments, the quantity of water lost is significant. On average, ET during the summer months offsets a good portion of the rainfall. Figure 1-3 shows a comparison of ET rates and rainfall in South Florida. Figure 1-3 shows that the ET rates are normally highest in the summer, which is typical across North America. Subtropical south Florida is different in that rainfall is also highest in the summer offsetting the ET loss. In the rest of North America, the summer ET rate is not offset by extensive rainfall.



Source: NOAA 2013 http://summitcountyvoice.com/2013/03/18/usgs-water-study-details-evapotranspiration-rates/. Courtesy USGS.

Figure 1-2 Evapotranspiration rates

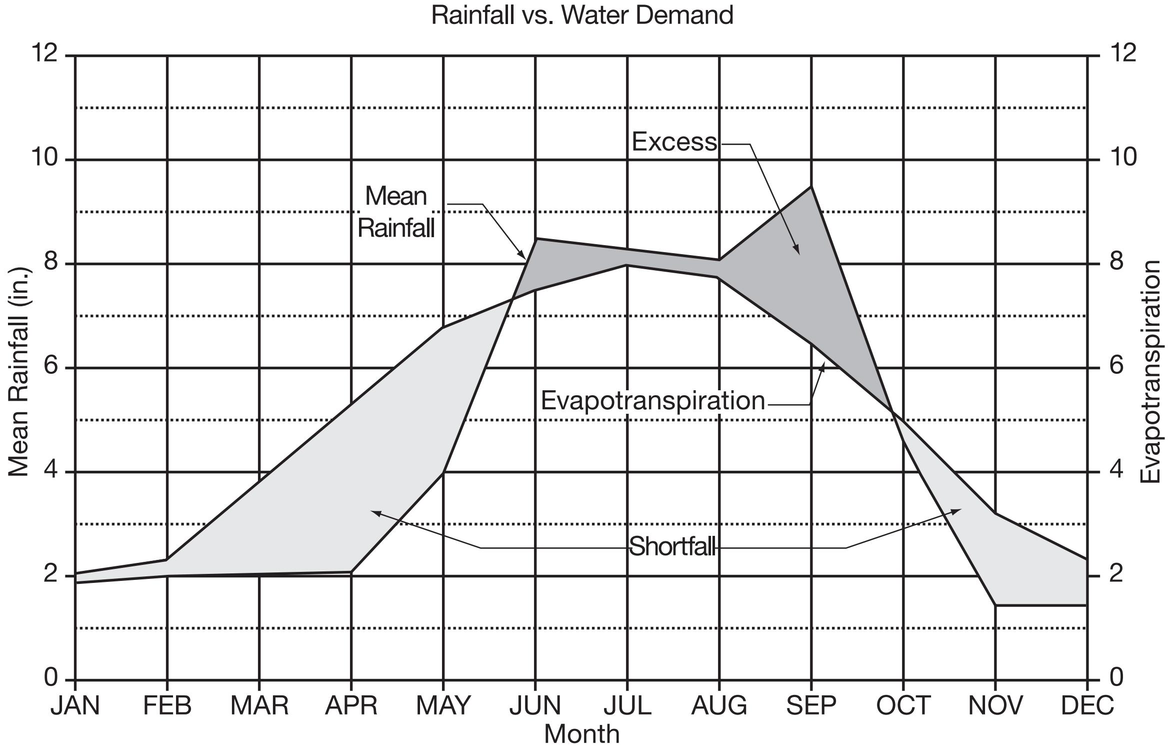


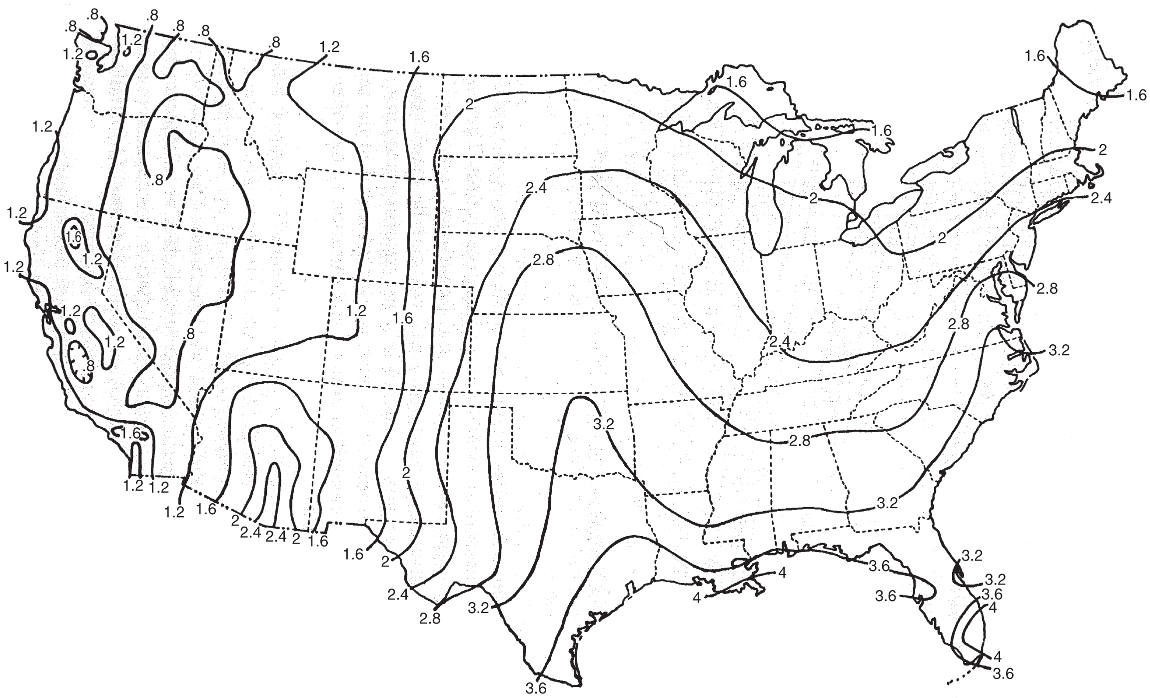
Figure 1-3 A comparison of ET rates and rainfall in South Florida

Precipitation

Precipitation occurs in several forms, including rain, snow, sleet, and hail. Water vapor from ET forms clouds. The intensity of the resulting rainfall is a major area of hydrologic study as it seems rainfall intensity is increasing with time. Rainfall intensity can vary up to 5 in. per hour in subtropical areas but is commonly 2–3 in. per hour across North America. Figure 1-4 shows intensities that occur in the continental United States (similar mapping may be available for Canada and Mexico). Rainfall intensity is relevant because the rain wets vegetation and other surfaces, then infiltrates the ground. Infiltration rates vary widely, depending on land use, development, the character and moisture content of the soil, and the intensity and duration of the precipitation event. Infiltration rates can vary from as much as 1 in./hr or 25 mm/hr in mature forests on sandy soils, to almost nothing in clay soils and paved areas. If and when the rate of precipitation exceeds the rate of infiltration, overland flow or runoff occurs. Figure 1-5 shows average annual precipitation in the United States. The data can be logically extended into Canada and Mexico along the borders.

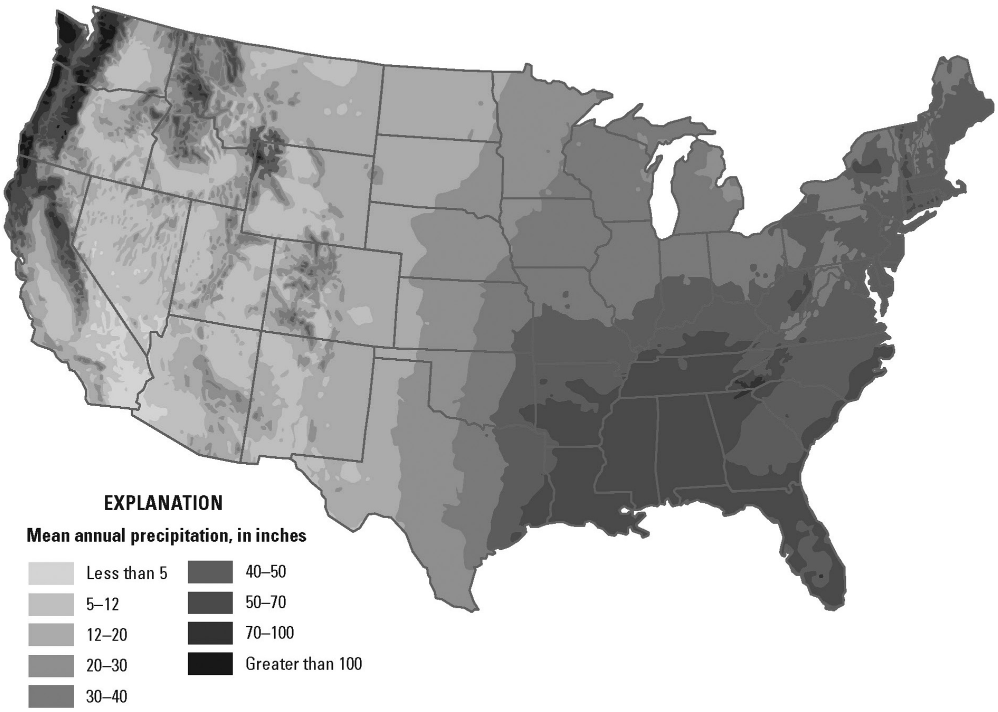
Surface Water

Precipitation that runs off the land, reaching streams, rivers, or lakes, or groundwater that discharges into these water bodies is surface water. Surface water bodies that mix with saltwater bodies along the coast are called *estuaries*; for example, where a river meets the ocean in a delta. Surface water flow is controlled by topography because water on the surface flows downward by gravity, eventually reaching the oceans.



Source: US National Weather Service 1998

Figure 1-4 One-hour rainfall (inches) to be expected once on average in 25 years



Source: NOAA 2002

Figure 1-5 Average annual precipitation (inches) in the United States (1961–1990)

GROUNDWATER CONCEPTS

The quantity and quality of groundwater depend on factors such as depth, rainfall, and geology. For example, the flow velocity and flow direction of groundwater depend on the permeability of sediment and rock layers, and the relative pressure of groundwater. A one-mile-square area 20-ft thick with a 25 percent porosity would hold one billion gallons of water. However, due to variable rates of groundwater flow and the impacts of withdrawals, such an area may not hold the one billion gallons at all times. The main concepts and factors related to groundwater include infiltration and recharge, unsaturated and saturated zones, and aquifers and confining beds. These are discussed in the following paragraphs.

Infiltration and Recharge

Precipitation that percolates downward through porous surface soils is the primary source of water for groundwater. Surface areas having this downward flow are called *recharge areas*. The characteristics of soil depend on the soil forming parent material, the climate, soil chemistry, the types of organisms in and on the soil, the topography of the land, and the amount of time these factors have acted on the material. Because vegetative types differ in their nutrient requirements and in their ability to live in water-saturated or saline areas, soil types also play a role in determining plant distribution.

Soil has the capacity to absorb some moisture initially, a factor called *initial infiltration*. Initial infiltration replaces moisture in the root or plant zones, where the roots for most vegetation exist. Because of the variable permeability and transmissivity of different soils, the rate of groundwater recharge from precipitation will vary. Recharge areas for deeper groundwater can be located far from the point of use. For an aquifer to have fresh water, there must be a source of recharge, some degree of flow (albeit slow), and a discharge area (to cause the flow). Otherwise, if there were no recharge or movement, the aquifer would become brackish through dissolution of the minerals in the rock.

Unsaturated and Saturated Zones

After precipitation has infiltrated the soil, it will travel down through two zones. The unsaturated zone occurs immediately below the land surface in most areas where pore space contains water and air. The unsaturated zone is almost invariably underlain by a zone in which all interconnected openings are full of water. This zone is referred to as the saturated zone and is illustrated in Figure 1-6.

Water in the saturated zone, technically called *groundwater*, is contained in interconnected pores located either below the water table in an unconfined aquifer or in a confined aquifer. Recharge of the saturated zone occurs by percolation of water from the land surface through the unsaturated zone. The unsaturated zone is, therefore, of great importance to groundwater hydrology. This zone may be divided usefully into three parts: the soil zone, the intermediate zone, and the upper part of the capillary fringe.

Soil zone. The soil zone typically extends from the land surface to a maximum depth of 3 to 5 ft (1 to 1.6 m). The soil zone supports plant growth, and it is crisscrossed by living roots, voids left by decayed roots of earlier vegetation, and animal and worm burrows. The porosity and permeability of the material in this zone tend to be higher than the porosity and permeability of the ground beneath it.

Intermediate zone. Below the soil zone is the intermediate zone, which differs in thickness from place to place, depending on the thickness of the soil zone and the depth to the capillary fringe. The intermediate zone is less porous than the soil zone because few roots or burrows penetrate it.

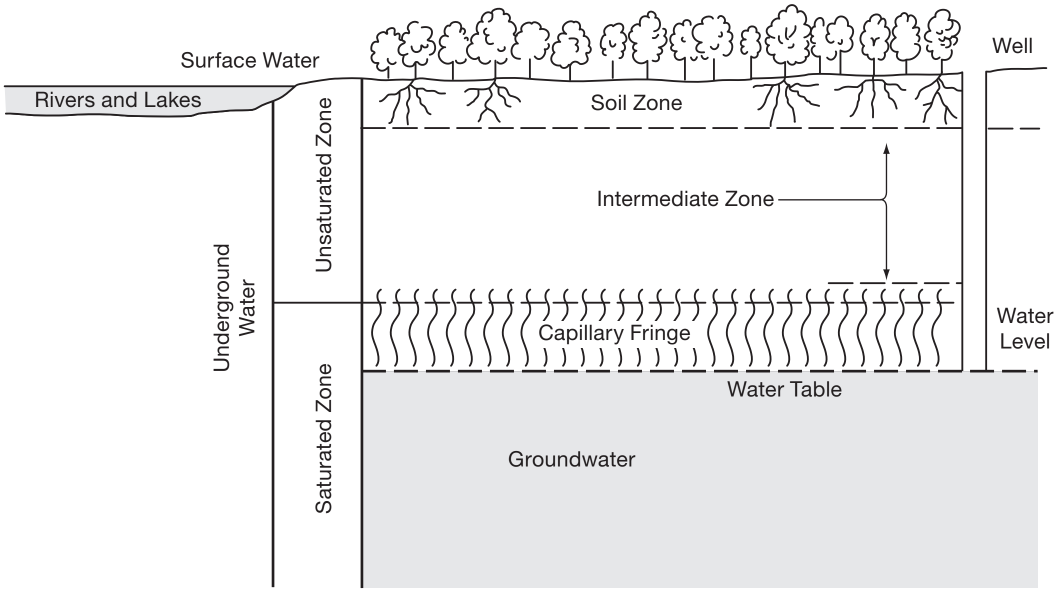


Figure 1-6 Water movement below the earth's surface

Capillary fringe. The capillary fringe is the subzone between the unsaturated and saturated zones. The capillary fringe occurs when a film of water clings to the surface of rock particles and rises in small-diameter pores against the pull of gravity. Water in the capillary fringe and in the overlying part of the unsaturated zone is under a negative hydraulic pressure, that is, less than atmospheric (barometric) pressure. The water table is the water level in the saturated zone at which the hydraulic pressure is equal to atmospheric pressure. Below the water table, the hydraulic pressure increases with increasing depth.

Aquifers and Confining Beds

Below the unsaturated soil zone, all rocks (including unconsolidated sediments) under the earth's surface can be classified either as aquifers, semi-confining units, or as confining units. An aquifer is rock that will yield water in a usable quantity to a well or spring. Some of the groundwater has been stored in aquifers for hundreds or even thousands of years. The older the rock, the more constituents the water might contain because of added contact time to dissolve the formation, although flow velocity also increases dissolution. A confining unit is rock having very low hydraulic conductivity that restricts the movement of groundwater either into or out of adjacent rock formations as shown in Figure 1-7.

Groundwater occurs in aquifers under two different conditions: *unconfined* and *confined*. Near the land surface, water may only partly fill an exposed aquifer. The upper surface of the saturated zone is free to rise and decline in direct relation to recharge by precipitation. The water in this type of aquifer is *unconfined*, and the aquifer is considered to be an unconfined or water-table aquifer. Wells that pump water from unconfined aquifers are water-table wells. The water level in these wells generally indicates the position of the water table in the surrounding aquifer. With unconfined aquifers, rainfall recharges them easily, so they are considered sustainable supplies.

Although clay layers (and some rock formations such as shale) have high porosity, water cannot easily flow through them. As such, they have *low hydraulic conductivity* and can be functionally impermeable. Hydraulic conductivity (K) is the ability of water to flow through a porous media. Clay or shale has very low K, which is why it is typically considered a *confining* unit as opposed to an aquifer. Water will tend to flow preferentially where

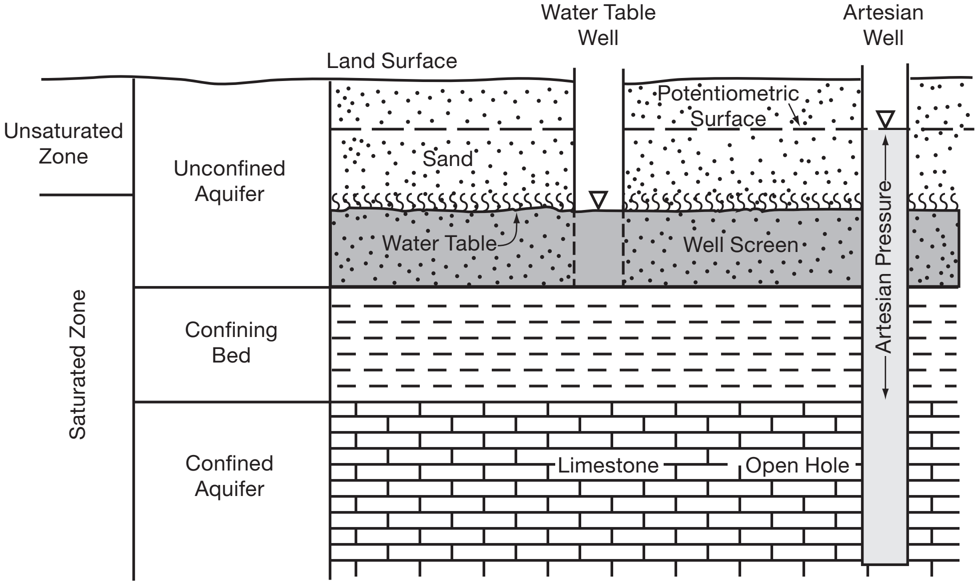


Figure 1-7 Geologic configuration of aquifers and confining beds

the resistance is lowest, and therefore clay is rarely the preferred route. Often, a clay or shale layer will intercept or overlay portions of an aquifer, making that aquifer a confined aquifer.

Where water completely fills an aquifer that is overlain by a confining bed, the water in the aquifer is said to be confined. Such aquifers are referred to as *confined aquifers*. Wells drilled into confined aquifers are referred to as *artesian wells* if the pressure of the water in the confined aquifer is above the top of the formation. If the water level in an artesian well stands above the land surface, the well is a *flowing artesian well*.

Under natural conditions, groundwater moves downgradient until it reaches the land surface at a spring or through a seep along the side or bottom of a stream channel or estuary, or, in deeper aquifers, i.e., the oceans. Groundwater in the shallowest part of the saturated zone moves from interstream areas toward streams or the coast. In many areas, the direction of groundwater movement can be derived from observations of land topography when the land slopes toward water bodies. Thus, the water table usually replicates the land surface as shown in Figure 1-8.

When a well (artesian or not) is pumped, the level of the aquifer falls as the water immediately surrounding the well is drawn through the pumping well. The falling level is called *drawdown*, and the three-dimensional cross-section is called the *cone of depression*. If the aquifer transmits water easily (i.e., has high transmissivity, which is a hydraulic property found by multiplying the hydraulic conductivity (*K*) by the thickness of the aquifer), the drawdown is slight and the cone of depression is flat and widespread as depicted in Figure 1-9. If the aquifer has low transmissivity, drawdown is significant and the cone of depression is steep. Higher flow rates result in steeper drawdown and, consequently, larger cones of depression. The cone of depression is also affected by the level of water within the aquifer. When investigating potential groundwater sources, engineers and hydrogeologists typically look for limestone, sandstone, and alluvial formations, which tend to have high transmissivity. The engineers and hydrogeologists avoid clay, shale, and similar zones, which have low transmissivity.

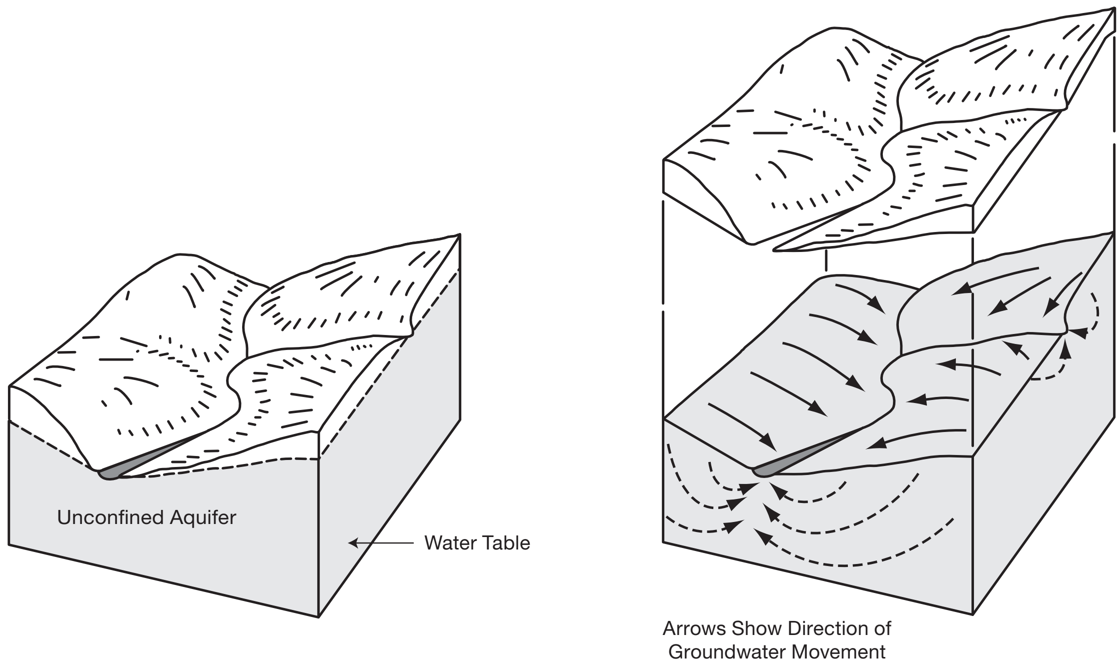


Figure 1-8 Groundwater movement as it relates to topography

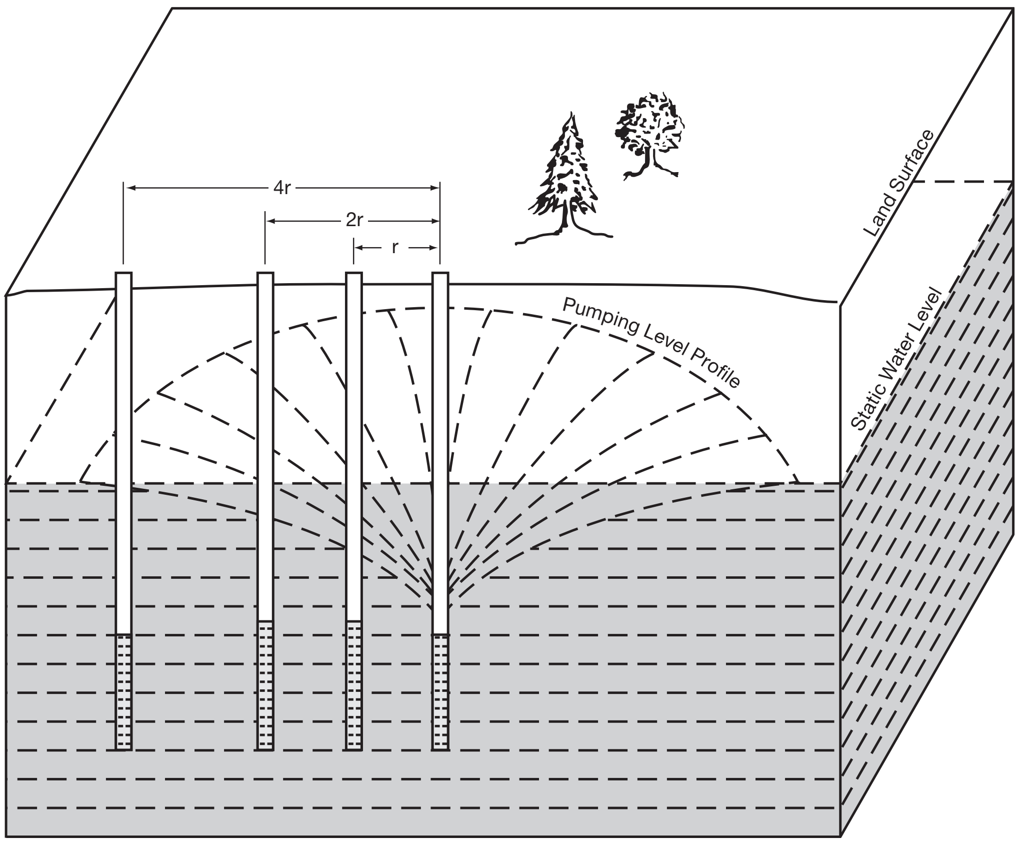


Figure 1-9 Development of a cone of depression

Formations in contact with groundwater affect water quality. Before groundwater is intercepted by a well, it is in lengthy contact with formation materials, and only moves slowly toward a well even when pumped. Groundwater also starts as recharged water that flows through a variety of formation materials before reaching an aquifer. Therefore, the types of rock strata that underlie the area have significant bearing on the quality and quantity of groundwater available and the ability of the rocks to store water.

MAJOR CONDITIONS THAT IMPACT GROUNDWATER

Along with an understanding of general groundwater concepts, it is important to recognize different conditions that impact groundwater. Two major conditions include subsidence and climate.

Land Surface Subsidence

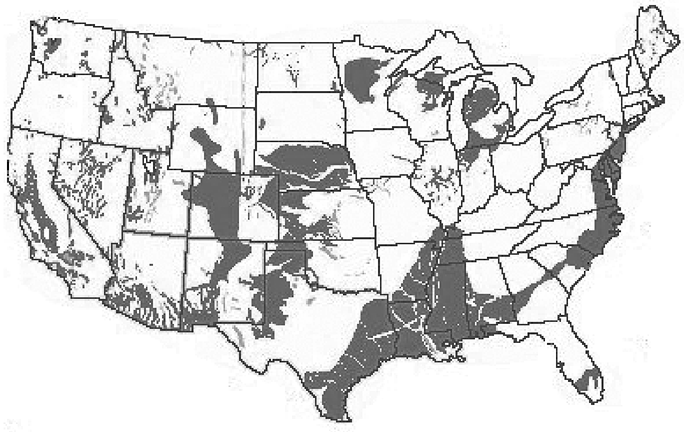
A significant consequence of groundwater development from unconsolidated or highly friable rock formations can be downward movement of the land surface, called *subsidence*. Subsidence can occur when the groundwater, which exerts pressure on the adjacent soil and rock, is removed, relieving the pressure. The formation then collapses, causing the surface topography to be altered. Recharging an aquifer that has collapsed will not restore the land surface to its prior state because the collapsed formation has less void space (which is why the collapse occurred). The collapse is caused by the reorientation of aquifer grains as a result of the loss of pore pressure exerted by the water in the aquifer. Development of groundwater needs to include consideration of possible land-surface subsidence, especially from overdevelopment. Figure 1-10 shows areas that US Geological Survey has identified as having significant land subsidence issues. In some areas, clays such as montmorillonite may exist beneath the surface, causing significant problems for water purveyors. These clays can be 46 to 55 percent porous, with their structure supported by the internal pore pressure of water. As pore pressure is reduced when water levels decline, most of the compression occurs in the clay units, causing land subsidence.

Estimating Subsidence

The magnitude of subsidence in areas subject to flooding either by tidal inundation or alteration of surface drainage should be estimated, especially in aquifers with high clay or sand content, or where prior subsidence has been noted. Subsidence along faults that could lead to structural damage must be estimated.

The most readily available of the necessary data is the amount of compressible material in the subsurface. Such data may be obtained from evaluation of logs of test wells. Data on water-level changes can be used to make estimates of pressure change (stress change) at various depths for various time intervals. Where subsidence has been well documented, subsidence data may be coupled with the amount of compressible material to determine compressibility. Unfortunately, the information needed is not available in sufficient detail in most areas.

Data on the degree of compressibility of the subsurface material can be used to predict subsidence, but the data are rarely readily available. Laboratory values of compressibility determined from tests of cores have been used with limited success as a result of the expense of obtaining undisturbed cores, and the difficulty in obtaining representative cores preclude their use for regional appraisal.



Source: USGS Circular 1182

Figure 1-10 Areas where land surface subsidence is an issue

Climate Impacts on Groundwater

In a geologic timescale, the earth's climate undergoes constant changes (Bloetscher 2008). Massive continental glaciers extended as far south as the 40th parallel in North America and Eurasia. There were several advances throughout the Pleistocene era, starting more than 600,000 years before present (BP) and extending to as recently as 10,000 years BP. These glacial advances and retreats profoundly altered the landscape, covering northern Europe and the northern United States with deep till and outwash soils, and developed massive, productive sand-and-gravel aquifers. Less than 5,000 years ago, the Sahara desert was a thriving, water soaked area that supported significant human population, but as the climate changed, it became more arid. It should also be appreciated that much groundwater available in the western United States is fossil water from the Pleistocene period. Brief interludes of warmer and cooler periods occurred during the Dark and Middle Ages (400–1300 AD).

The conclusions of the 2007 Intergovernmental Panel on Climate Change (IPCC) report noted that water resources would be one of the areas most affected by climate change. The most relevant impact to water resources and groundwater are (IPCC 2007):

- Projected warming in the twenty-first century shows geographical patterns similar to those observed over the last few decades, which may increase ET, and reduce the potential for infiltration to replenish groundwater.
- Warming is expected to be greatest over land and at the highest northern latitudes, and least over the southern oceans and parts of the north Atlantic Ocean.
- Snow cover is projected to contract.
- Widespread increases in thaw depth are projected over most permafrost regions.
- The more optimistic globally averaged rises in sea level at the end of the twenty-first century are between 0.18–0.38 m, but an extreme scenario gives a rise up to 5 m. Sea level rise will inundate low-lying areas and increase saltwater intrusion along coastlines.
- Temperature extremes, heat waves, and heavy precipitation events will continue to become more frequent.

- Increases in the amount of precipitation are very likely at high latitudes, but not as snow pack, whereas rainfall decreases are likely in most subtropical land regions.

It should be noted that there is significant uncertainty in the models used to prepare the IPCC reports to predict the actual intensity, spatial and time variability of rainfall and temperature for a given region in part because the models can only be calibrated against a very short period of time, and that as time has proceeded, the predicted changes have moderated to some degree to comport with observed changes. In any case, the main concern raised by global warming is that climatic variations alter the hydrologic cycle, and that the current data indicated that hydrological cycle is already being impacted: more intense rainfall, less recharge, less snowpack, higher seas, all of which result in less recharge (Dragoni 1998; Buffoni et al. 2002; Labat et al. 2004; Huntington 2006; IPCC 2007; Dragoni and Sukhija 2008).

ACHIEVING SUSTAINABILITY

Climate impacts on the hydrological cycle predicate a necessary discussion of sustainable use of water supplies. The key component in planning the use of water supplies is to determine how the hydrologic cycle provides water to the service area (e.g., recharge basin), in what quantities, and with what reliability. The reliability is a risk issue—is the precipitation consistent or are there significant fluctuations that disrupt ongoing basin development (Molak 2007)? It is widely recognized that

Withdrawals = Consumption + Returns (to hydrologic cycle)

However, the concept is not that simple, and buy-in to the concept of "sustainable water" depends on the profession or perspective of the person defining it. From a hydrologic perspective, the term *sustainable yield* is the amount of water that can be withdrawn from a source at rates that are less than their recharge potential and that do not deteriorate the source or basin. While many water providers attempt to develop sustainably, others have not. Within regionally sustainable situations, unsustainable pumping can occur locally. For example, much of the groundwater in the western United States appears to be unsustainable in the long term because of limited rainfall (Reilly et al. 2009).

Typically, there are a variety of uses competing for water resources, and each basin has unique characteristics (Bloetscher and Muniz 2008):

- Agriculture
- Ecosystems
- Urban demands
- Industrial demands
- Cooling water for power generation

From a practical perspective, sustainable development generally means addressing environmental, economic, and social concerns. Researchers can define a comprehensible concept of sustainability, but practitioners emphasize feasibility and limitation to sustainability of the ecosystem (Starkl and Brunner 2004). Water quantity and quality issues have significant fiscal impact on the potential users in the basin, and there are unrealized costs and benefits that are often ignored in the current water management framework (Bloetscher and Muniz 2008).

A sustainable world is not a rigid one, where population or productivity is constant; sustainability must adapt to constant change. The concept of sustainability requires rules, laws, and social constraints that are recognized and adhered to by all (Meadows and Randers 2005). At the present time, the desire to grow and develop economically is outweighing the rule-making process. These issues will be discussed in more depth in chapter 3.

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