Groundwater

CHAPTER

17

Groundwater provides over 190 billion liters (50 billion gallons) per day in support of the agricultural economy of the United States. (Photo by Michael Collier)

Worldwide, wells and springs provide water for cities, crops, livestock, and industry. In the United States, groundwater is the source of about 40 percent of the water used for all purposes (except hydroelectric power generation and power-plant cooling). Groundwater is the drinking water for more than 50 percent of the population, is 40 percent of the water used for irrigation, and provides more than 25 percent of industry's needs. In some areas, however, overuse of this basic resource has resulted in water shortage, streamflow depletion, land subsidence, contamination by saltwater, increased pumping cost, and groundwater pollution.

Importance of Groundwater

Groundwater

▸ Importance and Distribution of Groundwater

Groundwater is one of our most important and widely available resources, yet people's perceptions of the subsurface environment from which it comes are often unclear and incorrect. The reason is that the groundwater environment is largely hidden from view except in caves and mines, and the impressions people gain from these subsurface openings are misleading. Observations on the land surface give an impression that Earth is "solid." This view remains when we enter a cave and see water flowing in a channel that appears to have been cut into solid rock.

Because of such observations, many people believe that groundwater occurs only in underground "rivers." In reality, most of the subsurface environment is not "solid" at all. It includes countless tiny *pore spaces* between grains of soil and sediment, plus narrow joints and fractures in bedrock. Together, these spaces add up to an immense volume. It is in these small openings that groundwater collects and moves.

Considering the entire hydrosphere, or all of Earth's water, only about six-tenths of 1 percent occurs underground. Nevertheless, this small percentage, stored in the rocks and sediments beneath Earth's surface, is a vast quantity. When the oceans are excluded and only sources of fresh water are considered, the significance of groundwater becomes more apparent.

Table 17.1 contains estimates of the distribution of fresh water in the hydrosphere. Clearly the largest volume occurs as glacial ice. Second in rank is groundwater, with slightly more than 14 percent of the total. However, when ice is excluded and just liquid water is considered, more than 94 percent of all fresh water is groundwater. Without question, *groundwater represents the largest reservoir of fresh water that is readily available to humans.* Its value in terms of economics and human well-being is incalculable.

Geologically, groundwater is important as an erosional agent. The dissolving action of groundwater slowly removes soluble rock such as limestone, allowing surface depressions known as *sinkholes* to form as well as creating subterranean caverns (Figure 17.1). Groundwater is also an equalizer of streamflow. Much of the water that flows in rivers is not direct runoff from rain and snowmelt. Rather, a large percentage of precipitation soaks in and then moves slowly underground to stream channels. Groundwater is thus a form of storage that sustains streams during periods when rain does not fall. Therefore, when we see water flowing in a river during a dry period, it is rain that fell at some earlier time and was stored underground.

TABLE 17.1 Fresh Water of the Hydrosphere

Parts of the Hydrosphere	Volume of Fresh Water (km^3)	Share of Total Volume of Fresh Water (percent)
Ice sheets and glaciers	24,000,000	84.945
Groundwater	4,000,000	14.158
Lakes and reservoirs	155,000	0.549
Soil moisture	83,000	0.294
Water vapor in the atmosphere	14,000	0.049
River water	1,200	0.004
Total	28,253,200	100.00

Source: U.S. Geological Survey Water Supply Paper 2220, 1987.

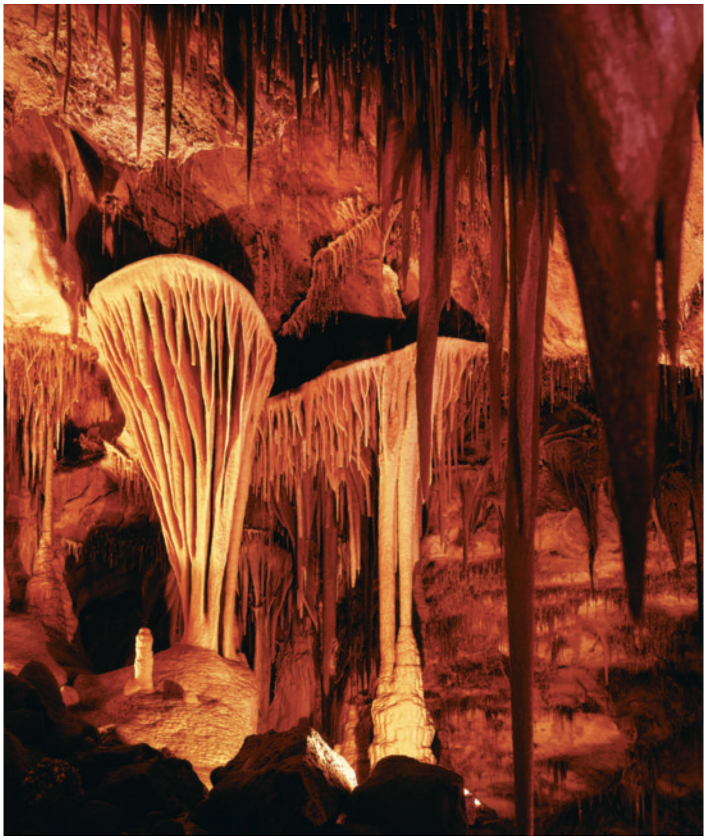
Distribution of Groundwater

Groundwater
▸ Importance and Distribution of Groundwater

When rain falls, some of the water runs off, some returns to the atmosphere by evaporation and transpiration, and the remainder soaks into the ground. This last path is the primary source of practically all subsurface water. The amount of water that takes each of these paths, however, varies greatly both in time and space. Influential factors include steepness of slope, nature of surface material, intensity of rainfall, and type and amount of vegetation. Heavy rains falling on steep slopes underlain by impervious materials will obviously result in a high percentage of the water running off. Conversely, if rain falls steadily and gently upon more gradual slopes composed of materials that are easily penetrated by the water, a much larger percentage of water soaks into the ground.

FIGURE 17.1 **A.** A view of the interior of Three Fingers Cave, Lincoln County, New Mexico. The dissolving action of groundwater created the cavern. Later, groundwater deposited the limestone decorations. (Photo by Harris Photographic/Tom Stack and Associates) **B.** Groundwater was responsible for creating these sinkholes in a limestone plateau north of Jajce, Bosnia and Herzegovina. (Photo by Jerome Wyckoff)

A.



B.

Some of the water that soaks in does not travel far, because it is held by molecular attraction as a surface film on soil particles. This near-surface zone is called the **zone of soil moisture.** It is crisscrossed by roots, voids left by decayed roots, and animal and worm burrows that enhance the infiltration of rainwater into the soil. Soil water is used by plants in life functions and transpiration. Some water also evaporates directly back into the atmosphere.

Water that is not held as soil moisture percolates downward until it reaches a zone where all of the open spaces in sediment and rock are completely filled with water (Figure 17.2). This is the **zone of saturation** (also called the *phreatic zone*). Water within it is called **groundwater.** The upper limit of this zone is known as the **water table.** Extending upward from the water table is the **capillary fringe** (*capillus* = hair). Here groundwater is held by surface tension in tiny passages between grains of soil or sediment. The area above the water table that includes the capillary fringe and the zone of soil moisture is called the **unsaturated zone** (also known as the *vadose zone*). Although a considerable amount of water can be present in the unsaturated zone this water cannot be pumped by wells because it clings too tightly to rock and soil particles. By contrast, below the water table the water pressure is great enough to allow water to enter wells, thus permitting groundwater to be withdrawn for use. We will examine wells more closely later in the chapter.

The Water Table

Groundwater
▸ Importance and Distribution of Groundwater

The water table, the upper limit of the zone of saturation, is a very significant feature of the groundwater system. The water table level is important in predicting the productivity of wells, explaining the changes in the flow of springs and streams, and accounting for fluctuations in the levels of lakes.

Variations in the Water Table

The depth of the water table is highly variable and can range from zero, when it is at the surface, to hundreds of meters in some places. An important characteristic of the water table is that its configuration varies seasonally and from year to year because the addition of water to the groundwater system is closely related to the quantity, distribution, and timing of precipitation. Except where the water table is at the surface, we cannot observe it directly. Nevertheless, its elevation can

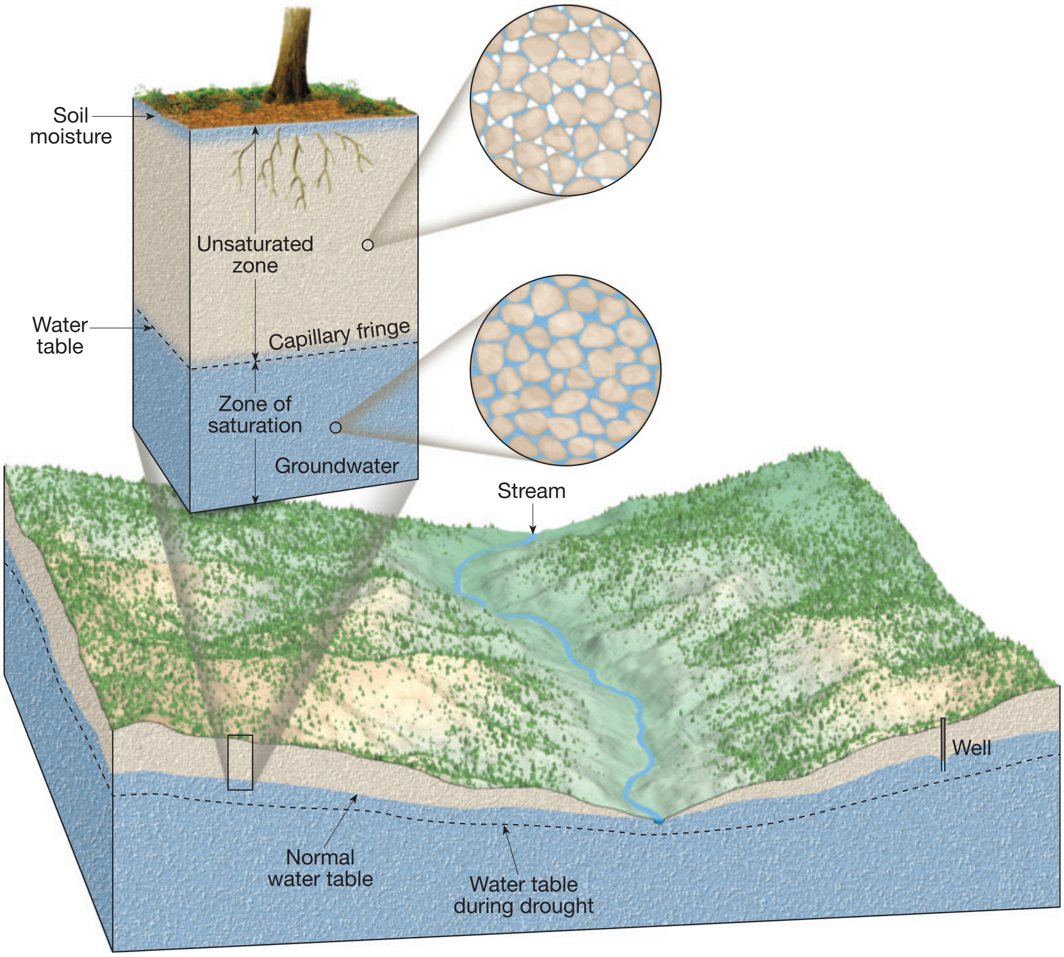


FIGURE 17.2 Distribution of underground water. The shape of the water table is usually a subdued replica of the surface topography. During periods of drought, the water table falls, reducing streamflow and drying up some wells.

be mapped and studied in detail where wells are numerous because the water level in wells coincides with the water table (Figure 17.3). Such maps reveal that the water table is rarely level, as we might expect a table to be. Instead, its shape is usually a subdued replica of the surface topography, reaching its highest elevations beneath hills and then descending toward valleys (Figure 17.2). Where a wetland (swamp) is encountered, the water table is right at the surface. Lakes and streams generally occupy areas low enough that the water table is above the land surface.

Several factors contribute to the irregular surface of the water table. One important influence is the fact that groundwater moves very slowly and at varying rates under different conditions. Because of this, water tends to "pile up" beneath high areas between stream valleys. If rainfall were to cease completely, these water-table "hills" would slowly subside and gradually approach the level of the valleys. However, new supplies of rainwater are usually added frequently enough to prevent this. Nevertheless, in times of extended drought (see Box 17.1), the water table may drop enough to dry up shallow wells (Figure 17.2). Other causes for the uneven water table are variations in rainfall and permeability from place to place.

Interaction between Groundwater and Streams

The interaction between the groundwater system and streams is a basic link in the hydrologic cycle. It can take place in one of three ways. Streams may gain water from the inflow of groundwater through the streambed. Such streams are called **gaining streams** (Figure 17.4A). For this to occur, the elevation of the water table must be higher than the level of the surface of the stream. Streams may lose water to the groundwater system by outflow through the streambed. The term **losing stream** is applied to this situation (Figure 17.4B, C). When this happens, the elevation of the water table must be lower than the surface of the stream. The third possibility is a combination of the first two—a stream gains in some sections and loses in others.

Losing streams can be connected to the groundwater system by a continuous saturated zone or they can be disconnected from the groundwater system by an unsaturated zone. Compare parts B and C in Figure 17.4. When the stream is disconnected, the water table may have a discernible bulge beneath the stream if the rate of water movement through the streambed and zone of aeration is greater

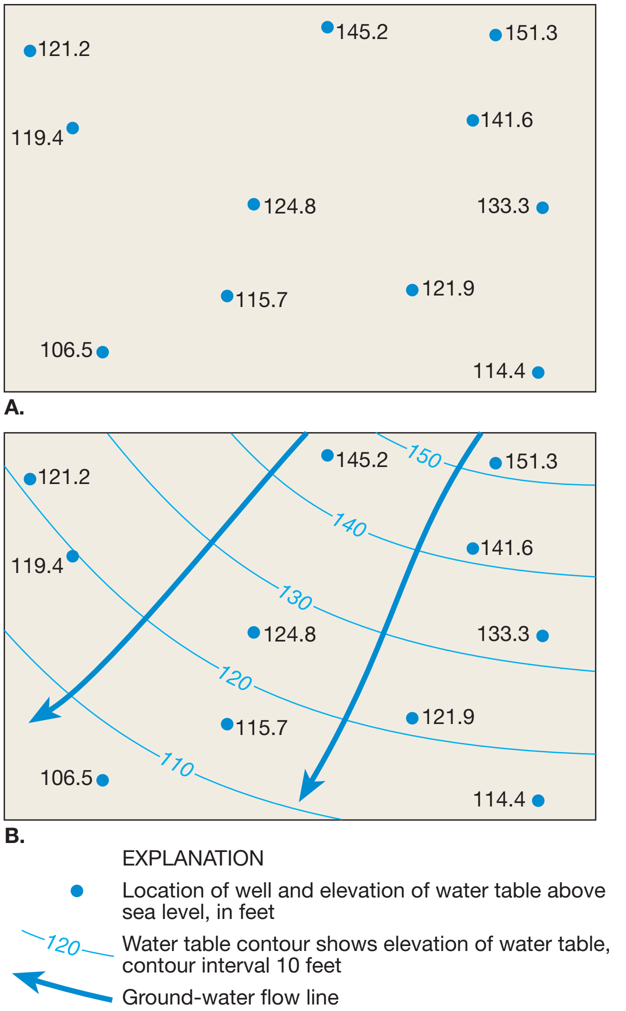
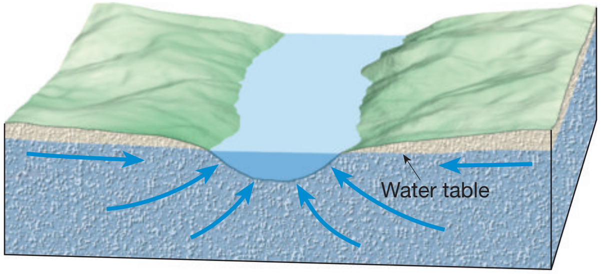


FIGURE 17.3 Preparing a map of the water table. The water level in wells coincides with the water table. **A.** First, the locations of wells and the elevation of the water table above sea level are plotted on a map. **B.** These data points are used to guide the drawing of water-table contour lines at regular intervals. On this sample map the interval is 10 feet. Groundwater flow lines can be added to show water movement in the upper portion of the zone of saturation. Groundwater tends to move approximately perpendicular to the contours and down the slope of the water table. (After U.S Geological Survey)

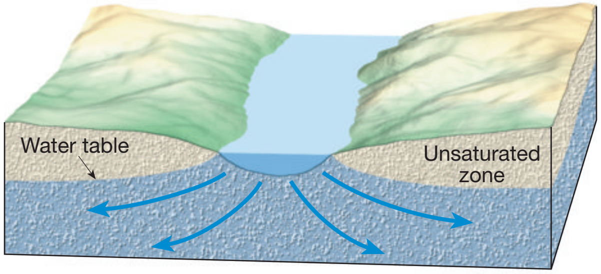
than the rate of groundwater movement away from the bulge.

In some settings, a stream might always be a gaining stream or always be a losing stream. However, in many situations flow direction can vary a great deal along a stream; some sections receive groundwater and other sections lose water to the groundwater system. Moreover, the direction of flow can change over a short time span as the result of storms adding water near the streambank or when temporary flood peaks move down the channel.

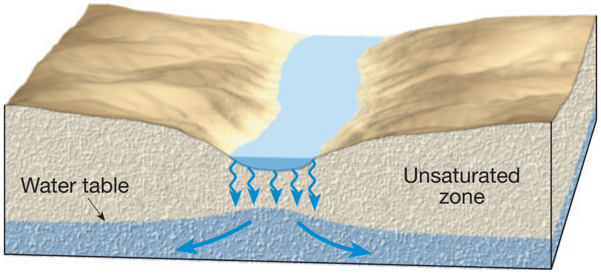
Groundwater contributes to streams in most geologic and climatic settings. Even where streams are primarily losing water to the groundwater system, certain sections may receive groundwater inflow during some seasons. In one study of 54 streams in all parts of the United States, the analysis indicated that 52 percent of the streamflow was contributed by groundwater. The groundwater contribution ranged from a low of 14 percent to a maximum of 90 percent. Groundwater is also a major source of water for lakes and wetlands.



A. Gaining stream



B. Losing stream (connected)



C. Losing stream (disconnected)

FIGURE 17.4 Interaction between the groundwater system and streams. **A.** Gaining streams receive water from the groundwater system. **B.** Losing streams lose water to the groundwater system. **C.** When losing streams are separated from the groundwater system by the unsaturated zone, a bulge may form in the water table. (After U.S. Geological Survey)

Factors Influencing the Storage and Movement of Groundwater

The nature of subsurface materials strongly influences the rate of groundwater movement and the amount of groundwater that can be stored. Two factors are especially important—porosity and permeability.

Porosity

Water soaks into the ground because bedrock, sediment, and soil contain countless voids or openings. These openings are similar to those of a sponge and are often called *pore*

BOX 17.1 ▸ EARTH AS A SYSTEM

Drought Impacts the Hydrologic System*

Drought is a period of abnormally dry weather that persists long enough to produce a significant hydrologic imbalance such as crop damage or water supply shortages. Drought severity depends upon the degree of moisture deficiency, its duration, and the size of the affected area.

Although natural disasters such as floods and hurricanes usually generate more attention, droughts can be just as devastating and carry a bigger price tag. On the average, droughts cost the United States $6 to $8 billion annually compared to $2.4 billion for floods and $1.2 to $4.8 billion for hurricanes. Direct economic losses from a severe drought in 1988 were estimated at $61 billion (2002 dollars).

Drought is different from other natural hazards in several ways. First, it occurs in a gradual, "creeping" way, making its onset and end difficult to determine. The effects of drought accumulate slowly over an extended time span and sometimes linger for years after the drought has ended. Second, there is not a precise and universally accepted definition of drought. This adds to the confusion about whether or not a drought is actually occurring and if it is, its severity. Third, drought seldom produces structural damages, so its social and economic effects are less obvious than damages from other natural disasters.

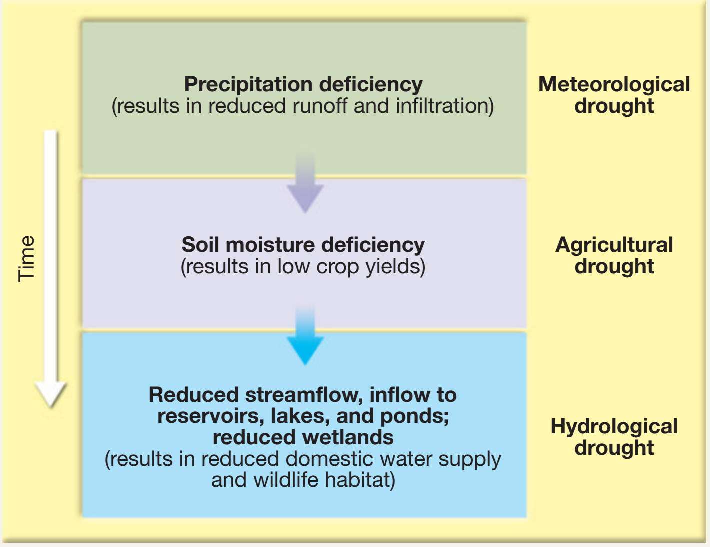


FIGURE 17.A Sequence of drought impacts. After the onset of meteorological drought, agriculture is affected first, followed by reductions in streamflow and water levels in lakes, reservoirs, and underground. When meteorological drought ends, agricultural drought ends as soil moisture is replenished. It takes a considerably longer time span for hydrological drought to end.

Definitions reflect four basic approaches to measuring drought: meteorological, agricultural, hydrological, and socioeconomic. *Meteorological drought* deals with the degree of dryness based on the departure of precipitation from normal values and the duration of the dry period. *Agricultural drought* is usually linked to a deficit of soil moisture. A plant's need for water depends on prevailing weather conditions, biological characteristics of the particular plant, its stage of growth, and various soil properties. *Hydrological drought* refers to deficiencies in surface and subsurface water supplies. It is measured as streamflow and as lake, reservoir, and groundwater levels. There is a time lag between the onset of dry conditions and a drop in streamflow, or the lowering of lakes, reservoirs, or groundwater levels. So hydrological measurements are not the earliest indicators of drought. *Socioeconomic drought* is a reflection of what happens when a physical water shortage affects people. Socioeconomic drought occurs when the demand for an economic good exceeds supply as a result of a shortfall in water supply. For example, drought can result in significantly reduced hydroelectric power production, which in turn may require conversion to more expensive fossil fuels and/or significant energy shortfalls.

There is a sequence of impacts associated with meteorological, agricultural, and hydrological drought (Figure 17.A). When meteorological drought begins, the agricultural sector is usually the first to be affected because of its heavy dependence on soil moisture. Soil moisture is rapidly depleted during extended dry periods. If precipitation deficiencies continue, those dependent on rivers, reservoirs, lakes, and groundwater may be affected.

When precipitation returns to normal, meteorological drought comes to an end. Soil moisture is replenished first, followed by streamflow, reservoirs and lakes, and finally groundwater. Thus, drought impacts may diminish rapidly in the agricultural sector because of its reliance on soil moisture but linger for months or years in other sectors that depend on stored surface or subsurface water supplies. Groundwater users, who are often the last to be affected following the onset of meteorological drought, may also be the last to experience a return to normal water levels. The length of the recovery period depends upon the intensity of the meteorological drought, its duration, and the quantity of precipitation received when the drought ends.

The impacts suffered because of drought are the product of both the meteorological event and the vulnerability of society to periods of precipitation deficiency. As demand for water increases as a result of population growth and regional population shifts, future droughts can be expected to produce greater impacts whether or not there is any increase in the frequency or intensity of meteorological drought.

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*Based in part on material prepared by the National Drought Mitigation Center (http:// drought.unl.edu).

spaces. The quantity of groundwater that can be stored depends on the **porosity** of the material, which is the percentage of the total volume of rock or sediment that consists of pore spaces. Voids most often are spaces between sedimentary particles, but also common are joints, faults, cavities formed by the dissolving of soluble rock such as limestone, and vesicles (voids left by gases escaping from lava).

Variations in porosity can be great. Sediment is commonly quite porous, and open spaces may occupy 10 to 50 percent of the sediment's total volume. Pore space depends on the size and shape of the grains, how they are packed together, the degree of sorting, and in sedimentary rocks, the amount of cementing material. For example, clay may have a porosity as high as 50 percent, whereas some gravels may have only 20 percent voids.

Where sediments are poorly sorted, the porosity is reduced because the finer particles tend to fill the openings among the larger grains (see Figure 7.6 on p. 199). Most igneous and metamorphic rocks, as well as some sedimentary rocks, are composed of tightly interlocking crystals so the voids between the grains may be negligible. In these rocks, fractures must provide the voids.

Permeability, Aquitards, and Aquifers

Porosity alone cannot measure a material's capacity to yield groundwater. Rock or sediment may be very porous yet still not allow water to move through it. The pores must be *connected* to allow water flow, and they must be *large enough* to allow flow. Thus, the **permeability** (*permeare* = to penetrate)of a material—its ability to *transmit* a fluid—is also very important.

Groundwater moves by twisting and turning through small interconnected openings. The smaller the pore spaces, the slower the water moves. This idea is clearly illustrated by examining the information about the water-yielding potential of different materials in Table 17.2. Here groundwater is divided into two categories: (1) the portion that will drain under the influence of gravity (called *specific yield*) and (2) the part that is retained as a film on particle and rock surfaces and in tiny openings (called *specific retention*). Specific yield indicates how much water is actually available for use, whereas specific retention indicates how much water remains bound in the material. For example, clay's ability to store water is great, owing to its high porosity, but its pore spaces are so small that water is unable to move through it. Thus, clay's porosity is high but because its permeability is poor, clay has a very low specific yield.

Impermeable layers that hinder or prevent water movement are termed **aquitards** (*aqua* = water, *tard* = slow). Clay is a good example. On the other hand, larger particles, such as sand or gravel, have larger pore spaces. Therefore, the water moves with relative ease. Permeable rock strata or sediment that transmit groundwater freely are called **aquifers** (*aqua* = water, *fer* = carry). Sands and gravels are common examples.

In summary, you have seen that porosity is not always a reliable guide to the amount of groundwater that can be produced, and permeability is significant in determining the rate of groundwater movement and the quantity of water that might be pumped from a well.

Movement of Groundwater

The movement of water in the atmosphere and on the land surface is relatively easy to visualize, but the movement of groundwater is not. Near the beginning of the chapter we mentioned the common misconception that groundwater occurs in underground rivers that resemble surface streams. Although subsurface streams do exist, they are *not* common. Rather, as you learned in the preceding sections, groundwater exists in the pore spaces and fractures in rock and sediment. Thus, contrary to any impressions of rapid flow that an underground river might evoke, the movement of most groundwater is exceedingly slow, from pore to pore. By exceedingly slow, we mean typical rates of a few centimeters each day.

Figure 17.5 depicts a simple example of a *groundwater flow system*—a three-dimensional body of Earth material saturated with moving groundwater. It shows groundwater moving along flow paths from areas of recharge to a zone of discharge along a stream. Discharge also occurs at springs, lakes, or wetlands, and in coastal areas, as groundwater seeps into bays or the ocean. Transpiration by plants whose

TABLE 17.2 Selected Values of Porosity, Specific Yield, and Specific Retention*

Material	Porosity	Specific Yield	Specific Retention
Clay	50	2	48
Sand	25	22	3
Gravel	20	19	1
Limestone	20	18	2
Sandstone (semiconsolidated)	11	6	5
Granite	0.1	0.09	0.01
Basalt (fresh)	11	8	3

*Values in percent by volume.
Source: U.S. Geological Survey Water Supply Paper 2220, 1987.

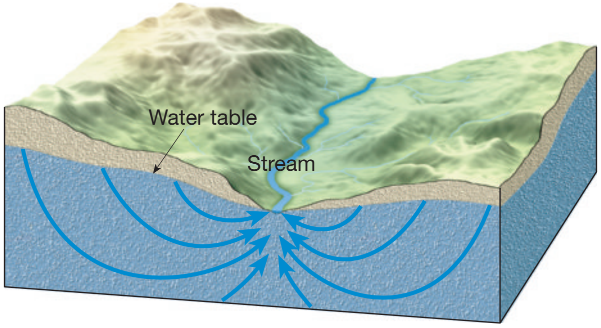

FIGURE 17.5 Arrows indicate groundwater movement through uniformly permeable material. The looping curves may be thought of as a compromise between the downward pull of gravity and the tendency of water to move toward areas of reduced pressure.

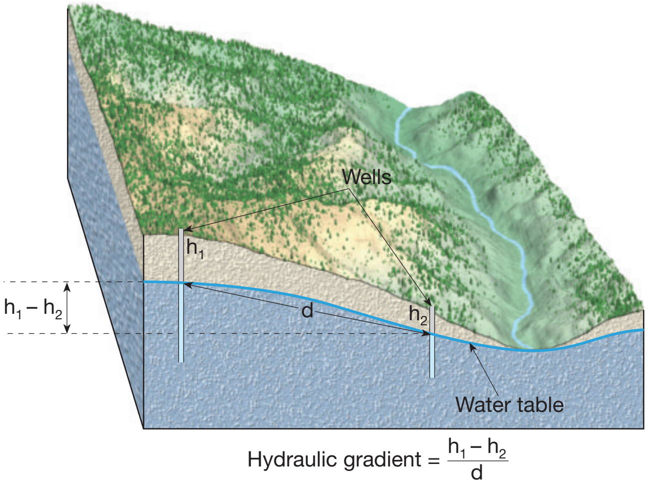

FIGURE 17.6 The hydraulic gradient is determined by measuring the difference in elevation between two points on the water table ($h_1 - h_2$) divided by the distance between them, *d.* Wells are used to determine the height of the water table.

roots extend to near the water table represents another form of groundwater discharge.

The energy that makes groundwater move is provided by the force of gravity. In response to gravity, water moves from areas where the water table is high to zones where the water table is lower. Although some water takes the most direct path down the slope of the water table, much of the water follows long, curving paths.

Figure 17.5 shows water percolating into a stream from all possible directions. Some paths clearly turn upward, apparently against the force of gravity, and enter through the bottom of the channel. This is easily explained: The deeper you go into the zone of saturation, the greater is the water pressure. Thus, the looping curves followed by water in the saturated zone may be thought of as a compromise between the downward pull of gravity and the tendency of water to move toward areas of reduced pressure. As a result, water at any given height is under greater pressure beneath a hill than beneath a stream channel, and the water tends to migrate toward points of lower pressure.

Darcy's Law

The foundations of our modern understanding of groundwater movement began in the mid-19th century with the work of the French engineer Henri Darcy. During this time, Darcy made measurements and conducted experiments in an attempt to determine whether the water needs of the city of Dijon in east–central France could be met by tapping local supplies of groundwater. Among the experiments carried out by Darcy was one that showed that the velocity of groundwater flow is proportional to the slope of the water table—the steeper the slope, the faster the water moves (because the steeper the slope, the greater the pressure difference between two points). The water-table slope is known as the **hydraulic gradient** and can be expressed as follows:

$$\text{hydraulic gradient} = \frac{h_1 - h_2}{d}$$

where h_1 is the elevation of one point on the water table, h_2 the elevation of a second point, and d is the horizontal distance between the two points (Figure 17.6).

Darcy also experimented with different materials such as coarse sand and fine sand by measuring the rate of flow through sediment-filled tubes that were tilted at varying angles. He found that the flow velocity varied with the permeability of the sediment—groundwater flows more rapidly through sediments having greater permeability than through materials having lower permeability. This factor is known as **hydraulic conductivity** and is a coefficient that takes into account the permeability of the aquifer and the viscosity of the fluid.

To determine discharge (Q), that is, the actual volume of water that flows through an aquifer in a specified time, the following equation is used:

$$Q = \frac{KA(h_1 - h_2)}{d}$$

where $\frac{h_1 - h_2}{d}$ is the hydraulic gradient, K is the coefficient that represents hydraulic conductivity, and A is the cross-sectional area of the aquifer. This expression has come to be called **Darcy's law** in honor of the pioneering French scientist-engineer.

Different Scales of Movement

The extent of groundwater flow systems varies from a few square kilometers or less to tens of thousands of square kilometers. The length of flow paths ranges from a few meters to tens and sometimes hundreds of kilometers. Figure 17.7 is a cross section of a hypothetical region in which a deep

Students Sometimes Ask . . .

How does the rate of groundwater movement compare to the velocity of streams?

Velocities of groundwater flow are generally orders of magnitude less than velocities of streamflow. A velocity of 1 foot per day or greater is a high rate of movement for groundwater, and groundwater velocities can be as low as 1 foot per year or 1 foot per decade. In contrast, rates of streamflow are generally measured in feet per second. A velocity of 1 foot per second equals about 16 miles per day.

groundwater flow system is overlain by and connected to several, more shallow local flow systems. The subsurface geology exhibits a complicated arrangement of high hydraulic-conductivity aquifer units and low hydraulic-conductivity aquitard units.

Starting near the top of Figure 17.7, the blue arrows represent water movement in several local groundwater systems that occur in the upper water table aquifer. They are separated by groundwater divides at the center of the hills and discharge into the nearest surface water body. Beneath these most shallow systems, red arrows show water movement in a somewhat deeper system in which groundwater does not discharge into the nearest surface water body, but into a more distant one. Finally, the black arrows show groundwater movement in a deep regional system that lies beneath the more shallow ones and is connected to them. The horizontal scale of the figure could range from tens to hundreds of kilometers.

Springs

Groundwater
▸ Springs and Wells

Springs have aroused the curiosity and wonder of people for thousands of years. The fact that springs were, and to some people still are, rather mysterious phenomena is not difficult to understand, for here is water flowing freely from the ground in all kinds of weather in seemingly inexhaustible supply, but with no obvious source.

Not until the middle of the 17th century did the French physicist Pierre Perrault invalidate the age-old assumption that precipitation could not adequately account for the amount of water emanating from springs and flowing in rivers. Over several years Perrault computed the quantity of water that fell on France's Seine River basin. He then calculated the mean annual runoff by measuring the river's discharge. After allowing for the loss of water by evaporation, he showed that there was sufficient water remaining to feed the springs. Thanks to Perrault's pioneering efforts and the measurements by many afterward, we now know that the

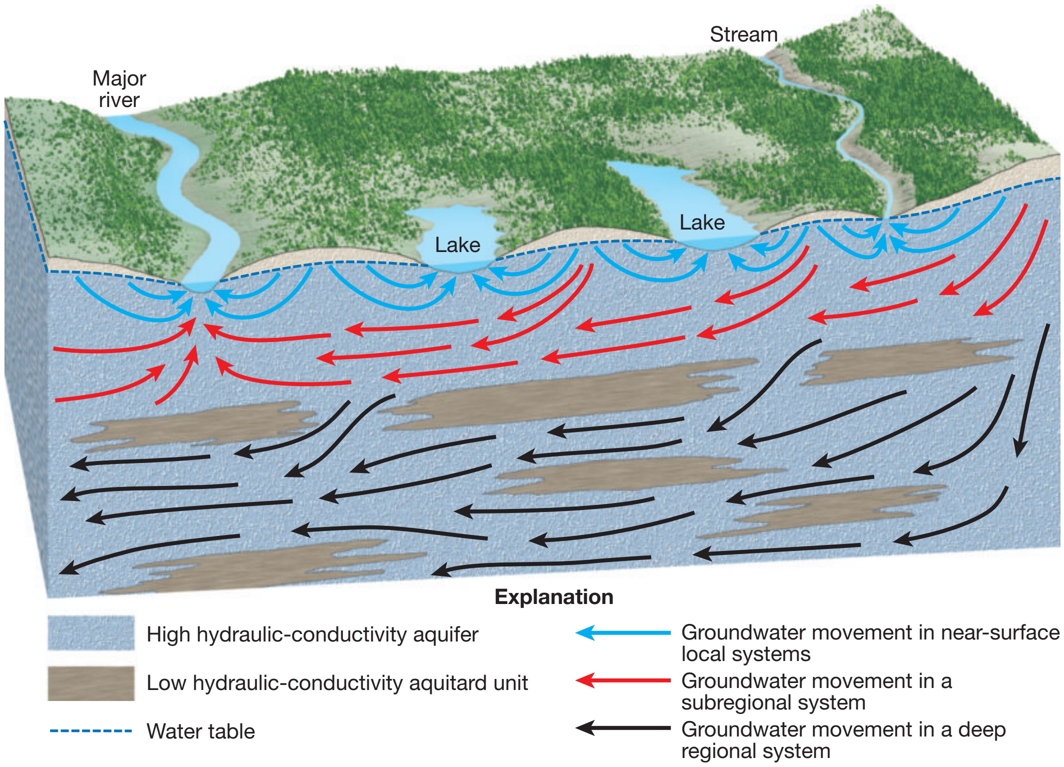

FIGURE 17.7 A hypothetical groundwater flow system that includes subsystems at different scales. Variations in surface topography and subsurface geology can produce a complex situation. The horizontal scale of the figure could range from tens to hundreds of kilometers. (After U. S. Geological Survey)

FIGURE 17.8 Spring in Arizona's Marble Canyon. (Photo by Michael Collier)

source of springs is water from the zone of saturation and that the ultimate source of this water is precipitation.

Whenever the water table intersects Earth's surface, a natural outflow of groundwater results, which we call a **spring** (Figure 17.8). Springs such as the one pictured in Figure 17.8 form when an aquitard blocks the downward movement of groundwater and forces it to move laterally. Where the permeable bed outcrops, a spring results. Another situation leading to the formation of a spring is illustrated in Figure 17.9. Here an aquitard is situated above the main water table. As water percolates downward, a portion of it is intercepted by the aquitard, thereby creating a localized zone of saturation and a **perched water table.**

Springs, however, are not confined to places where a perched water table creates a flow at the surface. Many geological situations lead to the formation of springs because subsurface conditions vary greatly from place to place. Even in areas underlain by impermeable crystalline rocks, permeable zones may exist in the form of fractures or solution channels. If these openings fill with water and intersect the ground surface along a slope, a spring will result.

Hot Springs and Geysers

By definition, the water in **hot springs** is 6–9°C (10–15°F) warmer than the mean annual air temperature for the localities where they occur. In the United States alone, there are more than 1000 such springs (Figure 17.10).

Temperatures in deep mines and oil wells usually rise with increasing depth, an average of about 2°C per 100 meters (1°F per 100 feet). Therefore, when groundwater circulates at great depths, it becomes heated. If it rises to the surface, the water may emerge as a hot spring. The water of some hot springs in the eastern United States is heated in this manner. However, the great majority (more than 95 percent) of the hot springs (and geysers) in the United States are found in the West (Figure 17.10). The reason for such a distribution is that the source of heat for most hot springs is cooling igneous rock, and it is in the West that igneous activity has occurred more recently.

Geysers are intermittent hot springs or fountains in which columns of water are ejected with great force at various intervals, often rising 30–60 meters (100–200 feet) into the air. After the jet of water ceases, a column of steam rushes out, usually with a thunderous roar. Perhaps the most famous geyser in the world is Old Faithful in Yellowstone National Park, which erupts about once each hour (Figure 17.11). The great abundance, diversity, and spectacular nature of Yellowstone's geysers and other thermal features undoubtedly was the primary reason for its becoming the first national park in the United States. Geysers are also found in other parts of the world, notably New Zealand and Iceland.

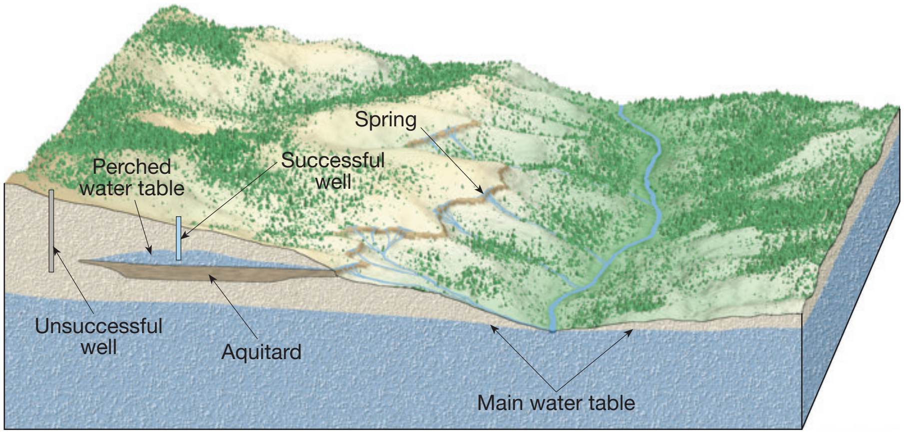

FIGURE 17.9 When an aquitard is situated above the main water table, a localized zone of saturation may result. Where the perched water table intersects the side of the valley, a spring flows. The perched water table also caused the well on the right to be successful, whereas the well on the left will be unsuccessful unless it is drilled to a greater depth.

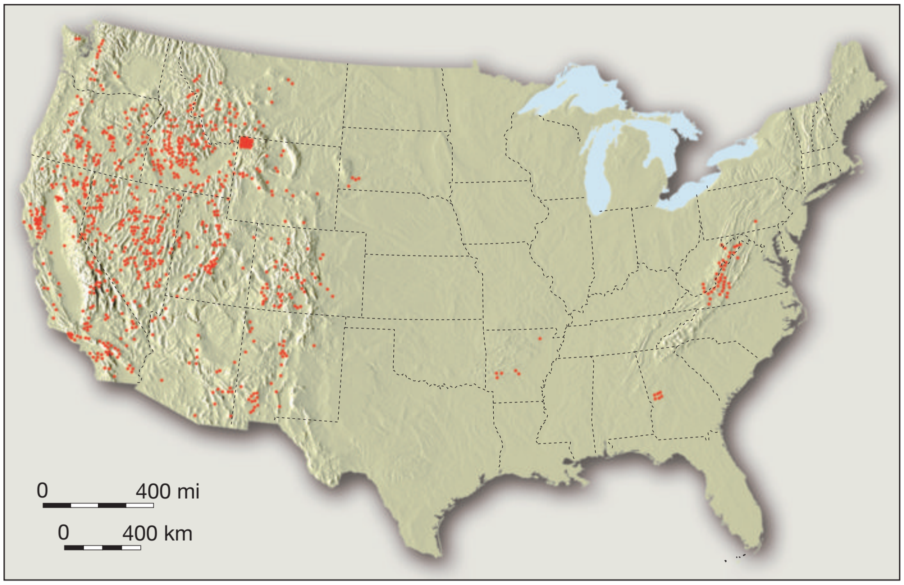

FIGURE 17.10 Distribution of hot springs and geysers in the United States. Note the concentration in the West, where igneous activity has been most recent. (After G. A. Waring, U.S. Geological Survey Professional Paper 492, 1965)

In fact, the Icelandic word *geysa,* to gush, gives us the name *geyser.*

Geysers occur where extensive underground chambers exist within hot igneous rocks. How they operate is shown in Figure 17.12. As relatively cool groundwater enters the chambers, it is heated by the surrounding rock. At the bottom of the chambers, the water is under great pressure because of the weight of the overlying water. This great pressure prevents the water from boiling at the normal surface temperature of 100°C (212°F). For example, water at the bottom of a 300-meter (1000-foot) water-filled chamber must attain nearly 230°C before it will boil. The heating causes the water to expand, with the result that some is forced out at the surface. This loss of water reduces the pressure on the remaining water in the chamber, which lowers the boiling point. A portion of the water deep within the chamber quickly turns to steam, and the geyser erupts (Figure 17.12). Following eruption, cool groundwater again seeps into the chamber and the cycle begins anew.

When groundwater from hot springs and geysers flows out at the surface, material in solution is often precipitated, producing an accumulation of chemical sedimentary rock. The material deposited at any given place commonly reflects the chemical makeup of the rock through which the water circulated. When the water contains dissolved silica, a material called *siliceous sinter* or *geyserite* is deposited around the spring. When the water contains dissolved calcium carbonate, a form of limestone called *travertine* or *calcareous tufa* is deposited. The latter term is used if the material is spongy and porous.

The deposits at Mammoth Hot Springs in Yellowstone National Park are more spectacular than most (Figure 17.13). As the hot water flows upward through a series of channels and then out at the surface, the reduced pressure allows carbon dioxide to separate and escape from the

FIGURE 17.11 A wintertime eruption of Old Faithful, one of the world's most famous geysers. It emits as much as 45,000 liters (almost 12,000 gallons) of hot water and steam about once each hour. (Photo by Marc Muench/David Muench Photography, Inc.)

Students Sometimes Ask . . .

I know Old Faithful in Yellowstone National Park is the most famous geyser. Is it the largest?

No. It appears as though that distinction goes to Yellowstone's Steamboat Geyser, at least if we use the word "large" to mean "tall." During a major eruption, Steamboat Geyser can spew plumes of water 90 meters (300 feet) high for as long as 40 minutes. Following this water phase, the steam phase features powerful bursts of hot mist that extend 150 meters (500 feet) into the sky. Like most of Yellowstone's geysers, Steamboat Geyser is not reliable like Old Faithful. Intervals between eruptions can vary from three days to 50 years. The geyser, which was completely dormant from 1911 to 1961, has erupted fewer than 10 times since 1989.

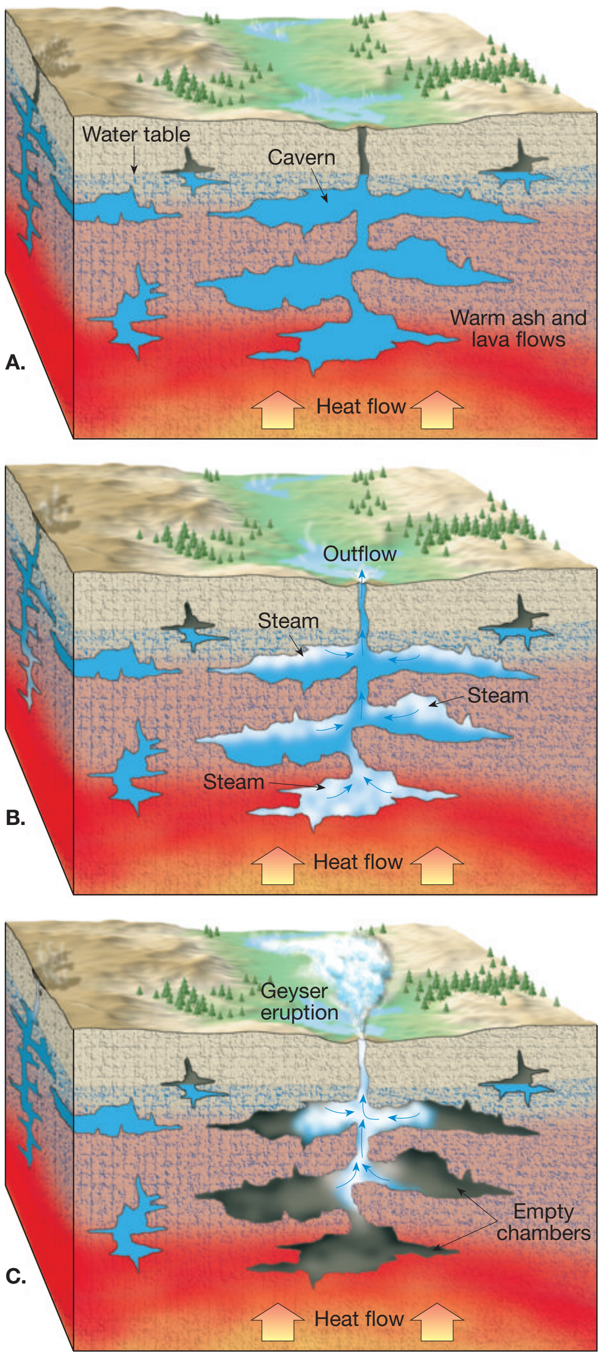

FIGURE 17.12 Idealized diagrams of a geyser. A geyser can form if the heat is not distributed by convection. **A.** In this figure, the water near the bottom is heated to near its boiling point. The boiling point is higher there than at the surface because the weight of the water above increases the pressure. **B.** The water higher in the geyser system is also heated; therefore, it expands and flows out at the top, reducing the pressure on the water at the bottom. **C.** At the reduced pressure on the bottom, boiling occurs. Some of the bottom water flashes into steam, and the expanding steam causes an eruption.

water. The loss of carbon dioxide causes the water to become supersaturated with calcium carbonate, which then precipitates. In addition to containing dissolved silica and calcium carbonate, some hot springs contain sulfur, which gives water a poor taste and unpleasant odor. Undoubtedly, Rotten Egg Spring, Nevada, is such a situation.

Wells

Groundwater
▸ Springs and Wells

The most common method for removing groundwater is the **well,** a hole bored into the zone of saturation. Wells serve as small reservoirs into which groundwater migrates and from which it can be pumped to the surface. The use of wells dates back many centuries and continues to be an important method of obtaining water today. By far the single greatest use of this water in the United States is irrigation for agriculture. More than 65 percent of the groundwater used each year is for this purpose. Industrial uses rank a distant second, followed by the amount used in city water systems and rural homes.

The water-table level may fluctuate considerably during the course of a year, dropping during the dry seasons and rising following periods of rain. Therefore, to ensure a continuous supply of water, a well must penetrate below the water table. Whenever water is withdrawn from a well, the water table around the well is lowered. This effect, termed **drawdown,** decreases with increasing distance from the well. The result is a depression in the water table, roughly conical in shape, known as a **cone of depression** (Figure 17.14). Because the cone of depression increases the hydraulic gradient near the well, groundwater will flow more rapidly toward the opening. For most smaller domestic wells, the cone of depression is negligible. However, when wells are heavily pumped for irrigation or for industrial

Students Sometimes Ask . . .

I have heard people say that supplies of groundwater can be located using a forked stick. Can this actually be done?

What you describe is a practice called "water dowsing." In the classic method, a person holding a forked stick walks back and forth over an area. When water is detected, the bottom of the "Y" is supposed to be attracted downward.

Geologists and engineers are dubious, to say the least. Case histories and demonstrations may seem convincing, but when dowsing is exposed to scientific scrutiny, it fails. Most "successful" examples of water dowsing occur in places where water would be hard to miss. In a region of adequate rainfall and favorable geology, it is difficult to drill and not find water!

FIGURE 17.13 Mammoth Hot Springs at Yellowstone National Park. Although most of the deposits associated with geysers and hot springs in Yellowstone Park are silica-rich geyserite, the deposits at Mammoth Hot Springs consist of a form of limestone called travertine. (Photo by Stephen Trimble)

purposes, the withdrawal of water can be great enough to create a very wide and steep cone of depression. This may substantially lower the water table in an area and cause nearby shallow wells to become dry. Figure 17.14 illustrates this situation.

Digging a successful well is a familiar problem for people in areas where groundwater is the primary source of supply. One well may be successful at a depth of 10 meters (33 feet), whereas a neighbor may have to go twice as deep to find an adequate supply. Still others may be forced to go deeper or try a different site altogether. When subsurface materials are heterogeneous, the amount of water a well is capable of providing may vary a great deal over short distances. For example, when two nearby wells are drilled to the same level and only one is successful, it may be caused by the presence of a perched water table beneath one of them. Such a case is shown in Figure 17.9. Massive igneous and metamorphic rocks provide a second example. These crystalline rocks are usually not very permeable except where they are cut by many intersecting joints and fractures. Therefore, when a well drilled into such rock does not intersect an adequate network of fractures, it is likely to be unproductive.

Artesian Wells

Groundwater
▸ Springs and Wells

In most wells, water cannot rise on its own. If water is first encountered at 30 meters depth, it remains at that level, fluctuating perhaps a meter or two with seasonal wet and dry periods. However, in some wells, water rises, sometimes overflowing at the surface. Such wells are abundant in the *Artois* region of northern France, and so we call these self-rising wells *artesian.*

To many people the term *artesian* is applied to any well drilled to great depths. This use of the term is incorrect. Others believe that an artesian well must flow freely at the surface (Figure 17.15). Although this is a more correct notion than the first, it represents too narrow a definition. The term **artesian** is applied to *any* situation in which groundwater under pressure rises above the level of the aquifer. As we shall see, this does not always mean a free-flowing surface discharge.

For an artesian system to exist, two conditions usually are met (Figure 17.15): (1) water is confined to an aquifer that is inclined so that one end can receive water; and (2) aquitards, both above and below the aquifer, must be present to prevent the water from escaping. (Such an aquifer is called a *confined aquifer.*) When such a layer is tapped, the pressure created by the weight of the water above will force the water to rise. If there were no friction, the water in the well would rise to the level of the water at the top of the aquifer. However, friction reduces the height of the pressure surface. The greater the distance from the recharge area (where water enters the inclined aquifer), the greater the friction and the less the rise of water.

In Figure 17.16, well 1 is a **nonflowing artesian well,** because at this location the pressure surface is below ground level. When the pressure surface is above the ground and a well is drilled into the aquifer, a **flowing artesian well** is created (well 2, Figure 17.16). Not all artesian systems are wells. *Artesian springs* also exist. Here groundwater may reach the surface by rising along a natural fracture such as a fault rather than through an artificially produced hole. In deserts, artesian springs are sometimes responsible for creating an oasis.

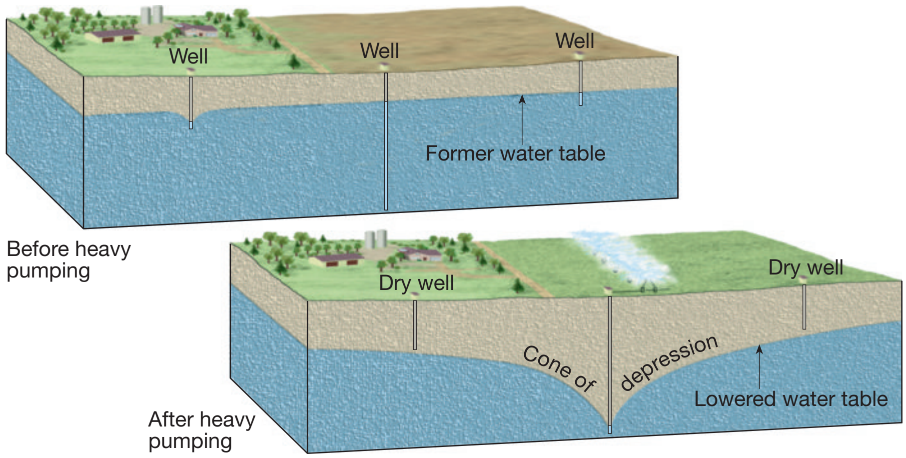

FIGURE 17.14 A cone of depression in the water table often forms around a pumping well. If heavy pumping lowers the water table, the shallow wells may be left dry.

FIGURE 17.15 Sometimes water flows freely at the surface when an artesian well is developed. However, for most artesian wells, the water must be pumped to the surface. (Photo by James E. Patterson)

Artesian systems act as conduits, often transmitting water great distances from remote areas of recharge to points of discharge. A well-known artesian system in South Dakota is a good example of this. In the western part of the state, the edges of a series of sedimentary layers have been bent up to the surface along the flanks of the Black Hills. One of these beds, the permeable Dakota Sandstone, is sandwiched between impermeable strata and gradually dips into the ground toward the east. When the aquifer was first tapped, water poured from the ground surface, creating fountains many meters high (Figure 17.17). In some places the force of the water was sufficient to power waterwheels. Scenes such as the one pictured in Figure 17.17, however, can no longer occur, because thousands of additional wells now tap the same aquifer. This depleted the reservoir, and the water table in the recharge area was lowered. As a consequence, the pressure dropped to the point where many wells stopped flowing altogether and had to be pumped.

On a different scale, city water systems can be considered examples of artificial artesian systems (Figure 17.18). The water tower, into which water is pumped, would represent the area of recharge, the pipes the confined aquifer, and the faucets in homes the flowing artesian wells.

Problems Associated with Groundwater Withdrawal

As with many of our valuable natural resources, groundwater is being exploited at an increasing rate. In some areas, overuse threatens the groundwater supply. In other places, groundwater withdrawal has caused the ground and everything resting on it to sink. Still other localities are concerned with the possible contamination of the groundwater supply.

Treating Groundwater as a Nonrenewable Resource

Many natural systems tend to establish a condition of equilibrium. The groundwater system is no exception. The water table's height reflects a balance between the rate of infiltration and the rate of discharge and withdrawal. Any imbalance will either raise or lower the water table. Long-term imbalances can lead to a significant drop in the water table if there is either a decrease in recharge due to prolonged drought, or an increase in groundwater discharge or withdrawal.

For many, groundwater appears to be an endlessly renewable resource because it is continually replenished by rainfall and melting snow. But in some regions, groundwater has been and continues to be treated as a *nonrenewable* resource. Where this occurs, the water available to recharge the aquifer falls significantly short of the amount being withdrawn.

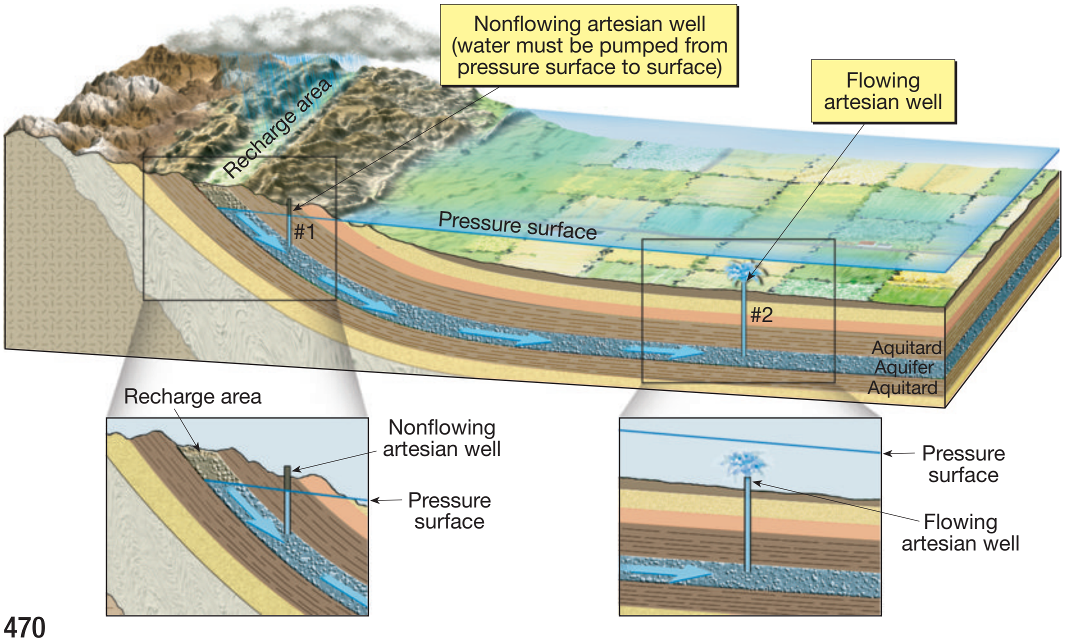

FIGURE 17.16 Artesian systems occur when an inclined aquifer is surrounded by impermeable beds.

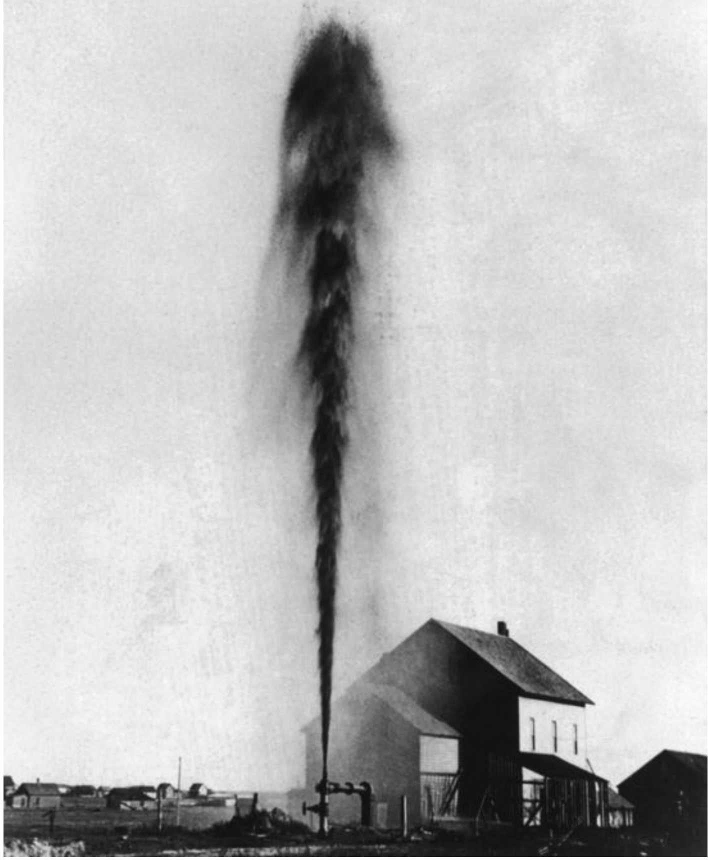

FIGURE 17.17 A “gusherlike” flowing artesian well in South Dakota in the early part of the twentieth century. Thousands of additional wells now tap the same confined aquifer; thus, the pressure has dropped to the point that many wells stopped flowing altogether and have to be pumped. (Photo by N. H. Darton, U.S. Geological Survey)

The High Plains provides one example. Here an extensive agricultural economy is largely dependent on irrigation (Figure 17.19). In some parts of the region, where intense irrigation has been practiced for an extended period, depletion of groundwater has been severe. Under these circumstances, it can be said that the groundwater is literally being “mined.” Even if pumping were to cease immediately, it could take hundreds or thousands of years for the groundwater to be fully replenished.

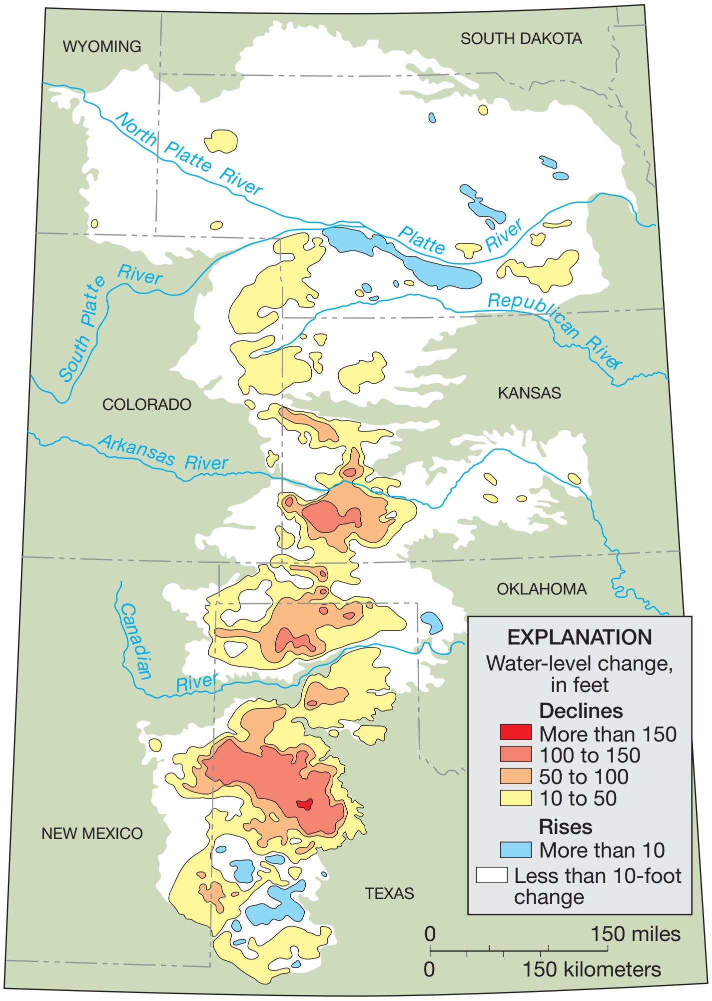

FIGURE 17.19 Changes in groundwater levels in the High Plains aquifer from predevelopment to 1997. Extensive pumping for irrigation has led to water level declines in excess of 100 feet in parts of Kansas, Oklahoma, Texas, and New Mexico. Water level rises have occurred where surface water is used for irrigation, such as along the Platte River in Nebraska. (After U.S. Geological Survey)

Subsidence

As you will see later in this chapter, surface subsidence can result from natural processes related to groundwater. However, the ground may also sink when water is pumped from wells faster than natural recharge processes can replace it. This effect is particularly pronounced in areas underlain by thick layers of unconsolidated sediments. As the water is withdrawn, the water pressure drops and the weight of the overburden is transferred to the sediment. The greater pressure packs the sediment grains tightly together, and the ground subsides. The size of the area affected by such subsidence is significant. In the contiguous United States, it amounts to an estimated 26,000 square kilometers—an area about the same size as the state of Massachusetts!

Many areas may be used to illustrate land subsidence caused by the excessive pumping of groundwater from relatively loose sediment. A classic example in the United States occurred in the San Joaquin Valley of California and is discussed in Box 17.2. Many other cases of land subsidence due to groundwater pumping exist in the United States, including Las Vegas, Nevada; New Orleans and Baton Rouge, Louisiana; and the Houston–Galveston area of Texas. In the

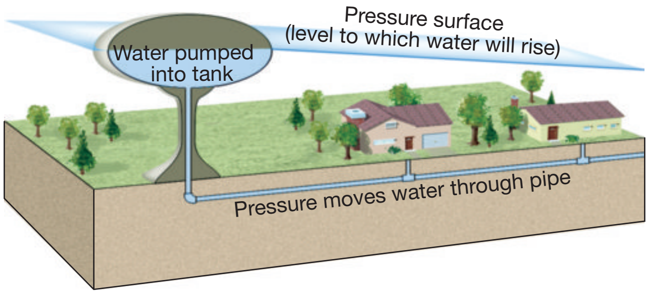

FIGURE 17.18 City water systems can be considered to be artificial artesian systems.

BOX 17.2 ▶ PEOPLE AND THE ENVIRONMENT

Land Subsidence in the San Joaquin Valley

The San Joaquin Valley is a broad structural basin that contains a thick fill of sediments. The size of Maryland, it constitutes the southern two-thirds of California's Central Valley, a flatland separating two mountain ranges—the Coast Ranges to the west and the Sierra Nevada to the east (Figure 17.B). The valley's aquifer system is a mixture of alluvial materials derived from the surrounding mountains. Sediment thicknesses average about 870 meters (about half a mile). The valley's climate is arid to semiarid, with average annual precipitation ranging from 12 to 35 centimeters (5 to 14 inches).

The San Joaquin Valley has a strong agricultural economy that requires large quantities of water for irrigation. For many years up to 50 percent of this need was met by groundwater. In addition, nearly every city in the region uses groundwater as its principal source for homes and industry.

FIGURE 17.B The shaded area shows California's San Joaquin Valley.

FIGURE 17.C The marks on this utility pole indicate the level of the surrounding land in preceding years. Between 1925 and 1975 this part of the San Joaquin Valley subsided almost 9 meters because of the withdrawal of groundwater and the resulting compaction of sediments. (Photo courtesy of U.S. Geological Survey)

Although development of the valley's groundwater for irrigation began in the late 1800s, land subsidence did not begin until the mid-1920s when withdrawals were substantially increased. By the early 1970s, water levels had declined up to 120 meters (400 feet). The resulting ground subsidence exceeded 8.5 meters (29 feet) at one place in the region (Figure 17.C). At that time, areas within the valley were subsiding faster than 0.3 meter (1 foot) per year.

Then, because surface water was being imported and groundwater pumping was being decreased, water levels in the aquifer recovered and subsidence ceased. However, during a drought in 1976–1977, heavy groundwater pumping led to renewed subsidence. This time water levels dropped much faster because of the reduced storage capacity caused by earlier compaction of sediments. In all, half the entire valley was affected by subsidence. According to the U.S. Geological Survey:

> Subsidence in the San Joaquin Valley probably represents one of the greatest single manmade alterations in the configuration of the Earth's surface. . . . It has caused serious and costly problems in construction and maintenance of water-transport structures, highways, and highway structures; also many millions of dollars have been spent on the repair or replacement of deep-water wells. Subsidence, besides changing the gradient and course of valley creeks and streams, has caused unexpected flooding, costing farmers many hundreds of thousands of dollars in recurrent land leveling.*

Similar effects have been documented in the San Jose area of the Santa Clara Valley, California, where between 1916 and 1966 subsidence approached 4 meters. Flooding of lands bordering the southern part of San Francisco Bay was one of the results. As was the case in the San Joaquin Valley, the subsidence stopped when imports of surface water were increased, allowing groundwater withdrawal rates to be decreased.

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*Ireland R. L., J. F. Poland, and F. S. Riley, *Land Subsidence in the San Joaquin Valley, California, as of 1980*, U.S. Geological Survey Professional Paper 437-I (Washington, D.C.: U.S. Government Printing Office, 1984), p. 11.

low-lying coastal area between Houston and Galveston, land subsidence ranges from 1.5 to 3 meters (5 to 9 feet). The result is that about 78 square kilometers (30 square miles) are permanently flooded.

Outside the United States, one of the most spectacular examples of subsidence occurred in Mexico City, which is built on a former lake bed. In the first half of the 20th century, thousands of wells were sunk into the water-saturated sediments beneath the city. As water was withdrawn, portions of the city subsided by as much as 6 to 7 meters. In some places buildings have sunk to such a point that access to them from the street is located at what used to be the second-floor level!

Saltwater Contamination

In many coastal areas the groundwater resource is being threatened by the encroachment of saltwater. To understand this problem, let us examine the relationship between fresh groundwater and salt groundwater. Figure 17.20A is a diagrammatic cross section that illustrates this relationship in a coastal area underlain by permeable homogeneous materials. Fresh water is less dense than saltwater, so it floats on the saltwater and forms a large lens-shaped body that may extend to considerable depths below sea level. In such a situation, if the water table is 1 meter above sea level, the base of the freshwater body will extend to a depth of about 40 meters below sea level. Stated another way, the depth of the fresh water below sea level is about 40 times greater than the elevation of the water table above sea level. Thus, when excessive pumping lowers the water table by a certain amount, the bottom of the freshwater zone will rise by 40 times that amount. Therefore, if groundwater withdrawal continues to exceed recharge, there will come a time when the elevation of the saltwater will be sufficiently high to be drawn into wells, thus contaminating the freshwater supply (Figure 17.20B). Deep wells and wells near the shore are usually the first to be affected.

In urbanized coastal areas, the problems created by excessive pumping are compounded by a decrease in the rate of natural recharge. As more and more of the surface is covered by streets, parking lots, and buildings, infiltration into the soil is diminished.

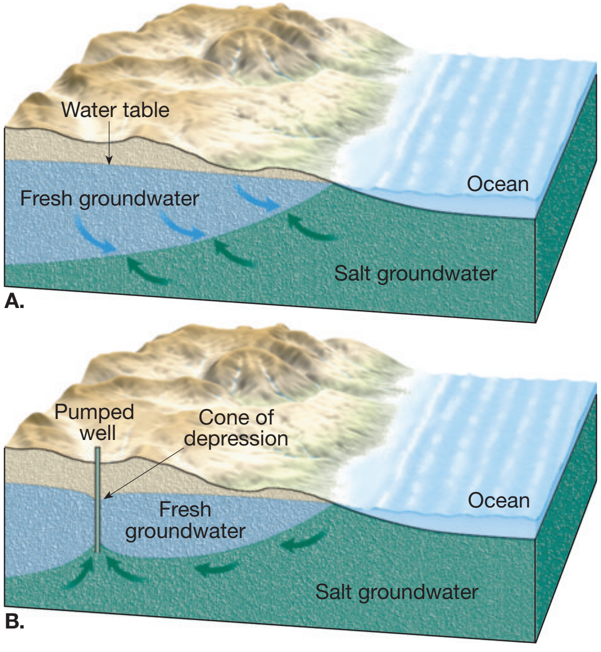


FIGURE 17.20 **A.** Because fresh water is less dense than saltwater, it floats on the saltwater and forms a lens-shaped body that may extend to considerable depths below sea level. **B.** When excessive pumping lowers the water table, the base of the freshwater zone will rise by 40 times that amount. The result may be saltwater contamination of wells.

In an attempt to correct the problem of saltwater contamination of groundwater resources, a network of recharge wells may be used. These wells allow wastewater to be pumped back into the groundwater system. A second method of correction is accomplished by building large basins. These basins collect surface drainage and allow it to seep into the ground. On New York's Long Island, where the problem of saltwater contamination was recognized more than 40 years ago, both of these methods have been employed with considerable success.

Contamination of freshwater aquifers by saltwater is primarily a problem in coastal areas, but it can also threaten noncoastal locations. Many ancient sedimentary rocks of marine origin were deposited when the ocean covered places that are now far inland. In some instances significant quantities of seawater were trapped and still remain in the rock. These strata sometimes contain quantities of fresh water and may be pumped for use by people. However, if fresh water is removed more rapidly than it is replenished, saline water may encroach and render the wells unusable. Such a situation threatened users of a deep (Cambrian age) sandstone aquifer in the Chicago area. To counteract this, water from Lake Michigan was allocated to the affected communities to offset the rate of withdrawal from the aquifer.

Groundwater Contamination

The pollution of groundwater is a serious matter, particularly in areas where aquifers provide a large part of the water supply. One common source of groundwater pollution is sewage. Its sources include an ever increasing number of septic tanks, as well as inadequate or broken sewer systems and farm wastes.

If sewage water that is contaminated with bacteria enters the groundwater system, it may become purified through natural processes. The harmful bacteria may be mechanically filtered by the sediment through which the water percolates, destroyed by chemical oxidation, and/or assimilated by other organisms. For purification to occur, however, the aquifer must be of the correct composition. For example, extremely permeable aquifers (such as highly fractured crystalline rock, coarse gravel, or cavernous limestone) have such large openings that contaminated groundwater may travel long distances without being cleansed. In this case, the water flows too rapidly and is not in contact with the surrounding material long enough for purification to occur. This is the problem at well 1 in Figure 17.21A.

On the other hand, when the aquifer is composed of sand or permeable sandstone, it can sometimes be purified after traveling only a few dozen meters through it. The openings between sand grains are large enough to permit water movement, yet the movement of the water is slow enough to allow ample time for its purification (well 2, Figure 17.21B).

Sometimes sinking a well can lead to groundwater pollution problems. If the well pumps a sufficient quantity of water, the cone of depression will locally increase the slope

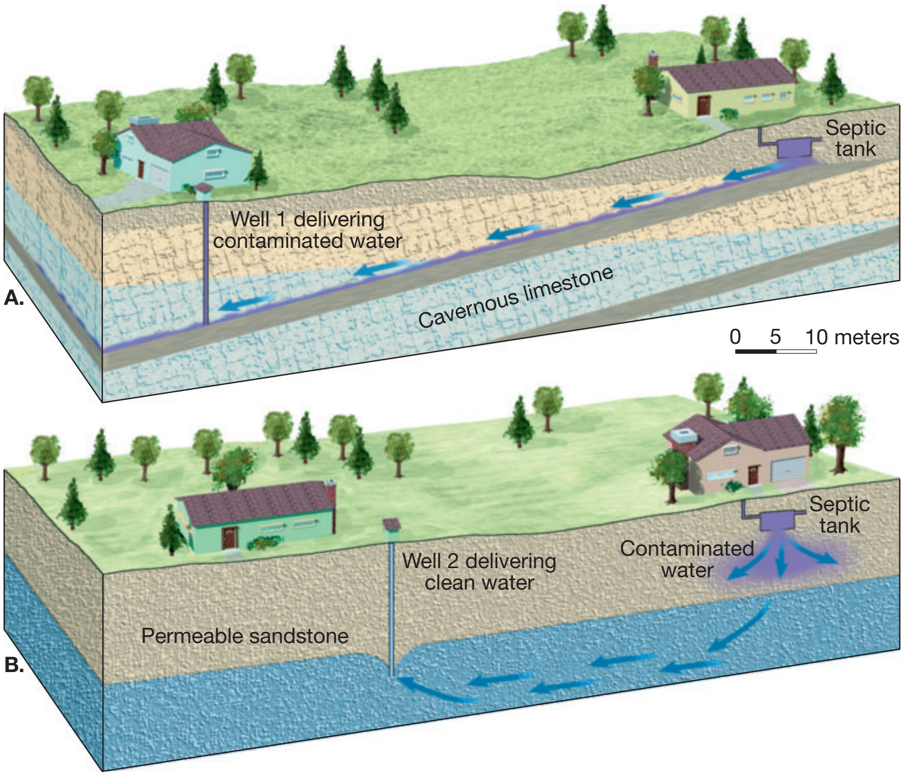


FIGURE 17.21 **A.** Although the contaminated water has traveled more than 100 meters before reaching well 1, the water moves too rapidly through the cavernous limestone to be purified. **B.** As the discharge from the septic tank percolates through the permeable sandstone, it is purified in a relatively short distance.

of the water table. In some instances the original slope may even be reversed. This could lead to the contamination of wells that yielded unpolluted water before heavy pumping began (Figure 17.22). Also recall that the rate of groundwater movement increases as the slope of the water table steepens. This could produce problems because a faster rate of movement allows less time for the water to be purified in the aquifer before it is pumped to the surface.

Other sources and types of contamination also threaten groundwater supplies (Figure 17.23). These include widely used substances such as highway salt, fertilizers that are spread across the land surface, and pesticides. In addition, a wide array of chemicals and industrial materials may leak from pipelines, storage tanks, landfills, and holding ponds. Some of these pollutants are classified as *hazardous,* meaning that they are either flammable, corrosive, explosive, or toxic. In land disposal, potential contaminants are heaped onto mounds or spread directly over the ground. As rainwater oozes through the refuse, it may dissolve a variety of organic and inorganic materials. If the leached material reaches the water table, it will mix with the groundwater and contaminate the supply. Similar problems may result from leakage of shallow excavations called holding ponds into which a variety of liquid wastes are disposed.

Because groundwater movement is usually slow, polluted water can go undetected for a long time. In fact, contamination is sometimes discovered only after drinking water has been affected and people become ill. By this time, the volume of polluted water may be very large, and even if the source of contamination is removed immediately, the problem is not solved. Although the sources of groundwater contamination are numerous, there are relatively few solutions.

Once the source of the problem has been identified and eliminated, the most common practice is simply to abandon the water supply and allow the pollutants to be flushed away gradually. This is the least costly and easiest solution, but the aquifer must remain unused for many years. To accelerate this process, polluted water is sometimes pumped out and treated. Following removal of the tainted water, the aquifer is allowed to recharge naturally, or in some cases the treated water or other fresh water is pumped back in. This process is costly, time-consuming, and it may be risky because there is no way to be certain that all of the contamination has been removed. Clearly, the most effective solution to groundwater contamination is prevention.

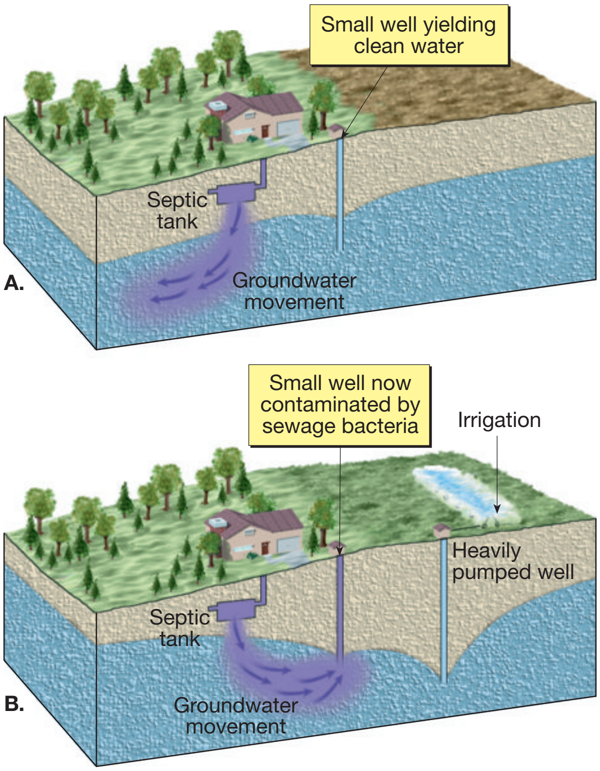


FIGURE 17.22 **A.** Originally the outflow from the septic tank moved away from the small well. **B.** The heavily pumped well changed the slope of the water table, causing contaminated groundwater to flow toward the small well.

FIGURE 17.23 Sometimes agricultural chemicals **A.** and materials leached from landfills **B.** find their way into the groundwater. These are two of the potential sources of groundwater contamination. (Photo **A** by Roy Morsch/Corbis/The Stock Market; Photo **B** by F. Rossotto/Corbis/The Stock Market)

The Geologic Work of Groundwater

Groundwater dissolves rock. This fact is key to understanding how caverns and sinkholes form. Because soluble rocks, especially limestone, underlie millions of square kilometers of Earth's surface, it is here that the groundwater carries on its important role as an erosional agent. Limestone is nearly insoluble in pure water but is quite easily dissolved by water containing small quantities of carbonic acid, and most groundwater contains this acid. It forms because rainwater readily dissolves carbon dioxide from the air and from decaying plants. Therefore, when groundwater comes in contact with limestone, the carbonic acid reacts with the calcite (calcium carbonate) in the rocks to form calcium bicarbonate, a soluble material that is then carried away in solution.

Students Sometimes Ask . . .

Is carbonic acid the only acid that creates limestone caverns?

No. It appears as though sulfuric acid (H_2SO_4) creates some caves. One example is Lechuquilla Cave in the Guadalupe Mountains near Carlsbad, New Mexico. Here solutions under pressure containing hydrogen sulfide (H_2S) derived from deep petroleum-rich sediments migrated upward through rock fractures. When these solutions mixed with groundwater containing oxygen, they formed sulfuric acid that then dissolved the limestone. Lechuquilla Cave is one of the deepest-known caves in the United States, with a vertical range of 478 meters (1568 feet), and is also one of the largest in the country, with 170 kilometers (105 miles) of passages.

Caverns

The most spectacular results of groundwater's erosional handiwork are limestone **caverns.** In the United States alone about 17,000 caves have been discovered and new ones are being found every year. Although most are relatively small, some have spectacular dimensions. Mammoth Cave in Kentucky and Carlsbad Caverns in southeastern New Mexico are famous examples. The Mammoth Cave system is the most extensive in the world, with more than 540 kilometers of interconnected passages. The dimensions at Carlsbad Caverns are impressive in a different way. Here we find the largest and perhaps most spectacular single chamber. The Big Room at Carlsbad Caverns has an area equivalent to 14 football fields and enough height to accommodate the U.S. Capitol building.

Most caverns are created at or just below the water table in the zone of saturation. Here acidic groundwater follows lines of weakness in the rock, such as joints and bedding planes. As time passes, the dissolving process slowly creates cavities and gradually enlarges them into caverns. Material that is dissolved by the groundwater is eventually discharged into streams and carried to the ocean.

In many caves, development has occurred at several levels, with the current cavern-forming activity occurring at the lowest elevation. This situation reflects the close relationship between the formation of major subterranean passages and the river valleys into which they drain. As streams cut their valleys deeper, the water table drops as the elevation of the river drops. Consequently, during periods when surface streams are rapidly downcutting, surrounding groundwater levels drop rapidly and cave passages are abandoned by the water while the passages are still relatively small in cross-sectional area. Conversely, when the entrenchment of streams is slow or negligible, there is time for large cave passages to form.

Certainly the features that arouse the greatest curiosity for most cavern visitors are the stone formations that give some caverns a wonderland appearance. These are not erosional features, like the cavern itself, but depositional features created by the seemingly endless dripping of water over great spans of time. The calcium carbonate that is left behind produces the limestone we call travertine. These cave deposits, however, are also commonly called *dripstone,* an obvious reference to their mode of origin. Although the formation of caverns takes place in the zone of saturation, the deposition of dripstone is not possible until the caverns are above the water table in the unsaturated zone. As soon as the chamber is filled with air, the stage is set for the decoration phase of cavern building to begin.

The various dripstone features found in caverns are collectively called **speleothems** (*spelaion* = cave, *them* = put), no two of which are exactly alike (Figure 17.24). Perhaps the most familiar speleothems are **stalactites** (*stalaktos* = trickling). These icicle-like pendants hang from the ceiling of the cavern and form where water seeps through cracks above. When the water reaches air in the cave, some of the dissolved carbon dioxide escapes from the drop, and calcite precipitates. Deposition occurs as a ring around the edge of the water drop. As drop after drop follows, each leaves an infinitesimal trace of calcite behind, and a hollow limestone tube is created. Water then moves through the tube, remains suspended momentarily at the end, contributes a tiny ring of calcite, and falls to the cavern floor. The stalactite just described is appropriately called a *soda straw* (Figure 17.25). Often the hollow tube of the soda straw becomes plugged or its supply of water increases. In either case, the water is forced to flow and hence deposit along the outside of the tube. As deposition continues, the stalactite takes on the more common conical shape.

Speleothems that form on the floor of a cavern and reach upward toward the ceiling are called **stalagmites** (*stalagmos* = dropping).The water supplying the calcite for stalagmite growth falls from the ceiling and splatters over the surface. As a result, stalagmites do not have a central tube and are usually more massive in appearance and rounded on their upper ends than stalactites. Given enough time, a downward-growing stalactite and an upward-growing stalagmite may join to form a *column.*

Karst Topography

Many areas of the world have landscapes that to a large extent have been shaped by the dissolving power of groundwater. Such areas are said to exhibit **karst topography,** named for the Kras Plateau in Slovenia located along the northeastern shore of the Adriatic Sea where such topography is strikingly developed. In the United States, karst landscapes occur in many areas that are underlain by limestone, including portions of Kentucky, Tennessee, Alabama, southern Indiana, and central and northern Florida. Generally, arid and semiarid areas are too dry to develop karst topography. When solution features exist in such regions, they are likely to be remnants of a time when rainier conditions prevailed.

Karst areas typically have irregular terrain punctuated with many depressions, called **sinkholes** or **sinks.** In the limestone areas of Florida, Kentucky, and southern Indiana, there are literally tens of thousands of these depressions varying in depth from just a meter or two to a maximum of more than 50 meters (Figure 17.26).

Sinkholes commonly form in two ways. Some develop gradually over many years without any physical disturbance to the rock. In these situations the limestone immediately below the soil is dissolved by downward-sweeping rainwater that is freshly charged with carbon dioxide. With time the bedrock surface is lowered and the fractures into which the water seeps are enlarged. As the fractures grow in size, soil subsides into the widening voids, from which it is removed by groundwater flowing in the passages below. These depressions are usually shallow and have gentle slopes.

By contrast, sinkholes can also form abruptly and without warning when the roof of a cavern collapses under its own weight. Typically, the depressions created in this manner are steep-sided and deep. When they form in populous areas, they may represent a

FIGURE 17.24 Speleothems are of many types, including stalactites, stalagmites, and columns. Big Room, Carlsbad Caverns National Park. The large stalagmite is called the Totem Pole. (Photo by David Muench/David Muench Photography)

FIGURE 17.25 "Live" soda straw stalactites. Lehman Caves, Great Basin National Park, Nevada. (Photo by Tom & Susan Bean, Inc.)

serious geologic hazard. Such a situation is clearly the case in Figure 17.26B and Box 17.3.

In addition to a surface pockmarked by sinkholes, karst regions characteristically show a striking lack of surface drainage (streams). Following a rainfall, the runoff is quickly funneled below ground through sinks. It then flows through caverns until it finally reaches the water table. Where streams do exist at the surface, their paths are usually short. The names of such streams often give a clue to their fate. In the Mammoth Cave area of Kentucky, for example, there is Sinking Creek, Little Sinking Creek, and Sinking Branch. Some sinkholes become plugged with clay and debris, creating small lakes or ponds. The development of a karst landscape is depicted in Figure 17.26.

Some regions of karst development exhibit landscapes that look very different from the sinkhole-studded terrain depicted in Figure 17.27. One striking example is an extensive region in southern China that is described as exhibiting *tower karst.* As Figure 17.28 shows, the term *tower* is appropriate because the landscape consists of a maze of isolated steep-sided hills that rise abruptly from the ground. Each is riddled with interconnected caves and passageways. This type of karst topography forms in wet tropical and subtropical regions having thick beds of highly jointed limestone. Here groundwater has dissolved large volumes of limestone, leaving only these residual towers. Karst development is more rapid in tropical climates due to the abundant rainfall and the greater availability of carbon dioxide from the decay of lush tropical vegetation. The extra carbon dioxide in the soil means there is more carbonic acid for dissolving limestone. Other tropical areas of advanced karst development include portions of Puerto Rico, western Cuba, and northern Vietnam.

FIGURE 17.26 **A.** This high-altitude infrared image shows an area of karst topography in central Florida. The numerous lakes occupy sinkholes. (Courtesy of USDA–ASCS) **B.** This small sinkhole formed suddenly in 1991 when the roof of a cavern collapsed, destroying this home in Frostproof, Florida. (Photo by *St. Petersburg Times*/Liaison Agency, Inc.)

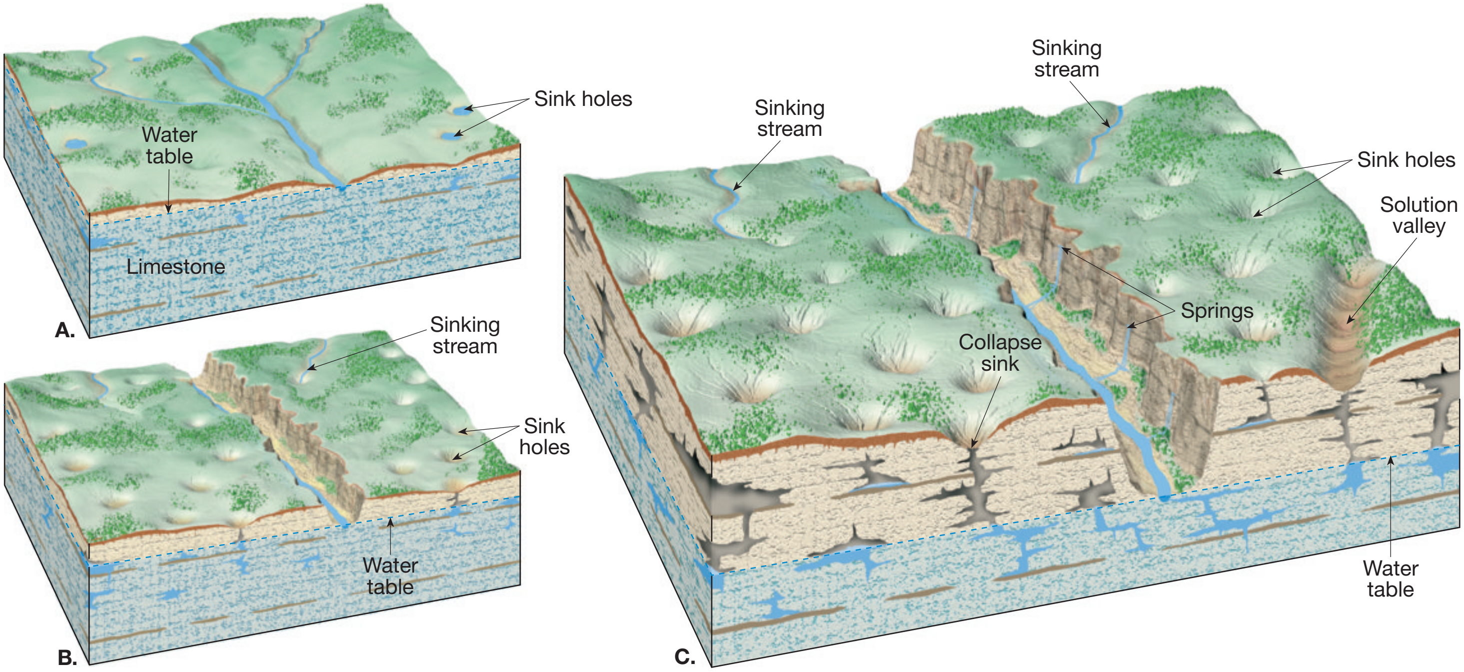
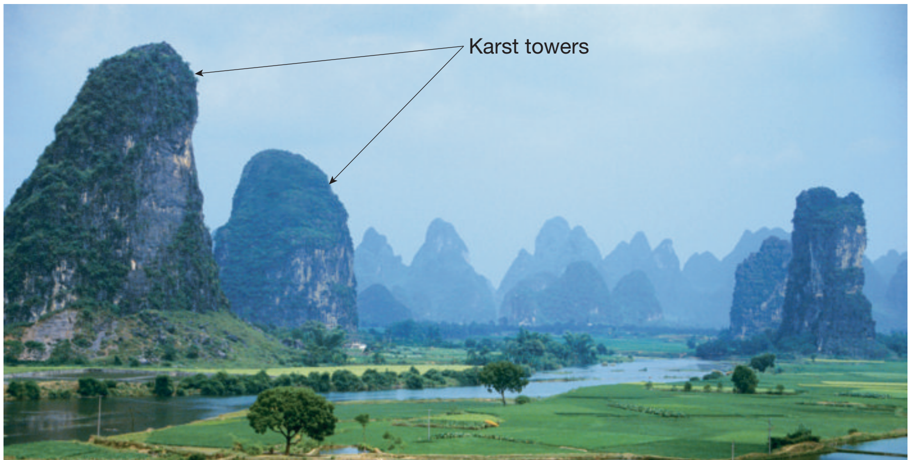


FIGURE 17.27 Development of a karst landscape. **A.** During early stages, groundwater percolates through limestone along joints and bedding planes. Solution activity creates and enlarges caverns at and below the water table. **B.** In this view, sinkholes are well developed and surface streams are funneled below ground. **C.** With the passage of time, caverns grow larger and the number and size of sinkholes increase. Collapse of caverns and coalescence of sinkholes form larger, flat-floored depressions. Eventually, solution activity may remove most of the limestone from the area, leaving only isolated remnants as in Figure 17.28 below.

A. **FIGURE 17.28** **A.** Painting of Chinese tower karst, "Peach Garden Land of Immortals," by Qiu Ying. (Asian Art and Archaeology, Inc./CORBIS–NY) **B.** One of the best-known and most distinctive regions of tower karst development is the Guilin District of southeastern China. (Photo by A.C. Waltham/Robert Harding World Imagery)

B.



BOX 17.3 ▶ PEOPLE AND THE ENVIRONMENT

The Case of the Disappearing Lake

Lake Chesterfield was a pleasant 9.3-hectare (23-acre) manmade lake in a quiet suburb of St. Louis, where people living along its shore could fish from their small paddleboats—until it disappeared! In June 2004 residents witnessed the entire lake drain in less than three days (Figure 17.D).

"It was like someone pulled the plug," said Donna Ripp, who lives across the street from the lake, which is now a giant mud hole. Ripp said she began to notice the water level sinking and that by the second day, the lake was half empty. A day later it was completely gone.

What happened? The culprit is clear. At the north end of the lake there is a gaping sinkhole estimated to be about 20 meters (70 feet) in diameter. What geologists are now investigating is what the larger subterranean network looks like. This part of Missouri has many caves, including many that are large enough for humans to explore.

FIGURE 17.D Residents examine emptied Lake Chesterfield, a 23-acre reservoir that drained in three days when a sinkhole opened beneath it. (Photo by Hillary Levin/*St. Louis Post Dispatch*)

Geologist David Taylor, who inspected the lake shortly after the water drained into the ground, said the sinkhole itself "is really not that big." But it doesn't take a very large sinkhole to knock out an entire lake. Taylor said a hole 0.3 meter (1 foot) in diameter can drain at least 3800 liters (about 1000 gallons) a minute. Taylor is the head of a St. Charles–based company called Strata Services, Inc., that specializes in repairing lakes that are draining into subterranean cavities. "In my business I have fixed hundreds of leaky lakes," he said.

But before Taylor can consider repairing Lake Chesterfield, he and his colleagues first must get a sense of the network of cavities under the lake—a task that he said is exceedingly difficult. "There's all kinds of crazy stuff going on down there," he said. "This is all subsurface work. It's very unpredictable and very difficult."

Taylor found that the subsurface cavity responsible for the sinkhole under Lake Chesterfield runs laterally underground for several kilometers. A tracing dye placed near the sinkhole reemerges in a spring about 5.5 kilometers (3.5 miles) from the lake. In order to develop a better picture of the subterranean cavities, Taylor drilled five test holes at 12-meter (40-foot) intervals, finding that two revealed empty cavities below. But he estimated that it would require 600 holes in a 12-meter grid to even begin to understand the region completely.

Once that picture emerges, Taylor's company then fills the cavities with a cementlike substance so that other sinkholes don't open and create a similar problem. "If we just put a Band-Aid over the hole and fill the lake back up, the same thing will happen again," he said.

In the meantime, nearby residents are getting a crash course on karst topography. "I didn't even know there were underground caves here until all this happened." Donna Ripp said.

Students Sometimes Ask . . .

Is limestone the only rock type that develops karst features?

No. For example, karst development can occur in other carbonate rocks such as marble and dolostone. In addition, evaporites such as gypsum and salt (halite) are highly soluble and are readily dissolved to form karst features including sinkholes, caves, and disappearing streams. This latter situation is termed *evaporite karst*.

Summary

- As a resource, *groundwater* represents the largest reservoir of fresh water that is readily available to humans. Geologically, the dissolving action of groundwater produces *caves* and *sinkholes.* Groundwater is also an equalizer of streamflow.
- Groundwater is water that completely fills the pore spaces in sediment and rock in the subsurface *zone of saturation.* The upper limit of this zone is the *water table.* The *zone of aeration* is above the water table where the soil, sediment, and rock are not saturated.
- The interaction between streams and groundwater takes place in one of three ways: streams gain water from the inflow of groundwater (*gaining stream*); they lose water through the streambed to the groundwater system (*losing stream*); or they do both, gaining in some sections and losing in others.
- Materials with very small pore spaces (such as clay) hinder or prevent groundwater movement and are called *aquitards. Aquifers* consist of materials with larger pore spaces (such as sand) that are permeable and transmit groundwater freely.
- Groundwater moves in looping curves that are a compromise between the downward pull of gravity and the tendency of water to move toward areas of reduced pressure.
- The primary factors influencing the velocity of groundwater flow are the slope of the water table (*hydraulic gradient*) and the permeability of the aquifer (*hydraulic conductivity*).
- *Springs* occur whenever the water table intersects the land surface and a natural flow of groundwater results. *Wells,* openings bored into the zone of saturation, withdraw groundwater and create roughly conical depressions in the water table known as *cones of depression. Artesian wells* occur when water rises above the level at which it was initially encountered.
- When groundwater circulates at great depths, it becomes heated. If it rises, the water may emerge as a *hot spring. Geysers* occur when groundwater is heated in underground chambers, expands, and some water quickly changes to steam, causing the geyser to erupt. The source of heat for most hot springs and geysers is hot igneous rock.
- Some of the current environmental problems involving groundwater include (1) *overuse* by intense irrigation, (2) *and subsidence* caused by groundwater withdrawal, (3) *saltwater contamination,* and (4) contamination by pollutants.
- Most *caverns* form in limestone at or below the water table when acidic groundwater dissolves rock along lines of weakness, such as joints and bedding planes. The various *dripstone* features found in caverns are collectively called *speleothems.* Landscapes that to a large extent have been shaped by the dissolving power of groundwater exhibit *karst topography,* an irregular terrain punctuated with many depressions, called *sinkholes* or *sinks.*

Review Questions

1. What percentage of fresh water is groundwater? If glacial ice is excluded and only liquid fresh water is considered, about what percentage is groundwater?
2. Geologically, groundwater is important as an erosional agent. Name another significant geological role for groundwater.
3. Compare and contrast the zones of aeration and saturation. Which of these zones contains groundwater?
4. Although we usually think of tables as being flat, the water table generally is not. Explain.
5. Although meteorological drought may have ended, hydrological drought may still continue. Explain. (See Box 17.1.)
6. Contrast a gaining stream and a losing stream.
7. Distinguish between porosity and permeability.
8. What is the difference between an aquitard and an aquifer?
9. Under what circumstances can a material have a high porosity but not be a good aquifer?
10. As illustrated in Figure 17.5, groundwater moves in looping curves. What factors cause the water to follow such paths?
11. Briefly describe the important contribution to our understanding of groundwater movement made by Henri Darcy.
12. When an aquitard is situated above the main water table, a localized saturated zone may be created. What term is applied to such a situation?
13. What is the source of heat for most hot springs and geysers? How is this reflected in the distribution of these features?
14. Two neighbors each dig a well. Although both wells penetrate to the same depth, one neighbor is successful and the other is not. Describe a circumstance that might explain what happened.
15. What is meant by the term *artesian?*
16. In order for artesian wells to exist, two conditions must be present. List these conditions.

17. When the Dakota Sandstone was first tapped, water poured freely from many artesian wells. Today these wells must be pumped. Explain.

18. What problem is associated with the pumping of groundwater for irrigation in the southern part of the High Plains?

19. Briefly explain what happened in the San Joaquin Valley as the result of excessive groundwater withdrawal (see Box 17.2).

20. In a particular coastal area, the water table is 4 meters above sea level. Approximately how far below sea level does the fresh water reach?

21. Why does the rate of natural groundwater recharge decrease as urban areas develop?

22. Which aquifer would be most effective in purifying polluted groundwater: coarse gravel, sand, or cavernous limestone?

23. What is meant when a groundwater pollutant is classified as hazardous?

24. Name two common speleothems and distinguish between them.

25. Areas whose landscapes largely reflect the erosional work of groundwater are said to exhibit what kind of topography?

26. Describe two ways in which sinkholes are created.

Key Terms

aquifer (p. 463)
aquitard (p. 463)
artesian (p. 469)
capillary fringe (p. 459)
cavern (p. 475)
cone of depression (p. 468)
Darcy's law (p. 464)
drawdown (p. 468)
flowing artesian well (p. 469)
gaining stream (p. 460)
geyser (p. 466)
groundwater (p. 459)
hot spring (p. 466)
hydraulic conductivity (p. 464)
hydraulic gradient (p. 464)
karst topography (p. 476)
losing stream (p. 460)
nonflowing artesian well (p. 469)
perched water table (p. 466)
permeability (p. 463)
porosity (p. 463)
sinkhole (sink) (p. 476)
speleothem (p. 476)
spring (p. 466)
stalactite (p. 476)
stalagmite (p. 476)
unsaturated zone (p. 459)
water table (p. 459)
well (p. 468)
zone of saturation (p. 459)
zone of soil moisture (p. 459)

Web Resources

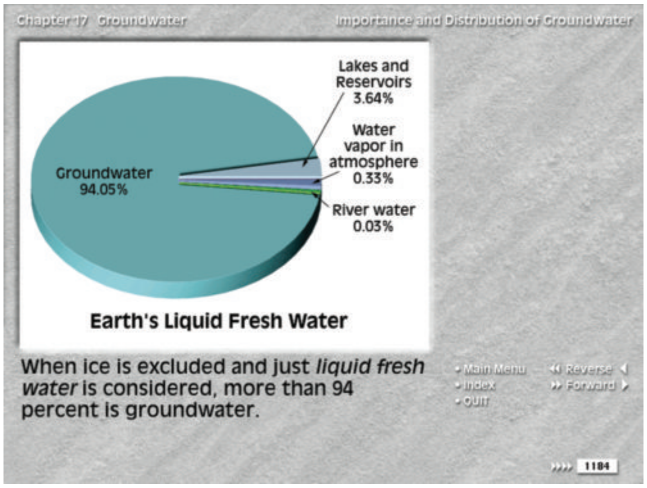
The *Earth* Website uses the resources and flexibility of the Internet to aid in your study of the topics in this chapter. Written and developed by geology instructors, this site will help improve your understanding of geology. Visit **http://www.prenhall.com/tarbuck** and click on the cover of *Earth 9e* to find:

- Online review quizzes.
- Critical thinking exercises.
- Links to chapter-specific Web resources.
- Internet-wide key-term searches.

http://www.prenhall.com/tarbuck

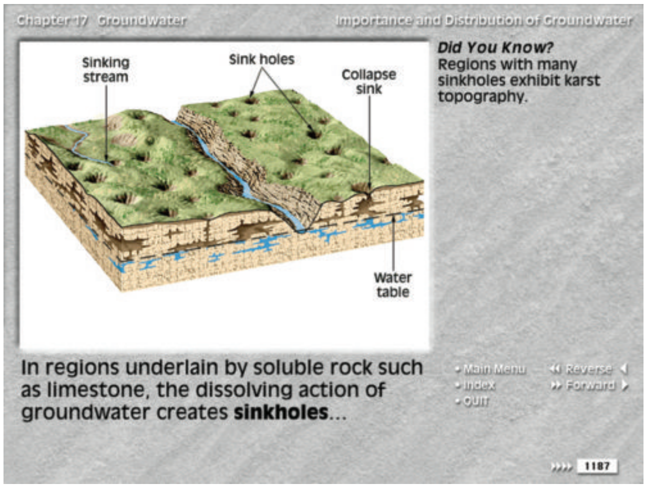
GEODe: Earth

GEODe: Earth makes studying faster and more effective by reinforcing key concepts using animation, video, narration, interactive exercises and practice quizzes. A copy is included with every copy of *Earth.*



Earth's Liquid Fresh Water

When ice is excluded and just *liquid fresh water* is considered, more than 94 percent is groundwater.



Did You Know? Regions with many sinkholes exhibit karst topography.

In regions underlain by soluble rock such as limestone, the dissolving action of groundwater creates **sinkholes**...