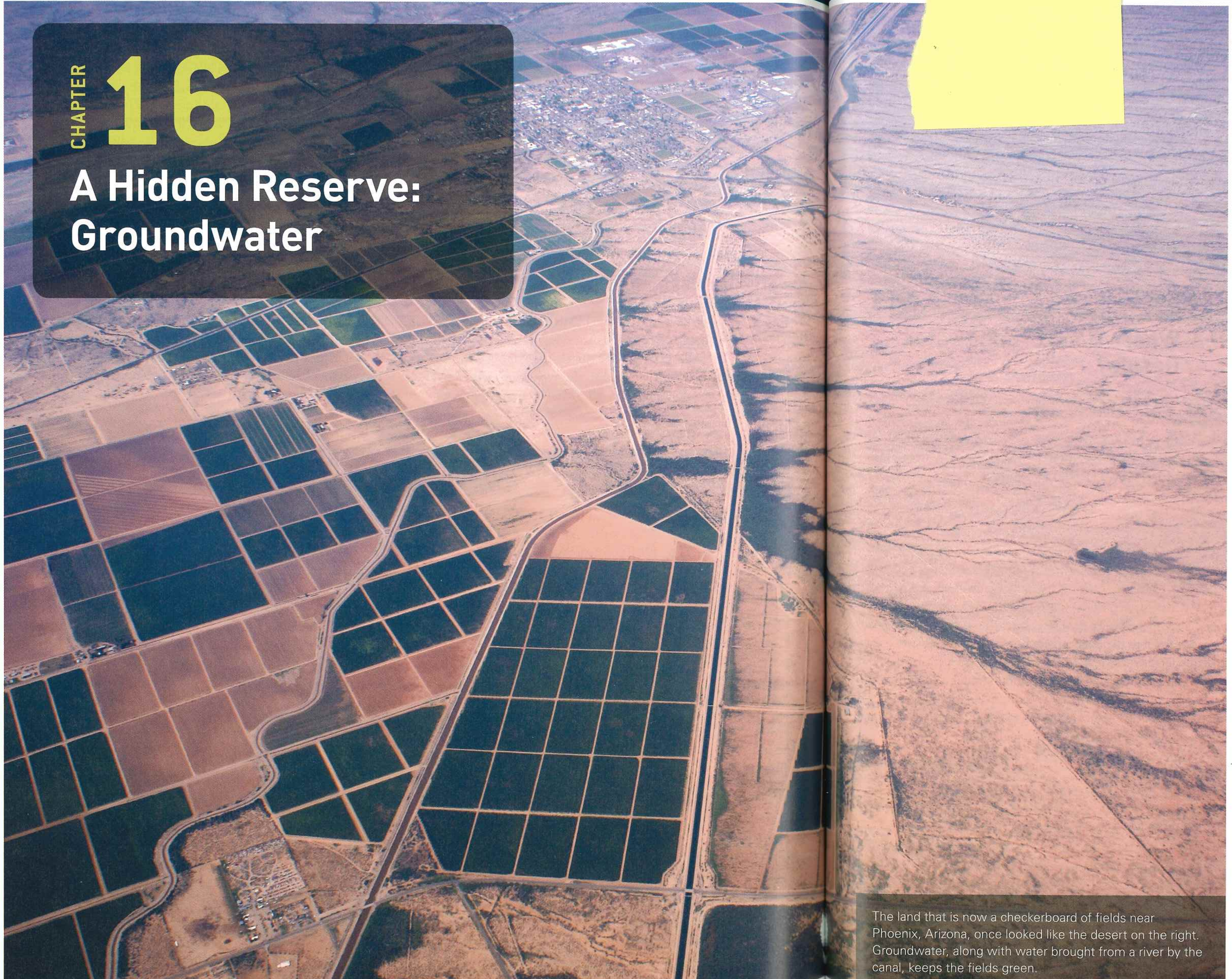
CHAPTER 16

A Hidden Reserve: Groundwater



The land that is now a checkerboard of fields near Phoenix, Arizona, once looked like the desert on the right. Groundwater, along with water brought from a river by the canal, keeps the fields green.

Chapter Objectives

By the end of this chapter, you should know . . .

- what groundwater is, where it comes from, and the factors controlling its flow.
- the difference between porosity and permeability.
- the difference between aquifers and aquitards, and the nature of the water table.
- the various types of wells and springs that provide access to groundwater.
- how hot springs and geysers originate.
- how groundwater supplies can be damaged or depleted, and how to address these problems.
- how caves and karst landscapes originate and evolve.

When the rain falls and enters the earth, when a pearl drops into the depth of the sea, you can dive in the sea and find the pearl, you can dig in the earth and find the water.

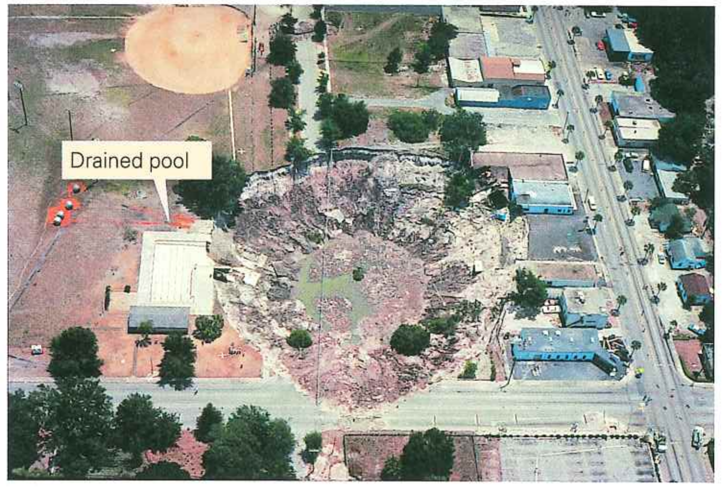
—Mei Yao-ch'en (Chinese poet, 1002–1060)

16.1 Introduction

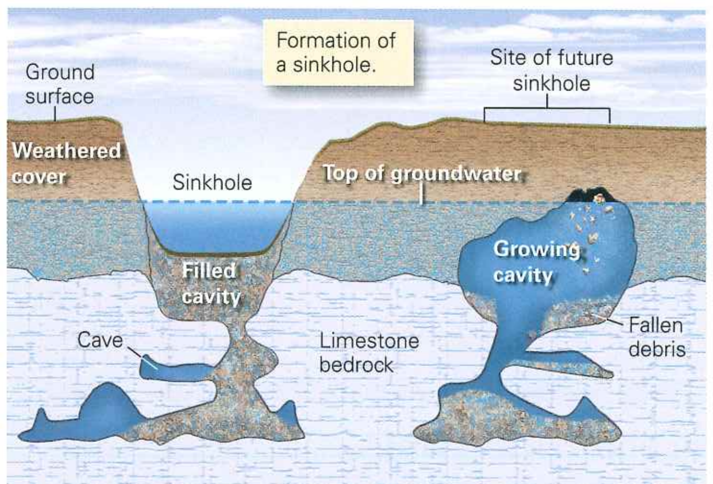
Imagine Mae Rose Owens's surprise when, on May 8, 1981, she looked out her window and discovered that a large sycamore tree in the backyard of her Winter Park, Florida, home had suddenly disappeared. It wasn't a particularly windy day, so the tree hadn't blown over—it had just vanished! When Owens went outside to investigate, she found that more than the tree had disappeared. Her whole backyard had become a deep, gaping pit. The pit continued to grow for a few days until finally it swallowed Owens's house and six other buildings, as well as the municipal swimming pool, part of a road, and several expensive Porsches in a car dealer's lot (Fig. 16.1a).

What had happened in Winter Park? The bedrock beneath the town consists of limestone, a fairly soluble rock. Water had gradually dissolved the limestone, carving open rooms, or caverns, underground. On May 8, the roof of a cavern underneath Owens's backyard began to collapse, forming a circular depression called a **sinkhole** (Fig. 16.1b). The sycamore tree and the rest of the neighborhood simply dropped down into the sinkhole. It would have taken too much effort to fill in the sinkhole with soil, so the community allowed it to fill with water, and now it's a circular lake, the centerpiece of a pleasant municipal park.

FIGURE 16.1 Development of sinkholes in central Florida.



(a) The Winter Park sinkhole, as seen from a helicopter.



(b) As overburden slowly washes into underlying caves, a cavity forms. When the roof of this cavity collapses, a sinkhole forms (not to scale).

(c) An airplane view of Florida sinkholes that have become lakes.

Similar lakes appear throughout central Florida (**Fig. 16.1c**), and elsewhere worldwide.

The Winter Park sinkhole is one of the more dramatic reminders that significant quantities of water reside underground. This water, which occupies the cracks and other openings in between the solid components of rock or sediments, or occurs in underground lakes or streams, is called **groundwater**. Though we can easily see Earth's surface water (in lakes, rivers, streams, marshes, glaciers, and oceans) and atmospheric water (in clouds and rain), groundwater lies hidden beneath the surface. Nevertheless, groundwater accounts for about two-thirds of the Earth's freshwater resources used by homes, agriculture, and industry. In this chapter, we examine where subsurface water comes from, how it flows, and how it interacts with rock and sediment.

16.2 Where Does Groundwater Reside?

The Underground Reservoir

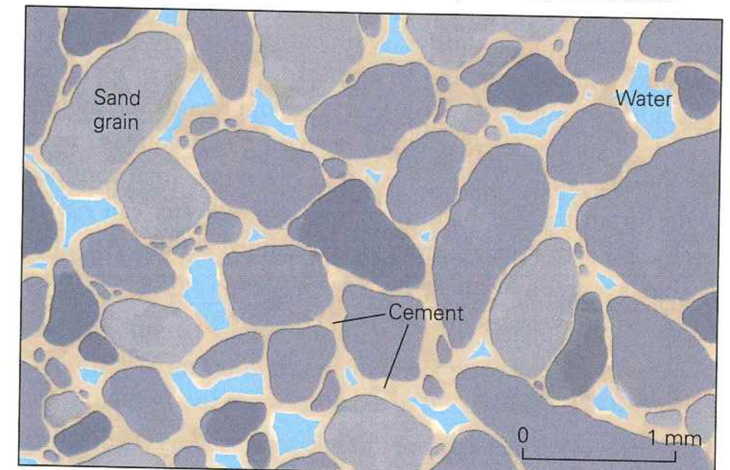
As we saw in Interlude F, water moves among various reservoirs during the *hydrologic cycle*. Of the water that falls on land, some evaporates directly back into the atmosphere, some gets trapped in glaciers, and some becomes runoff that enters a network of streams and lakes that drains to the sea. The remainder sinks or percolates downward, by a process called infiltration, into the ground. In effect, the upper part of the crust behaves like a giant sponge that can soak up water.

Of the water that does infiltrate, some descends only into the soil and wets the surfaces of grains and organic material making up the soil. This water, called **soil moisture**, later evaporates back into the atmosphere or gets sucked up by the roots of plants and transpires back into the atmosphere. But some water sinks deeper into sediment or rock, and along with water trapped in rock at the time the rock formed, makes up groundwater. Groundwater slowly flows underground for anywhere from a few months to tens of thousands of years before returning to the surface to pass once again into other reservoirs of the hydrologic cycle.

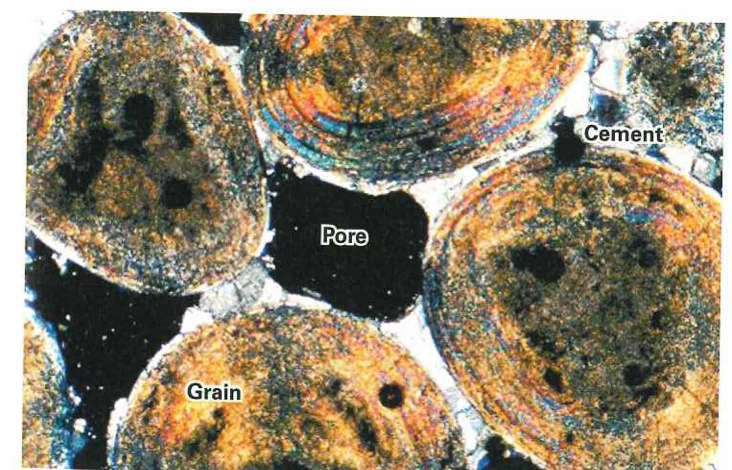
Porosity: Open Space in Rock and Regolith

Contrary to popular belief, only a small proportion of underground water occurs in caves. Most groundwater resides in relatively small open spaces between grains of sediment or between grains of seemingly solid rock, or within cracks of various sizes. The term **pore** refers to any open space within a volume of sediment, or within a body of rock, and the term **porosity** refers to the total amount of open space within a material, specified as a percentage. For example, if we say that a block of rock has 30% porosity, then 30% of the block consists of pores. Geologists distinguish between two basic kinds of porosity—primary and secondary.

FIGURE 16.2 Porosity is the open space in rock or sediment, whereas permeability is the degree to which the pores are connected.

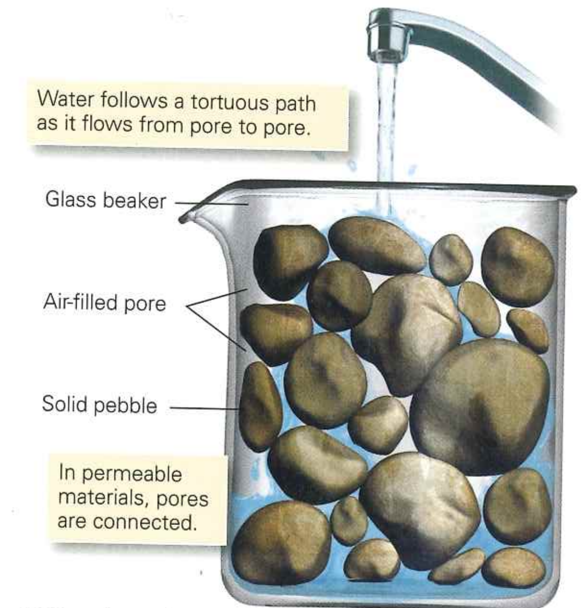


(a) Isolated pores in a sandstone occur in the spaces between grains. Water or air can fill pores.



(b) A photograph of a thin section shows tiny pores in a limestone. Here, the grains consist of calcite spheres, and the cement of calcite crystals.

(c) Limestone outcrop on the coast of Ireland contains abundant fractures that provide secondary porosity.



(d) Gravel contains pore space, because clasts don't fit together tightly. The connection of pores produces permeability.

Primary porosity develops during sediment deposition and during rock formation (**Fig. 16.2a,b**). It includes the pores between clastic grains that exist because the grains don't fit together tightly during deposition. Secondary porosity refers to new pore space produced in rocks some time after the rock first formed. For example, when rocks fracture, the opposing walls of the fracture do not fit together tightly, so narrow spaces remain in between. Thus, joints and faults may provide secondary porosity for water (**Fig. 16.2c**). As groundwater passes through rock, it may dissolve and remove some minerals, creating solution cavities that also provide secondary porosity.

Permeability: The Ease of Flow

If solid rock completely surrounds a pore, the water in the pore cannot flow to another location. For groundwater to flow, pores must be linked by conduits (openings). The ability of a material to allow fluids to pass through an interconnected network of pores is a characteristic known as **permeability**. Groundwater flows easily through a material, such as loose gravel, that has *high permeability*. In gravel, the water is able to pass quickly from pore to pore, so if you pour water into a gravel-filled jar, it will trickle down to the bottom of the jar, where it displaces air and fills the pores (**Fig. 16.2d**). In tightly packed sediments or in rock, the water flows more slowly because it follows a tortuous path through tiny conduits. Water flows slowly or not at all through an *impermeable material*. Put another way, an impermeable material has low permeability or even no permeability. The permeability of a material depends on several factors:

- *Number of available conduits*: As the number of conduits increases, permeability increases.
- *Size of the conduits*: More fluids can travel through wider conduits than through narrower ones.
- *Straightness of the conduits*: Water flows more rapidly through straight conduits than it does through crooked ones.

Note that the factors that control permeability in rock or sediment resemble those that control the ease with which traffic moves through a city. Traffic can flow quickly through cities with many straight, multilane boulevards, whereas it flows slowly through cities with only a few narrow, crooked streets. Porosity and permeability are *not* the same feature. A material whose pores are isolated from each other can have high porosity but low permeability.

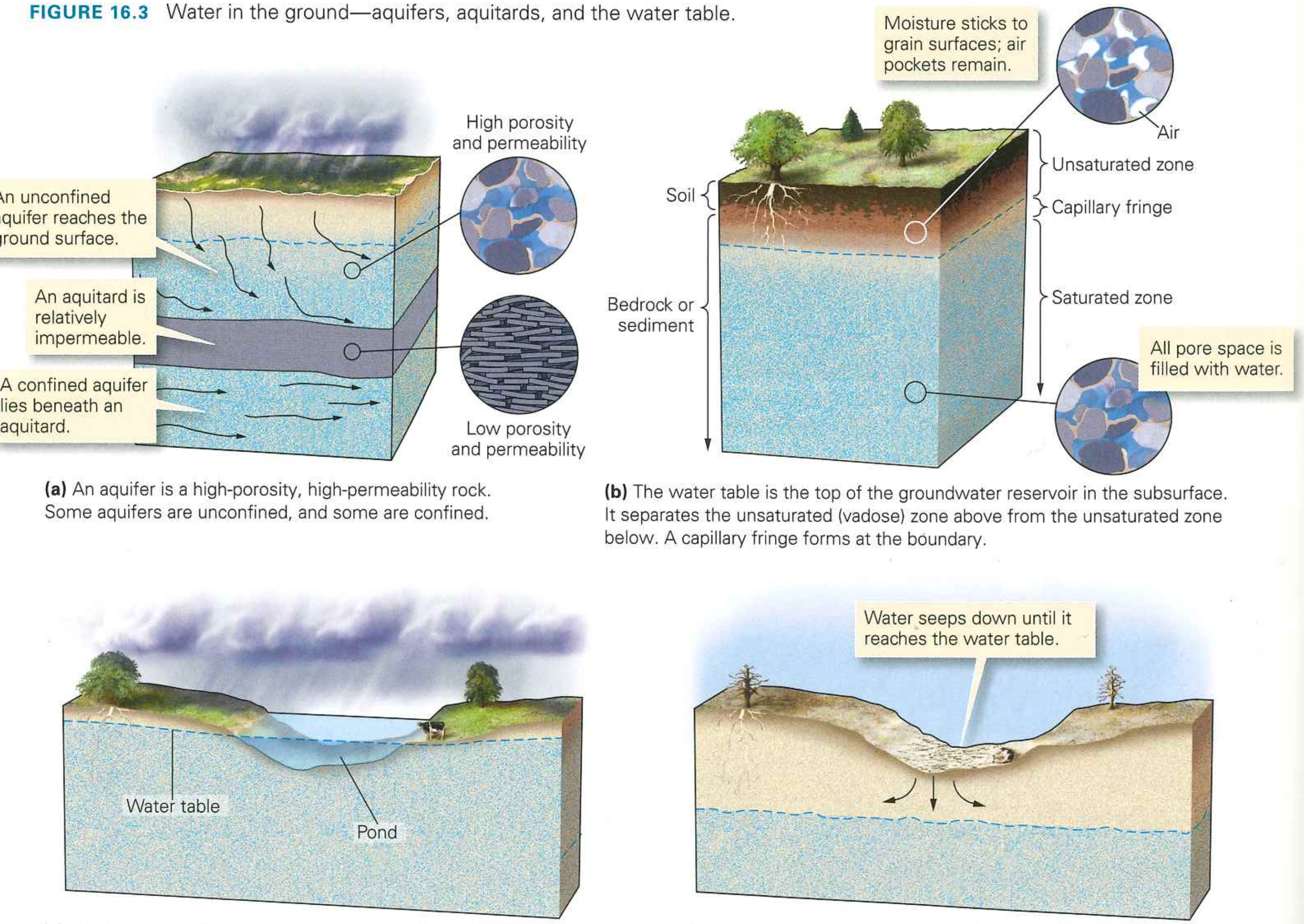
Aquifers and Aquitards

With the concept of permeability in mind, hydrogeologists distinguish between an **aquifer**, sediment or rock with high permeability and porosity, and an **aquitard**, sediment or rock that does not transmit water easily and therefore retards the motion of water. An aquifer that is not overlain by an aquitard is an *unconfined aquifer*. Water can infiltrate down into an unconfined aquifer from the Earth's surface, and groundwater can rise to reach the Earth's surface from an unconfined aquifer. An aquifer that is overlain by an aquitard is a *confined aquifer*—its water is isolated from the ground surface (Fig. 16.3a).

The Water Table

Infiltrating water can enter permeable sediment and bedrock by percolating along cracks and through conduits connecting pores. Nearer the ground surface, water only partially fills pores, leaving some space that remains filled with air (Fig. 16.3b). The region

FIGURE 16.3 Water in the ground—aquifers, aquitards, and the water table.



(a) An aquifer is a high-porosity, high-permeability rock. Some aquifers are unconfined, and some are confined.

(b) The water table is the top of the groundwater reservoir in the subsurface. It separates the unsaturated (vadose) zone above from the unsaturated zone below. A capillary fringe forms at the boundary.

(c) Where the water table lies close to the ground surface, ponds remain filled—the water table is the surface of the pond.

(d) In dry regions, the water table sinks deep below the surface. Water that collects temporarily in low areas sinks into the subsurface.

of the subsurface in which water only partially fills pores is called the *unsaturated zone*. Deeper down, water completely fills, or saturates, the pores. This region is the *saturated zone*. In a strict sense, geologists use the term "groundwater" specifically for subsurface water in the saturated zone, where water completely fills pores.

The term **water table** refers to the horizon that separates the unsaturated zone above from the saturated zone below. Typically, surface tension, the electrostatic attraction of water molecules to each other and to mineral surfaces, causes water to seep up from the water table (just as water rises in a thin straw), filling pores in the **capillary fringe**, a thin layer at the base of the unsaturated zone. Note that the water table forms the top boundary of groundwater in an unconfined aquifer.

The depth of the water table in the subsurface varies greatly with location. In some places, the water table defines the surface of a permanent stream, lake, or marsh, and thus effectively lies above the ground level (Fig. 16.3c). Elsewhere, the water table lies hidden below the ground surface. In humid regions, it typically lies within a few meters of the surface, whereas in arid regions, it may lie hundreds of meters below the surface. Rainfall rates affect the water table depth in a given locality (Fig. 16.3d)—the water table drops during the dry season and rises during the wet season. Streams or ponds that hold water during the wet season may, therefore, dry up during the dry season because their water infiltrates into the ground below.

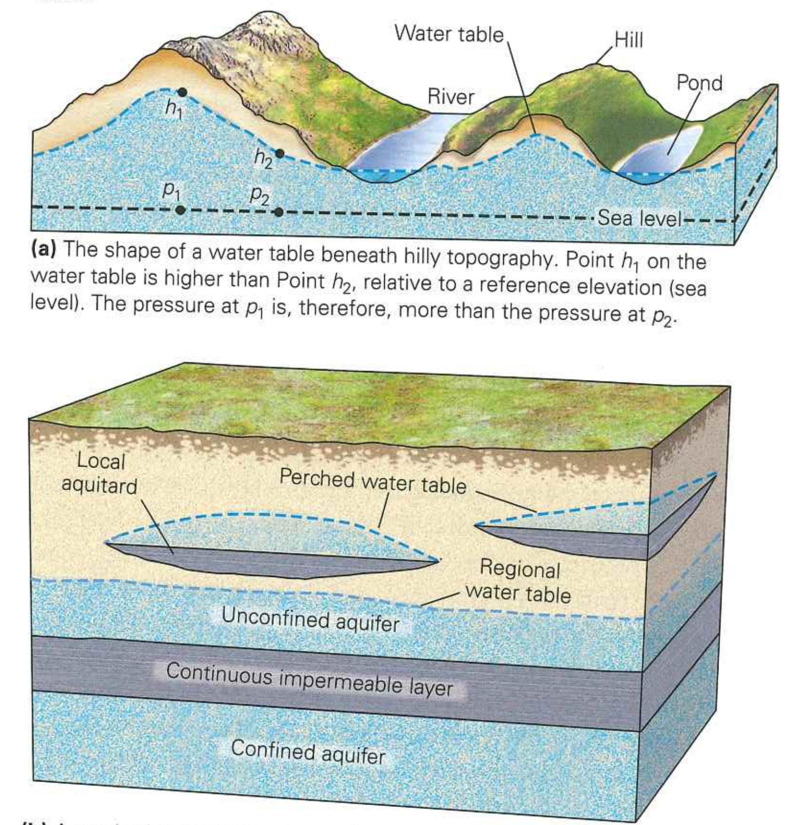
Topography of the Water Table

In hilly regions, if the subsurface has relatively low permeability, the water table is not a planar surface. Rather, its shape mimics, in a subdued way, the shape of the overlying topography (Fig. 16.4a). This means that the water table lies at a higher elevation beneath hills than it does beneath valleys. But the relief (the vertical distance between the highest and lowest elevations) of the water table is not as great as that of the overlying land, so the surface of the water table tends to be smoother than that of the landscape.

At first thought, it may seem surprising that the elevation of the water table varies as a consequence of ground-surface topography. After all, when you pour a bucket of water into a pond, the surface of the pond immediately adjusts to remain horizontal. The elevation of the water table varies because groundwater moves so slowly through rock and sediment that it cannot quickly assume a horizontal surface. When rain falls on a hill and water infiltrates down to the water table, the water table rises a little. When it doesn't rain, the water table sinks slowly, but so slowly that when rain falls again, the water table rises before it has had time to sink very far.

In some locations, lens-shaped layers of impermeable rock (such as shale) may lie within a thick aquifer. A mound of groundwater accumulates above such aquitard lenses. The result is a **perched water table**, a groundwater top surface that

FIGURE 16.4 Factors that influence the position of the water table.



(a) The shape of a water table beneath hilly topography. Point h_1 on the water table is higher than Point h_2, relative to a reference elevation (sea level). The pressure at p_1 is, therefore, more than the pressure at p_2.

(b) A perched water table occurs where a mound of groundwater becomes trapped above a localized aquitard that lies above the regional water table.

lies above the regional water table because the underlying lens of impermeable rock or sediment prevents the groundwater from sinking down to the regional water table (Fig. 16.4b).

Take-Home Message

Most underground water fills pores and cracks in rock or sediment. Porosity refers to the total amount of open space within a material, whereas permeability indicates the degree to which pores connect. Aquifers have high porosity and permeability; aquitards don't.

16.3 Groundwater Flow

What happens to groundwater over time? Does it just sit, unmoving, like the water in a stagnant puddle, or does it flow and eventually find its way back to the surface? Countless measurements confirm that groundwater enjoys the latter fate—groundwater indeed flows, and in some cases it moves great distances underground. Let's examine factors that drive groundwater flow.

In the unsaturated zone—the region between the ground surface and the water table—water percolates straight down, like the water passing through a drip coffee maker, for this water moves only in response to the downward pull of gravity. But in the zone of saturation—the region below the water table—water flow is more complex, for in addition to the downward pull of gravity, water responds to differences in pressure. Pressure can cause groundwater to flow sideways, or even upward. (If you've ever watched water spray from a fountain, you've seen pressure pushing water upward.) Thus, to understand the nature of groundwater flow, we must first understand the origin of pressure in groundwater. For simplicity, we'll consider only the case of groundwater in an unconfined aquifer.

Pressure in groundwater at a specific point underground is caused by the weight of all the overlying water from that point up to the water table. (The weight of overlying rock does not contribute to the pressure exerted on groundwater, for the contact points between mineral grains bear the rock's weight.) Thus, a point at a greater depth below the water table feels more pressure than does a point at lesser depth. If the water table is horizontal, the pressure acting on an imaginary horizontal reference plane at a specified depth below the water table is the same everywhere. But if the water table is not horizontal, as shown in Figure 16.4a, the pressure at points on a horizontal reference plane at depth changes with location. For example, the pressure acting at point p_1, which lies below the hill in Figure 16.4a, is greater than the pressure acting at point p_2, which lies below the valley, even though both p_1 and p_2 are at the same elevation.

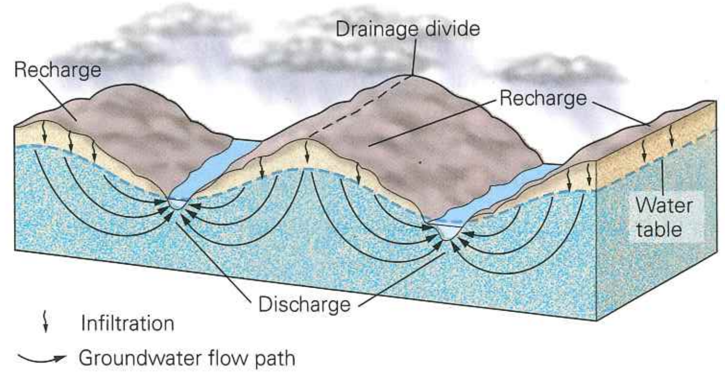
Both the elevation of a volume of groundwater and the pressure within the water provide energy that, if given the chance, will cause the water to flow. Physicists refer to such stored energy as *potential energy*. The potential energy available to drive the flow of a given volume of groundwater at a location is called the **hydraulic head**. To measure the hydraulic head at a point in an aquifer, hydrogeologists drill a vertical hole down to the point and then insert a pipe in the hole. The height above a reference elevation (for example, sea level) to which water rises in the pipe represents the hydraulic head—water rises higher in the pipe where the head is higher. As a rule, *groundwater flows from regions where it has higher hydraulic head to regions where it has lower hydraulic head*. This statement generally implies that groundwater regionally flows from locations where the water table is higher to locations where the water table is lower.

Hydrogeologists have calculated how hydraulic head changes with location underground, by taking into account both the effect of gravity and the effect of pressure. These calculations reveal that groundwater flows along concave-up curved paths, as illustrated in cross section (**Fig. 16.5a, b**). These curved paths eventually take groundwater from regions where the water table is high (under a hill) to regions where the water table is low (below a valley), but because of flow-path shape, some groundwater may flow deep down into the crust along the first part of its path and then may flow back up, toward the ground surface, along the final part of its path. The location where water enters the ground (where the flow direction has a downward trajectory) is called the **recharge area**, and the location where groundwater flows back up to the surface is called the **discharge area** (see Fig. 16.5a).

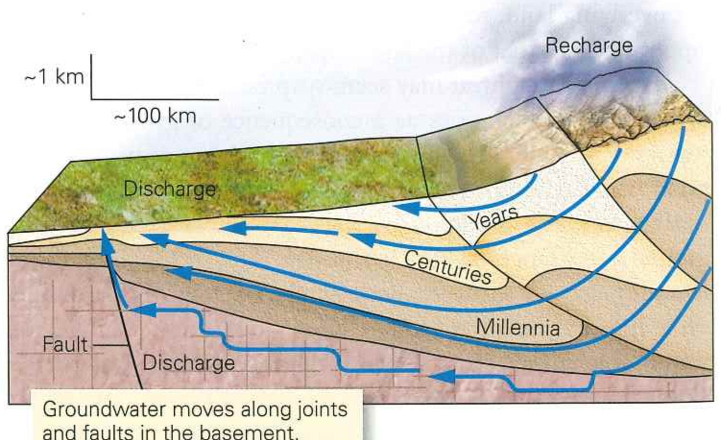
Flowing water in an ocean current moves at up to 3 km per hour, and water in a steep river channel can reach speeds of up to 30 km per hour. In contrast, groundwater moves at less than a snail's pace, between 0.01 and 1.4 m per day (about 4 to 500 m per year). Groundwater moves much more slowly than surface water, for two reasons. First, groundwater moves by percolating through a complex, crooked network of tiny conduits, so it must travel a much greater distance than it would if it could follow a straight path. Second, friction between groundwater and conduit walls slows down the water flow.

Simplistically, the velocity of groundwater flow depends on the slope of the water table and the permeability of the material through which the groundwater is flowing. Thus,

FIGURE 16.5 The flow of groundwater.



(a) Groundwater flows from recharge areas to discharge areas. Typically, the flow follows curving paths.



(b) The large hydraulic head resulting from uplift of a mountain belt may drive groundwater hundreds of kilometers, across regional sedimentary basins. Deeper flow paths take longer.

CONSIDER THIS . . . BOX 16.1

Darcy's Law for Groundwater Flow

The rate at which groundwater flows at a given location depends on the permeability of the material containing the groundwater; groundwater flows faster in a more permeable material than it does in a less permeable material. The rate also depends on the **hydraulic gradient**, the change in hydraulic head per unit of distance between two locations, as measured along the flow path.

To calculate the hydraulic gradient, we divide the difference in hydraulic head between two points by the distance between the two points as measured along the flow path. This can be written as a formula:

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

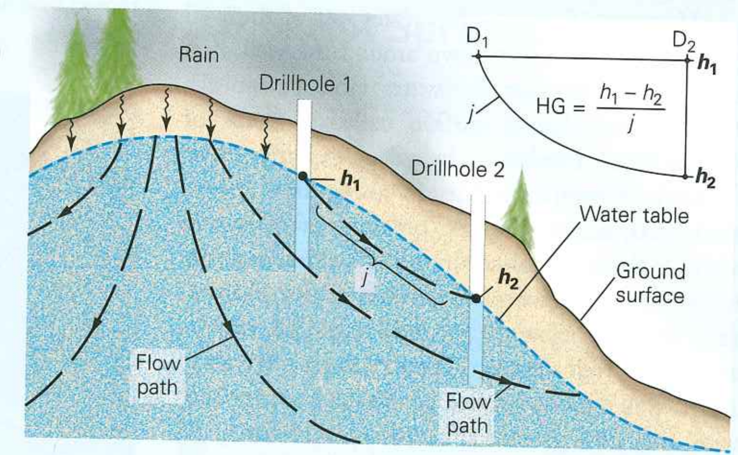
where $h_1 - h_2$ is the difference in head (given in meters or feet, because head can be represented as an elevation) between two points along the water table, and j is the distance between the two points as measured along the flow path (**Fig. Bx16.1**). A hydraulic gradient exists anywhere that the water table has a slope. Typically, the slope of the water table is so small that the path length is almost the same as the horizontal distance between two points. So, in general, the hydraulic gradient is roughly equivalent to the slope of the water table.

In 1856, a French engineer named Henry Darcy carried out a series of experiments designed to characterize factors that control the velocity at which groundwater flows between two locations (1 and 2), each of which has a different hydraulic head (h_1 and h_2). Darcy represented the velocity of flow by a quantity called the discharge (Q), meaning the volume of water passing through an imaginary vertical plane perpendicular to the groundwater's flow path in a given time. He found that the discharge depends on the the hydraulic head ($h_1 - h_2$); the area (A) of the imaginary plane through which the groundwater is passing; and a number called the hydraulic conductivity (K). The hydraulic conductivity represents the ease with which a fluid can flow through a material. This, in turn, depends on many factors (such as the viscosity and density of the fluid), but mostly it reflects the permeability of the material. The relationship that Darcy discovered, now known as **Darcy's law**, can be written in the form of an equation as:

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

The equation states that if the hydraulic gradient increases, discharge increases, and that as conductivity increases, discharge increases. Put in simpler terms, the flow rate of groundwater increases as the permeability increases and as the slope of the water table gets steeper.

FIGURE Bx16.1 The level to which water rises in a drillhole is the hydraulic head (h). The hydraulic gradient (HG) is the difference in head divided by the length of the flow path.



groundwater flows faster through high-permeability rocks than it does through low-permeability rocks, and it flows faster in regions where the water table has a steep slope than it does in regions where the water table has a gentle slope. For example, groundwater flows relatively slowly (~2 m per year) through a low-permeability aquifer under the Great Plains, but flows relatively quickly (~30 m per year) through a high-permeability aquifer under a steep hillslope. In detail, hydrogeologists use Darcy's Law to determine flow rates at a location (**Box 16.1**).

Take-Home Message

Gravity and pressure cause groundwater to flow slowly from recharge to discharge areas. In essence, the rate of flow depends on the water table's slope and on permeability. Groundwater can follow curving flow paths that take it deep into the crust.

16.4 Tapping Groundwater Supplies

We can obtain groundwater at wells or springs. **Wells** are holes that people dig or drill to obtain water. **Springs** are natural outlets from which groundwater flows. Wells and springs provide welcome sources of water but must be treated with care if they are to last.

Wells

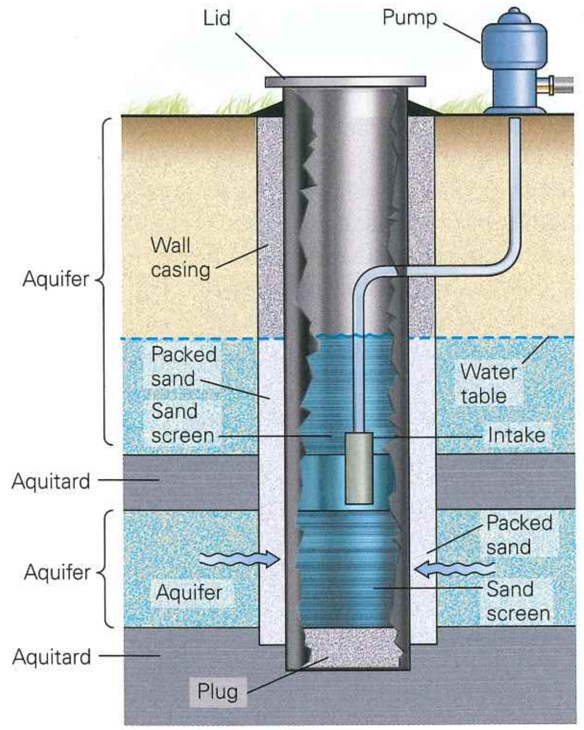
In an **ordinary well**, the base of the well penetrates an aquifer below the water table (Fig. 16.6a). Water from the pore space in the aquifer seeps into the well and fills it to the level of the water table. Drilling into an aquitard, or into rock that lies above the water table, will not supply water, and thus yields a *dry well*. Some ordinary wells are seasonal and function only during the rainy season, when the water table rises. During the dry season, the water table lies below the base of the well, so the well is dry.

To obtain water from an ordinary well, you either pull water up in a bucket or pump the water out. As long as the rate at which groundwater fills the well exceeds the rate at which water is removed, the level of the water table near the well remains about the same. However, if users pump water out of the well too fast, then the water table sinks down around the well, in a process called *drawdown*, so that the water table becomes a downward-pointing, cone-shaped surface called a **cone of depression** (Fig. 16.6b, c). Drawdown by a deep well may cause shallower wells that have been drilled nearby to run dry.

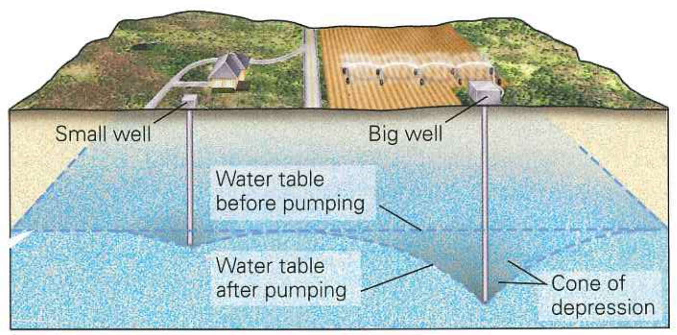
An **artesian well**, named for the province of Artois in France, penetrates confined aquifers in which water is under enough pressure to rise on its own to a level above the surface of the aquifer. If this level lies below the ground surface, the well is a *nonflowing* artesian well. But if the level lies above the ground surface, the well is a *flowing* artesian well, and water actively fountains out of the ground (Fig. 16.7a). Artesian wells occur in special situations where a confined aquifer lies beneath a sloping aquitard.

We can understand why artesian wells exist if we look first at the configuration of a city water supply (Fig. 16.7b). Water companies pump water into a high tank that has a significant hydraulic head relative to the surrounding areas. If the water were connected by a water main to a series of vertical pipes, pressure caused by the elevation of the water in the high tank would make the water rise in the pipes until it reached an imaginary surface, called a *potentiometric surface*, that lies above the ground. This pressure drives water through water mains to household water systems without requiring pumps. In an artesian system, water enters a tilted, confined aquifer that

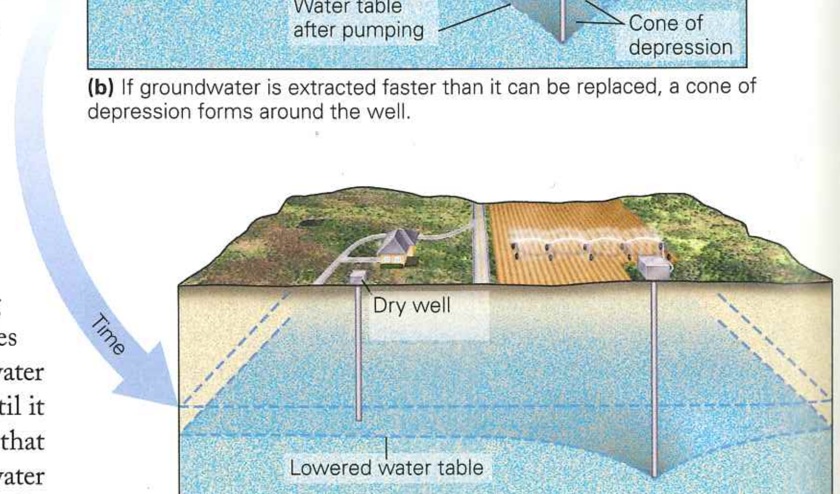
FIGURE 16.6 Pumping groundwater at a normal well affects the water table.



(a) A modern ordinary well sucks up water with an electric pump. The packed sand filters the water.



(b) If groundwater is extracted faster than it can be replaced, a cone of depression forms around the well.



(c) Pumping by the big well may lower the water table enough to cause the nearby small well to go dry.

intersects the ground in the hills of a high-elevation recharge area (Fig. 16.7c). The confined groundwater flows down to the adjacent plains, which lie at a lower elevation. The potentiometric surface to which the water would rise, were it not confined, lies above this aquifer. Pressure in the confined aquifer pushes water up a well.

Springs

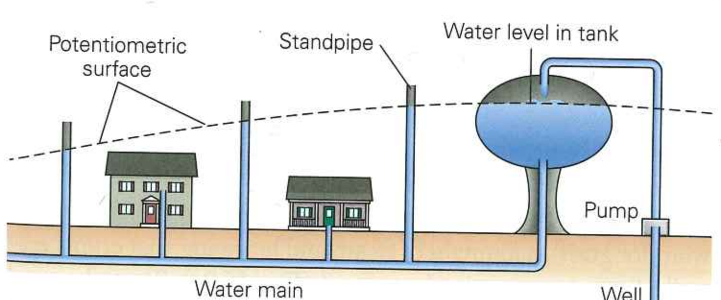
Many towns were founded next to springs, places where groundwater naturally flows or seeps onto the Earth's surface, for springs can provide fresh, clear water for drinking or irrigation, without the expense of drilling or digging. Some springs spill water onto dry land. Others bubble up through the bed of a stream or lake. Springs form under a variety of conditions:

- Where the ground surface intersects the water table in a discharge area (Fig. 16.8a); such springs typically occur in valley floors, where they may add water to lakes or streams.
- Where flowing groundwater collides with a steep, impermeable barrier, and pressure pushes it up to the ground along the barrier (Fig. 16.8b).
- Where a perched water table intersects the surface of a hill (Fig. 16.8c).
- Where downward-percolating water runs into a relatively impermeable layer and migrates along the top surface of the layer to a hillslope (Fig. 16.8d).
- Where a network of interconnected fractures channels groundwater to the surface of a hill (Fig. 16.8e).
- Where the ground surface intersects a natural fracture (joint) that taps a confined aquifer in which the pressure is sufficient to drive the water to the surface; such an occurrence is an **artesian spring**.

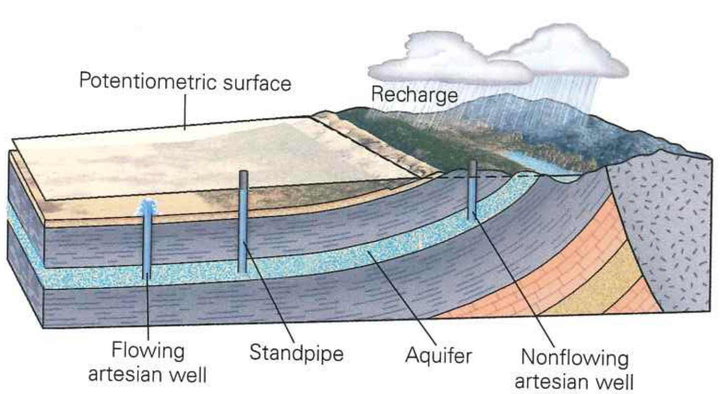
Springs can provide water in regions that would otherwise be uninhabitable. For example, oases in deserts may develop around a spring. An **oasis** is a wet area, where plants can grow, in an otherwise bone-dry region.

FIGURE 16.7 Artesian wells, where water rises from the aquifer without pumping.

(a) A flowing artesian well in a Missouri field.



(b) The configuration of a city water supply. Water rises in vertical pipes up to the level of the potentiometric surface.



(c) The configuration of a regional artesian system.

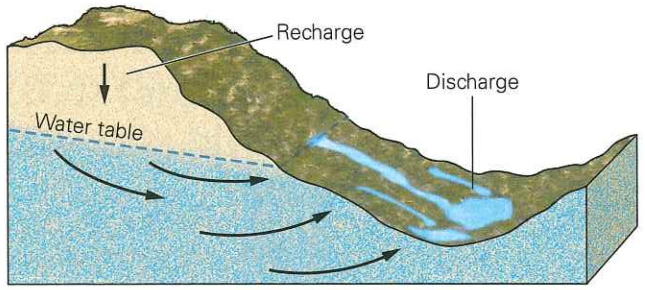
Take-Home Message

Groundwater can be obtained at wells (built by people) and springs (natural outlets). In ordinary wells, water must be lifted to the surface, but in artesian wells and springs, it rises due to its hydraulic head. Pumping of groundwater lowers the water table.

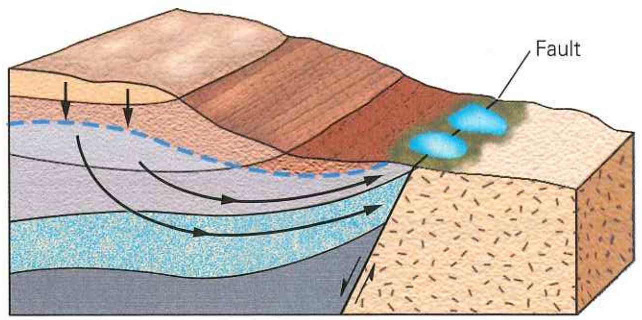
16.5 Hot Springs and Geysers

Hot springs, springs that emit water ranging in temperature from about 30° to 104°C, are found in two geologic settings. First, they occur where very deep groundwater, heated in warm bedrock at depth, flows up to the ground surface. This water brings heat with it as it rises. Such hot springs form in places where faults or fractures provide a high-permeability conduit for deep water, or where the water emitted in a discharge region followed a trajectory that first carried it deep into the crust. Second, hot springs develop in **geothermal regions**, places where volcanism currently takes place or has

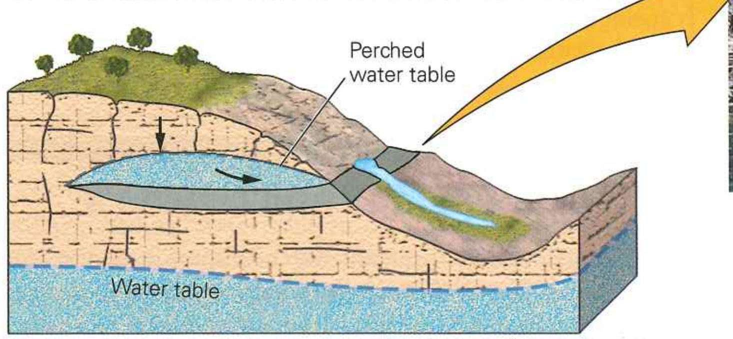
FIGURE 16.8 Geological settings in which springs form.



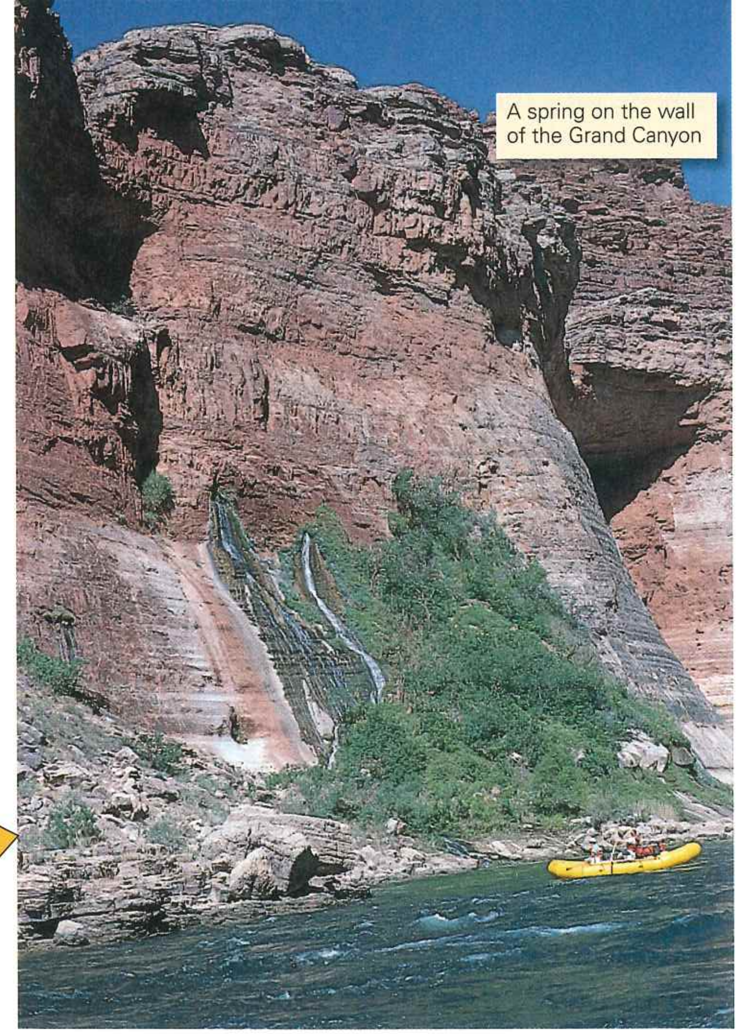
(a) Groundwater reaches the ground surface in a discharge zone.

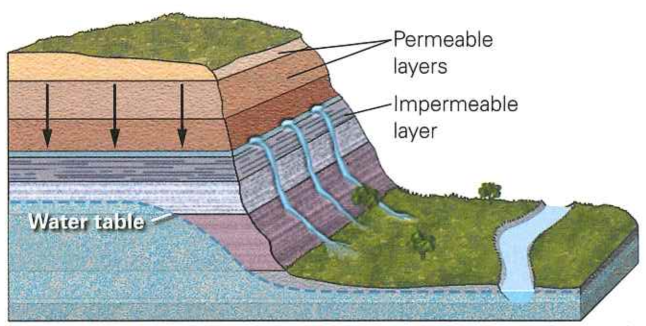


(b) Where groundwater reaches an impermeable barrier, it rises.

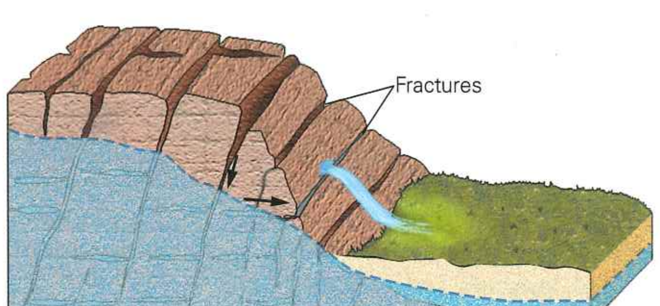


(c) Groundwater seeps where a perched water table intersects a slope.





(d) Groundwater seeps out of a cliff face at the top of a relatively impermeable bed.



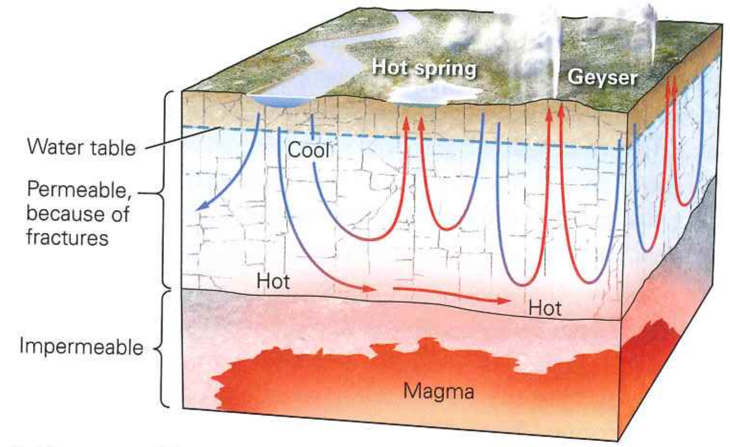
(e) A network of interconnected fractures channels water to the surface of a hill.

occurred recently, so that magma and/or very hot rock resides close to the Earth's surface (**Fig. 16.9a**). Hot groundwater dissolves minerals from rock that it passes through because water becomes a more effective solvent when hot, so people use the water emitted at hot springs as relaxing mineral baths (**Fig. 16.9b**). Natural pools of geothermal water may become brightly colored—the gaudy greens, blues, and oranges of these pools come from thermophyllic (heat-loving) bacteria and archaea that thrive in hot water and metabolize the sulfur-containing minerals dissolved in the groundwater (**Fig. 16.9c**).

Numerous distinctive geologic features form in geothermal regions as a result of the eruption of hot water. In places where the hot water rises into soils rich in volcanic ash and clay, a viscous slurry forms and fills bubbling mud pots. Bubbles of steam rising through the slurry cause it to splatter about in goopy drops. Where geothermal waters spill out of natural springs and then cool, dissolved minerals in the water precipitate, forming colorful mounds or terraces of travertine and other chemical sedimentary rocks (**Fig. 16.9d**).

Under special circumstances, geothermal water emerges from the ground in a **geyser** (from the Icelandic spring, Geysir, and the word for gush), a fountain of steam and hot water that erupts episodically from a vent in the ground (**Fig. 16.9e**). To understand why a geyser erupts, we first need a picture of its underground plumbing. Beneath a geyser lies a network of irregular fractures in very hot rock; groundwater sinks and fills these fractures. Heat transfers from the rock to the groundwater and makes the water's

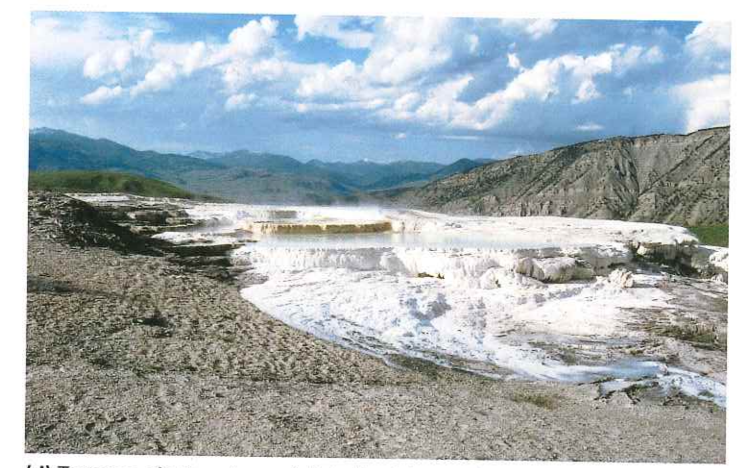
FIGURE 16.9 Geothermal waters and examples of their manifestation in the landscape.



(a) Geysers and hot springs occur where groundwater, heated at depth, rises to the surface.

(b) Hot springs in Iceland, warmed by magma below, attract tourists from around the world.

(c) Colorful bacteria- and archaea-laden pools, Yellowstone National Park, Wyoming.



(d) Terraces of minerals precipitated at Mammoth Hot Springs, Yellowstone.

(e) The Old Faithful geyser, in Yellowstone, erupts predictably.

temperature rise. Since the boiling point of water (the temperature at which water vaporizes) increases with increasing pressure, hot groundwater at depth can remain in liquid form even if its temperature has become greater than the boiling point of water at the Earth's surface. When such "superheated" groundwater begins to rise through a conduit toward the surface, pressure in it decreases until eventually some of the water transforms into steam. The resulting expansion causes water higher up to spill out of the conduit at the ground surface. When this spill happens, pressure in the conduit, from the weight of overlying water, suddenly decreases. A sudden drop in pressure causes the superhot water at depth to turn into steam instantly, and this steam quickly rises, ejecting all the water and steam above it out of the conduit in a geyser eruption. Once the conduit empties, the eruption ceases, and the conduit fills once again with water that gradually heats up, starting the eruptive cycle all over again.

Take-Home Message

In geothermal regions, or in localities where discharged groundwater followed a flow path deep into the crust, hot springs appear. Geysers develop under special circumstances where pressure builds up sufficiently to eject water and steam forcefully.

16.6 Groundwater Problems

Since prehistoric times, groundwater has been an important resource that people have relied on for drinking, irrigation, and industry. Groundwater feeds the lushness of desert oases in the Sahara, the amber grain in the North American high plains, and the growing cities of sunny arid regions.

Though groundwater accounts for about 95% of the liquid freshwater on the planet, accessible groundwater cannot be replenished quickly, and this leads to shortages. Groundwater contamination is also a growing tragedy. Such pollution, caused when toxic wastes and other impurities infiltrate down to the water table, may be invisible to us but may ruin a water supply for generations to come. In this section, we'll take a look at problems associated with the use of groundwater supplies.

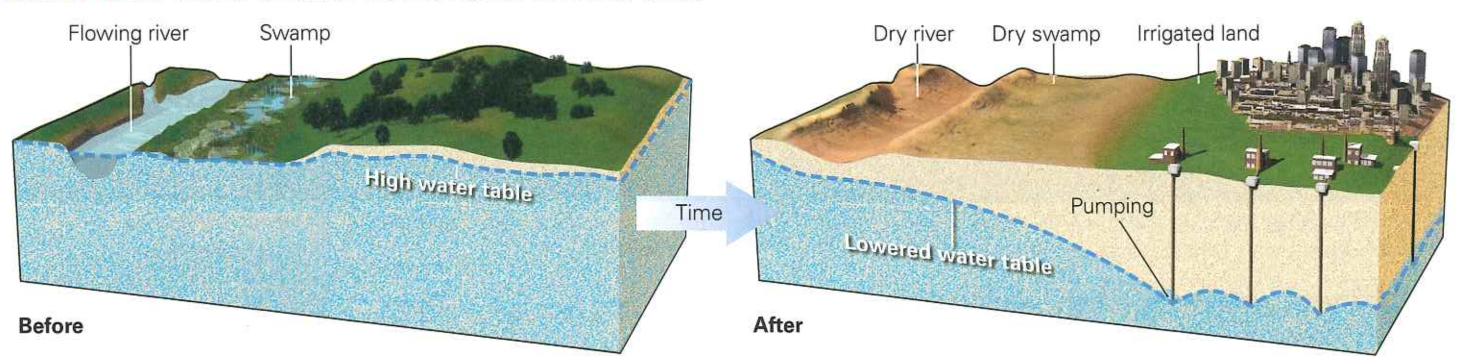
Depletion of Groundwater Supplies

Is groundwater a renewable resource? In a time frame of 10,000 years, the answer is yes, for the hydrologic cycle will eventually resupply depleted reserves. But in a time frame of 100 to 1,000 years—the span of a human lifetime or a civilization—groundwater in many regions may be a *nonrenewable* resource. By pumping water out of the ground at a rate faster than nature replaces it, people are effectively "mining" the groundwater supply. In fact, in portions of the desert Sunbelt region of the United States, supplies of young groundwater have already been exhausted, and deep wells now extract 10,000-year-old groundwater. Some of this ancient water has been in rock so long that it has become too mineralized to be usable. A number of other problems accompany the depletion of groundwater.

- *Lowering the water table*: When we extract groundwater from wells at a rate faster than it can be resupplied by nature, the water table drops. First, a cone of depression forms locally around the well; then the water table gradually becomes lower in a broad region. As a consequence, existing wells, springs, and rivers, and swamps dry up (**Fig. 16.10a, b**). To continue tapping into the water supply, we must drill progressively deeper.

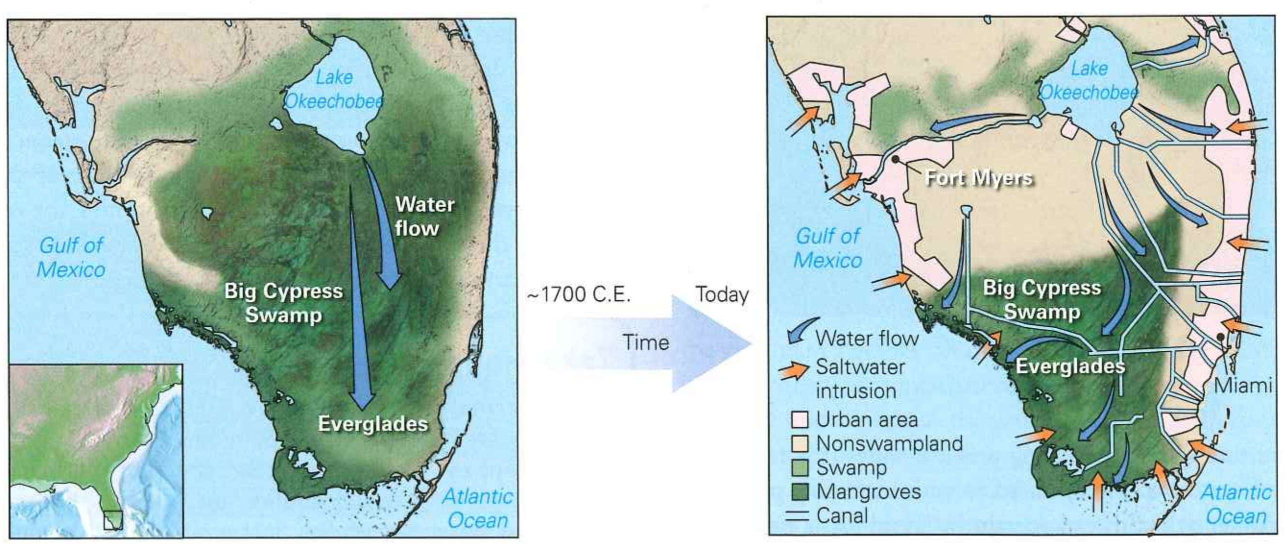
  Notably, the water table can also drop when people divert surface water from the recharge area. Such a problem has developed in the Everglades of southern Florida, a huge swamp where, before the expansion of Miami and the development of agriculture, the water table lay at the ground surface (**Fig. 16.10c, d**). Diversion of water from the Everglades' recharge area into canals has significantly lowered the water table, causing parts of the Everglades to dry up.
- *Reversing the flow direction of groundwater*: The cone of depression that develops around a well creates a local slope to the water table. The resulting hydraulic gradient may be large enough to reverse the flow direction of nearby groundwater (**Fig. 16.11a, b**). Such reversals can allow contaminants, seeping out of a septic tank, to contaminate the well.
- *Saline intrusion*: In coastal areas, fresh groundwater lies in a layer above saline (salty) water that entered the aquifer from the adjacent ocean (**Fig. 16.11c, d**). Because fresh water is less dense than saline water, it floats above the saline water. If people pump water out of a well too quickly, the boundary between the saline water and the fresh groundwater rises. And if this boundary rises above the base of the well, then the well will start to yield useless saline water. Geologists refer to this phenomenon as saline intrusion.
- *Pore collapse and land subsidence*: When groundwater fills the pore space of a rock or sediment, it holds the grains apart, for water cannot be compressed. The extraction of water from a pore eliminates the support holding the grains apart, because the air that replaces the water *can* be compressed. As a result,

FIGURE 16.10 Effects of human modification of the water table.



(a) Before humans start pumping groundwater, the water table is high. A swamp and permanent stream exist.

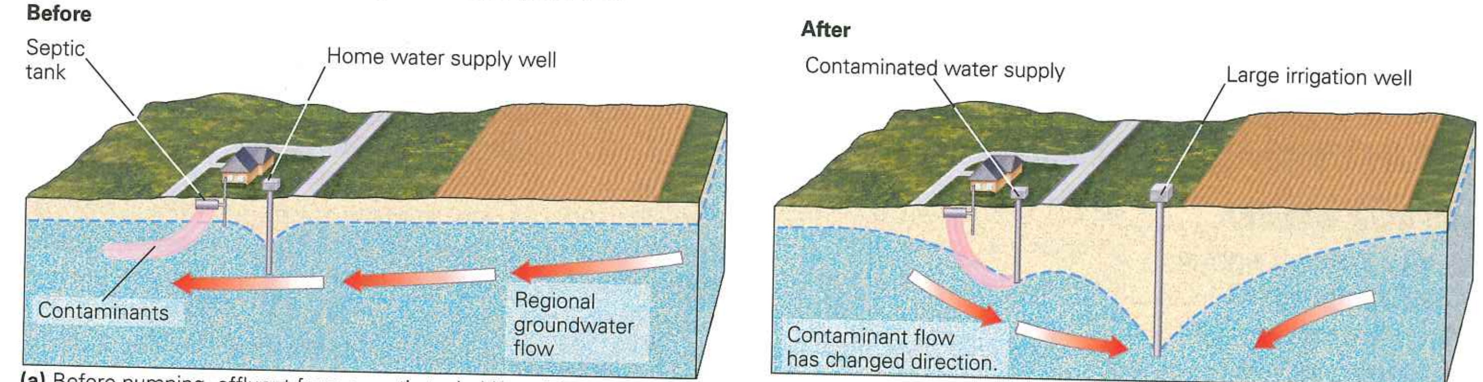
(b) Pumping for consumers in a nearby city causes the water table to sink in, so the swamp dries up.



(c) The Florida Everglades before the advent of urban growth and intensive agriculture.

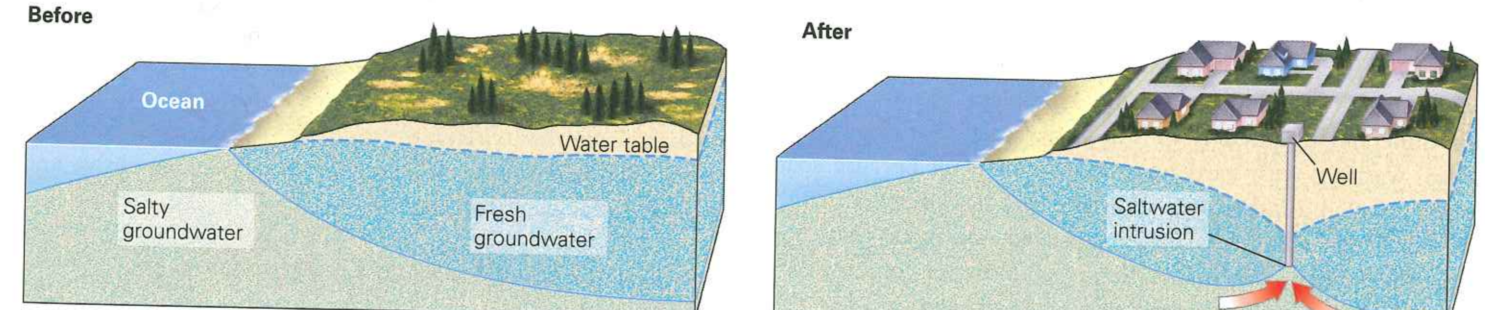
(d) Channelization and urbanization have removed water from recharge areas, disrupting flow paths.

FIGURE 16.11 Some causes of groundwater problems.



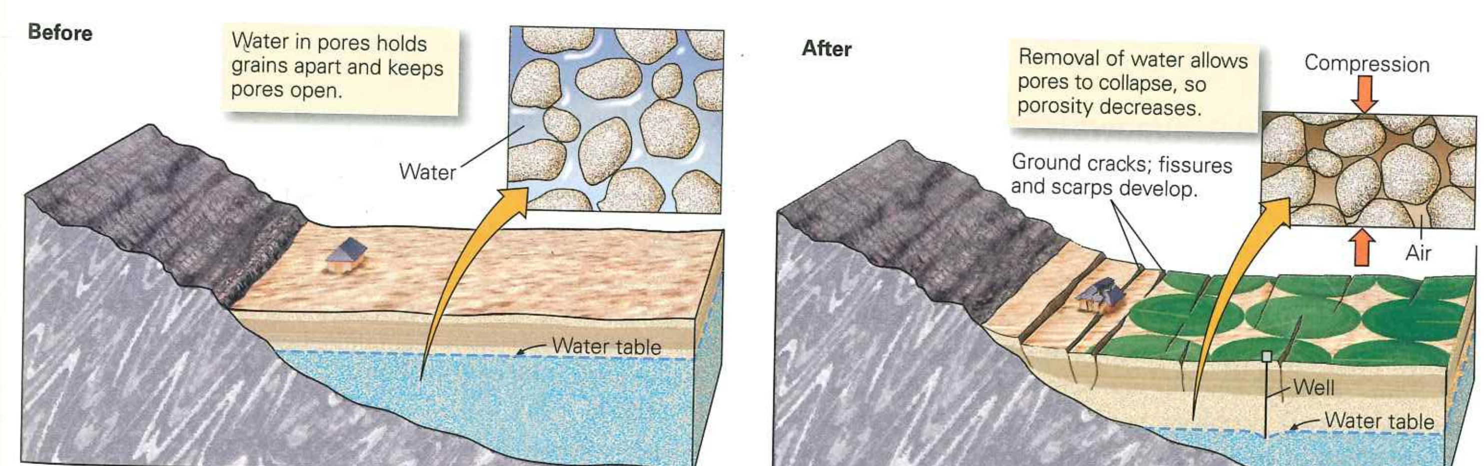
(a) Before pumping, effluent from a septic tank drifts with the regional groundwater flow, and the home well pumps clean water.

(b) After pumping by a nearby irrigation well, effluent flows into the home well in response to the new local slope of the water table.



(c) Before pumping, fresh groundwater forms a lens below the ground.

(d) If the freshwater is pumped too fast, saltwater from below is sucked up into the well. This is saltwater intrusion.



(e) When intensive irrigation removes groundwater, pore space in an aquifer collapses.

(f) As a result, the land surface sinks, leading to the formation of ground fissures and causing houses to crack.

the grains pack more closely together. Such **pore collapse** permanently decreases the porosity and permeability of a rock, and thus lessens its value as an aquifer (**Fig. 16.11e, f**).

Pore collapse also decreases the volume of the aquifer, with the result that the ground above the aquifer sinks. Such land subsidence may cause fissures at the surface to develop and the ground to tilt. Buildings constructed over regions undergoing land subsidence may themselves tilt, or their foundations may crack. In the San Joaquin Valley of California, the land surface subsided by 9 m between 1925 and 1975, because water was removed to irrigate farm fields.

Natural Groundwater Quality

Much of the world's groundwater is crystal clear, and pure enough to drink right out of the ground. Rocks and sediment are natural filters capable of removing suspended solids—these solids get trapped in tiny pores or stick to the surfaces of clay flakes. In fact, the commercial distribution of bottled groundwater ("spring water") has become a major business worldwide. But dissolved chemicals, and in some cases methane, may make some natural groundwater unusable. For example, groundwater that has passed through salt-containing strata may become salty and unsuitable for irrigation or drinking. Groundwater that has passed through limestone or dolomite contains dissolved calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions; this water, called **hard water**, can be a problem because carbonate minerals precipitate from it to form "scale" that clogs pipes. Also, washing with hard water can be difficult because soap won't develop a lather. Groundwater that has passed through iron-bearing rocks may contain dissolved iron oxide that precipitates to form rusty stains. Some groundwater contains dissolved hydrogen sulfide, which comes out of solution when the groundwater rises to the surface; hydrogen sulfide is a poisonous gas that has a rotten-egg smell. In recent years, concern has grown about arsenic, a highly toxic chemical that enters groundwater when arsenic-bearing minerals dissolve in groundwater.

id you ever wonder . . .
here does bottled "spring water" come from?

Human-Caused Groundwater Contamination

As we've noted, some contaminants in groundwater occur naturally. But in recent decades, contaminants have increasingly been introduced into aquifers because of human activity (**Fig. 16.12a**). These contaminants include agricultural waste (pesticides, fertilizers, and animal sewage), industrial waste (dangerous organic and inorganic chemicals), effluent from "sanitary" landfills and septic tanks (including bacteria and viruses), petroleum products and other chemicals that do not dissolve in water, radioactive waste (from weapons manufacture, power plants, and hospitals), and acids leached from sulfide minerals in coal and metal mines. The cloud of contaminated groundwater that moves away from the source of contamination is called a **contaminant plume** (**Fig. 16.12b**).

The best way to avoid such **groundwater contamination** is to prevent contaminants from entering groundwater in the first place. This can be done by placing contaminants in sealed containers or on impermeable bedrock so that they are isolated from aquifers. If such a site is not available, the storage area should be lined with plastic or with a thick layer of clay, for the clay not only acts as an aquitard, but it can bond to contaminants. Fortunately, in some cases, natural processes can clean up groundwater contamination. Chemicals may be absorbed by clay, oxygen in the water may oxidize the chemicals, and bacteria in the water may metabolize the chemicals, thereby turning them into harmless substances.

Where contaminants do make it into an aquifer, environmental engineers drill test wells to determine which way and how fast the contaminant plume is flowing; once they know the flow path, they can close wells in the path to prevent consumption of contaminated water. Engineers may attempt to clean the groundwater by drilling a series of extraction wells to pump it out of the ground. If the contaminated water does not rise fast enough, engineers drill injection wells to force clean water or steam into the ground beneath the contaminant plume (**Fig. 16.12c**). The injected fluids then push the contaminated water up into the extraction wells.

More recently, environmental engineers have begun exploring techniques of **bioremediation**: injecting oxygen and nutrients into a contaminated aquifer to foster growth of bacteria that can react with and break down molecules of contaminants. Needless to say, cleaning techniques are expensive and generally only partially effective.

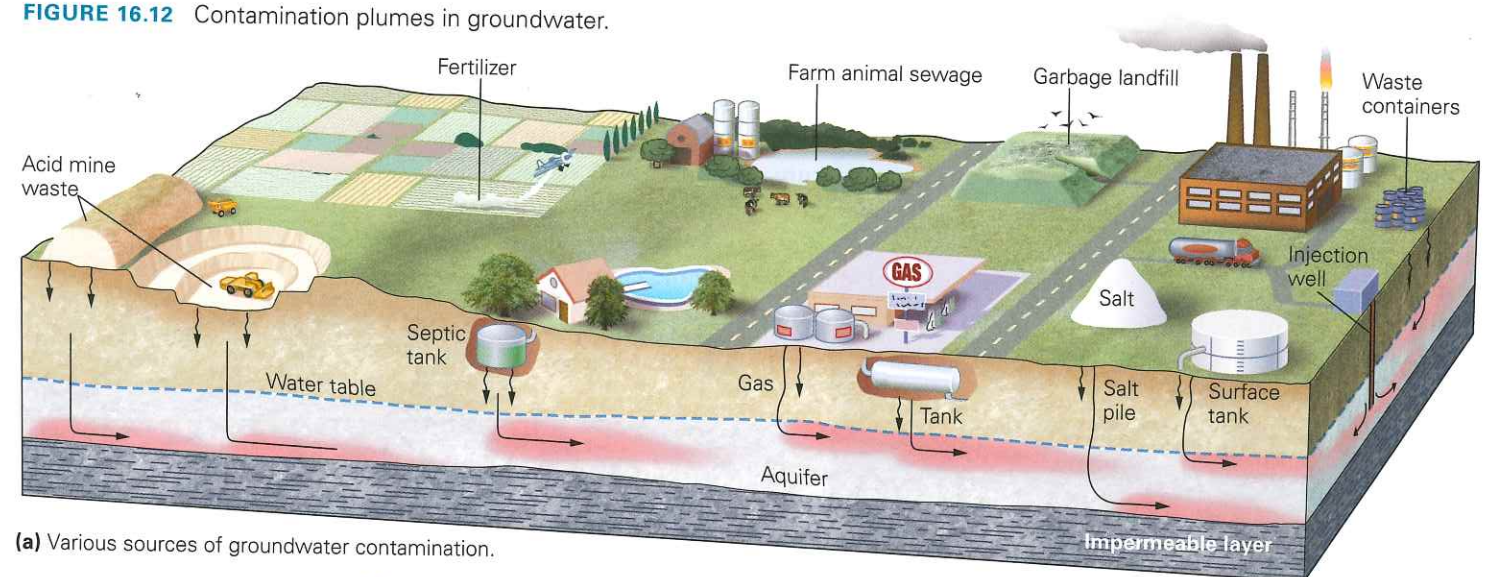
Unwanted Effects of Rising Water Tables

We've seen the negative consequences of sinking water tables, but what happens when the water table rises? Is that necessarily good? Sometimes, but not always. If the water table rises above the level of a house's basement, water seeps through the foundation and floods the basement floor. Catastrophic damage occurs when a rising water table weakens the base of a hillslope or a failure surface underground triggers landslides and slumps.

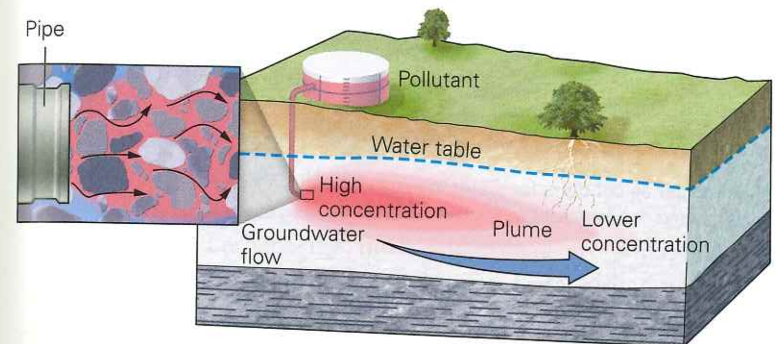
Take-Home Message

Groundwater usage can cause problems. Too much pumping lowers the water table, causing land subsidence and/or saltwater intrusion. Contamination can ruin a groundwater supply, for remediation of groundwater is extremely expensive.

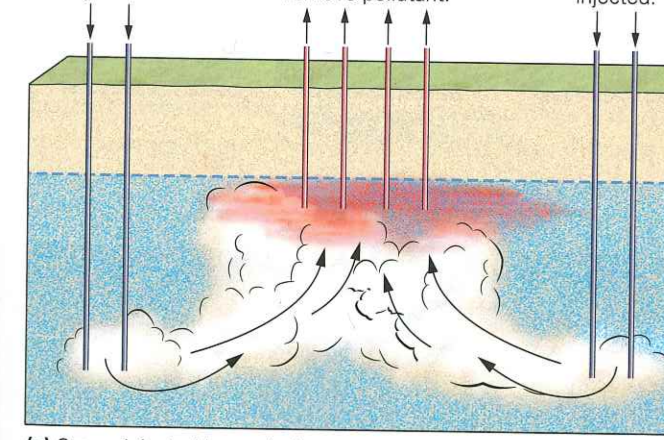
FIGURE 16.12 Contamination plumes in groundwater.



(a) Various sources of groundwater contamination.



(b) A contaminant plume as seen in cross section. The darker the color, the greater the concentration of contaminant.



(c) Steam injected beneath the contamination drives the contaminated water upward in the aquifer, where pumping wells remove it.

16.7 Caves and Karst

The Development of Caves

In 1799, as legend has it, a hunter by the name of Houchins was tracking a bear through the woods of Kentucky when the bear suddenly disappeared on a hillslope. Baffled, Houchins plunged through the brambles trying to sight his prey. Suddenly he felt a draft of surprisingly cool air flowing down the slope from uphill. Now curious, Houchins climbed up the hill and found a dark portal into the hillslope beneath a ledge of rocks. Bear tracks were all around—was the creature inside? He returned later with a lantern and cautiously stepped into the passageway. After walking a short distance, he found himself in a large, underground room. Houchins had discovered Mammoth Cave, an immense network of natural tunnels and subterranean chambers—a walk through the entire network would extend for 630 km!

Most large cave networks develop in limestone bedrock because limestone dissolves relatively easily in corrosive groundwater. Generally, the corrosive component in groundwater is dilute carbonic acid (H_2CO_3), which forms when water absorbs carbon dioxide (CO_2) from materials, such as soil, that it has passed through. When carbonic acid comes in contact with calcite ($CaCO_3$) in limestone, it reacts to produce HCO_3^{1-} and Ca^{2+} ions, which then dissolve.

Did you ever wonder . . .
why do huge underground caverns form?

In recent years, geologists have discovered that about 5% of limestone caves around the world form due to reactions with sulfuric-acid-bearing water—Carlsbad Caverns in New Mexico serves as an example. Such caves form where limestone overlies strata containing oil, because microbes can convert the sulfur in the oil to hydrogen sulfide gas, which rises and reacts with oxygen to produce sulfuric acid, which in turn eats into limestone and reacts to produce gypsum and CO_2 gas.

Geologists debate about the depth at which limestone cave networks form. Some limestone dissolves above the water table, but it appears that most cave formation takes place in limestone that lies just below the water table, for in this interval the acidity of the groundwater remains high, the mixture of groundwater and newly added rainwater is not yet saturated with dissolved ions, and groundwater flow is fastest. The association between cave formation and the water table helps explain why openings in a cave network align along the same horizontal plane.

The Character of Cave Networks

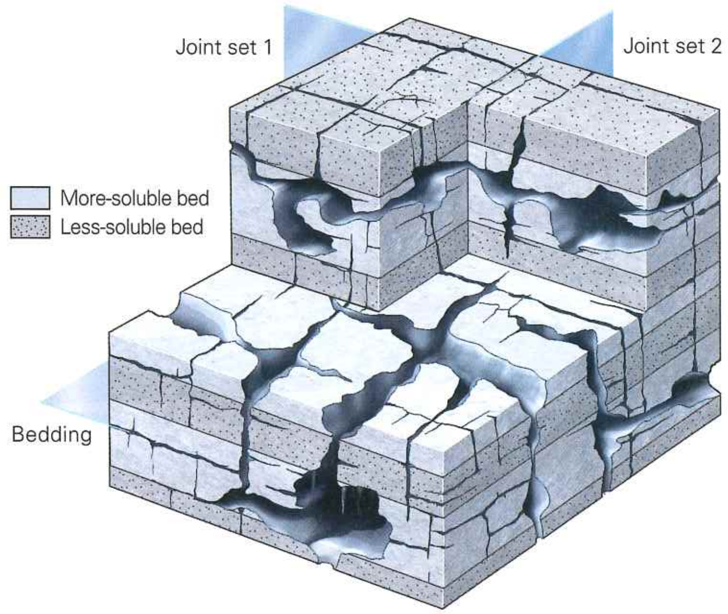
As we have noted, caves in limestone usually occur as part of a network. Cave networks include rooms, or chambers, which are large, open spaces sometimes with cathedral-like ceilings, and tunnel-shaped or slot-shaped passages. (See **Geology at a Glance**, pp. 490–491.) Some chambers may host underground lakes, and some passageways may serve as conduits for underground streams. The shape of the cave network reflects variations in permeability and in the composition of the rock from which the caves formed. Larger open spaces developed where the limestone was most soluble and where groundwater flow was fastest. Thus, in a sequence of strata, caves develop preferentially in the more soluble limestone beds. Passages in cave networks typically follow preexisting joints, for the joints provide secondary porosity along which groundwater can flow faster (**Fig. 16.13a**). Because joints commonly occur in orthogonal systems (consisting of two sets of joints oriented at right angles to each other; see Chapter 9), passages may form a grid.

Precipitation and the Formation of Speleothems

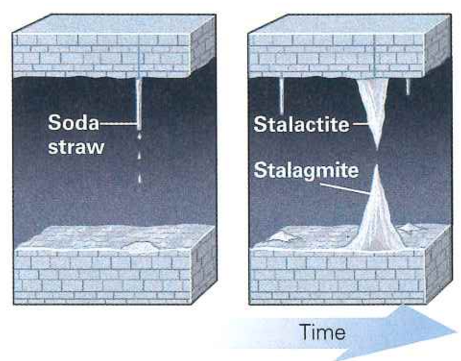
When the water table drops below the level of a cave, the cave becomes an open space filled with air. In places where downward-percolating groundwater containing dissolved calcite emerges from the rock above the cave and drips from the ceiling, the surface of the cave gradually changes. As soon as this water reenters the air, it evaporates a little and releases some of its dissolved carbon dioxide. As a result, calcium carbonate (limestone) precipitates out of the water and produces a type of travertine. The various intricately shaped formations that grow in caves by the accumulation of dripstone are called **speleothems**.

Cave explorers (spelunkers) and geologists have developed a detailed nomenclature for different kinds of speleothems (**Fig. 16.13b**). Where water drips from the ceiling of the cave, the precipitated limestone builds *dripstone*. Initially, calcite precipitates around the outside of the drip, forming a delicate, hollow tube called a soda straw. But eventually, the soda straw fills up, and water migrates down the margin of the cone to form a more massive, solid icicle-like cone called a **stalactite**. Where the drips hit the floor, the resulting precipitate builds an upward-pointing cone called a **stalagmite**.

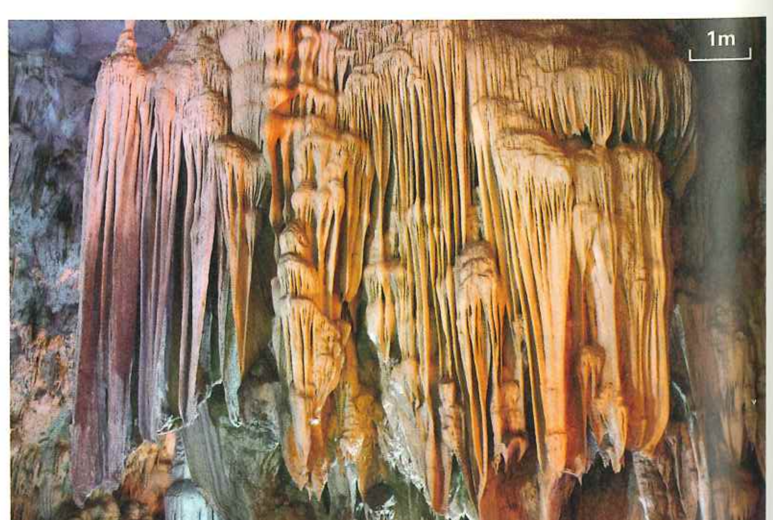
FIGURE 16.13 Development of karst, dripstone, and flowstone.



(a) Joints act as conduits for water in cave networks. Caves and passageways follow joints, and preferentially form in more-soluble beds.



(b) The evolution of dripstone.



(c) Flowstone on the wall of a cave in Vietnam.

If the process of dripstone formation in a cave continues long enough, stalagmites merge with overlying stalactites to create travertine columns. In some cases, groundwater flows along the surface of a wall and precipitates to produce drape-like sheets of travertine called *flowstone* (**Fig. 16.13c**). The travertine of caves tends to be translucent and, when lit from behind, glows with an eerie amber light.

The Formation of Karst Landscapes

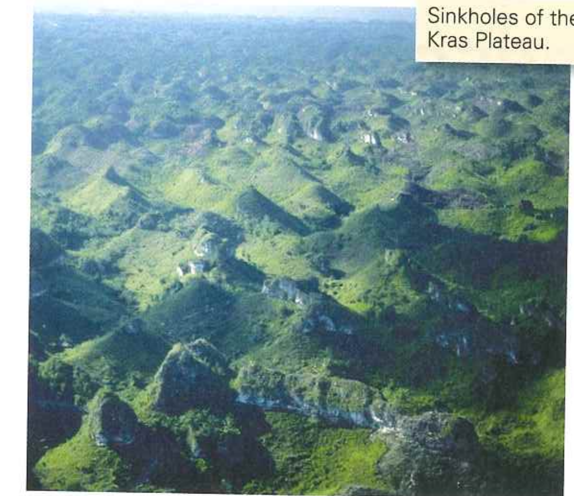
Limestone bedrock underlies most of the Kras Plateau in Slovenia, along the east coast of the Adriatic Sea. The name *kras*, which means rocky ground, is apt because this region includes abundant rock exposures (**Fig. 16.14a**). Geologists refer to regions such as the Kras Plateau, where surface landforms develop when limestone bedrock dissolves both at the surface and in underlying cave networks, as **karst landscapes** or karst terrains—from the Germanized version of kras (**See for Yourself P**).

Karst landscapes typically display a number of distinct landforms. Perhaps the most widespread are sinkholes (see Fig. 16.1), circular depressions that form either when the ground collapses into an underground cave below (as we discussed early in this chapter) or when surface bedrock dissolves in acidic water on the floor of a bog or pond. Not all of the caves or passageways beneath a karst landscape have collapsed, and this situation leads to unusual drainage patterns. Specifically, where surface streams intersect cracks (joints) or holes that link to caverns or passageways below, the water cascades downward into the subsurface and disappears (**Fig. 16.14b**). Such **disappearing streams** may flow through passageways underground and reemerge from a cave entrance downstream. In cases where the ground collapses over a long, joint-controlled passage, sinkholes may be elongate and canyon-like. Remnants of cave roofs remain as natural bridges. Ridges or walls between adjacent sinkholes tend to be steep-sided. Over time, the walls erode, leaving only jagged, isolated spires—a karst landscape dominated by such spires is called tower karst. The surreal collection of pinnacles constituting the tower karst landscape in the Guilin region of China inspired generations of artists who portray them on scroll paintings (**Fig. 16.15**).

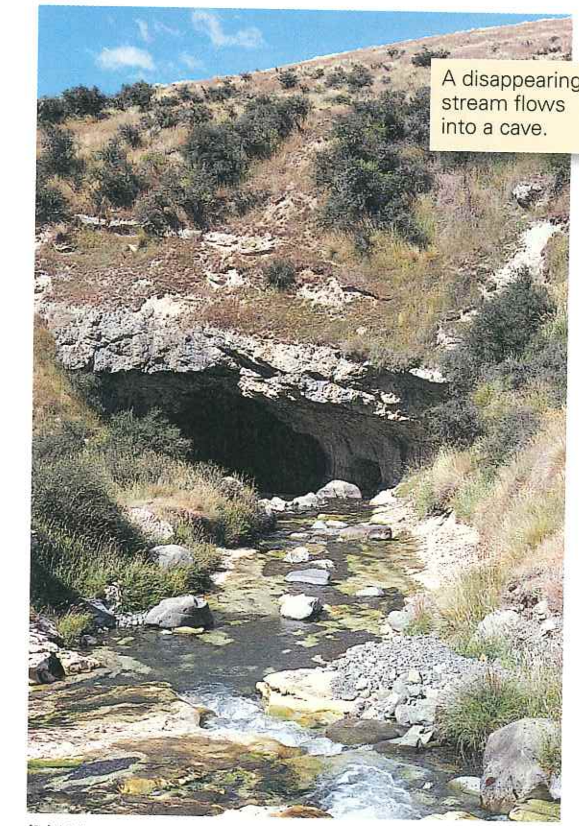
Karst landscapes form in a series of stages (**Fig. 16.16a–c**).

- *The establishment of a water table in limestone*: The story of a karst landscape begins after the formation of a thick interval of limestone in which the water table lies underground.
- *The formation of a cave network*: Once the water table has been established, dissolution begins and a cave network develops.
- *A drop in the water table*: If the water table later becomes lower, either because of a decrease in rainfall or because nearby rivers downcut and drain the region, newly formed caves dry out. Downward-percolating water emerges from the roofs of the caves; dripstone and flowstone precipitate.
- *Roof collapse*: If rocks fall off the roof of a cave for a long time, the roof eventually collapses. Such collapse creates sinkholes and troughs, leaving behind hills, ridges, and natural bridges.

FIGURE 16.14 Features of karst landscapes.



(a) Karst terrains typically have a rough, rocky surface.



(b) Water may flow underground in a karst terrain.

Caves and Karst Landscapes

Limestone pavement, Ireland

Natural Bridge, Virginia

Spelunker crawling in a cave

...les

Underground pool, Mexico

Limestone is soluble in acidic water. Much of the water that falls to the ground as rain, or seeps through the ground as groundwater, tends to be acidic, so in regions of the Earth where bedrock consists of limestone, we find signs of dissolution. Underground openings that develop by dissolution are called caves or caverns. Some of these may be large, open rooms, whereas others are long, narrow passages. Underground lakes and streams may cover the floor. A cave's location depends on the orientation of bedding and joints, for these features localize the flow of groundwater.

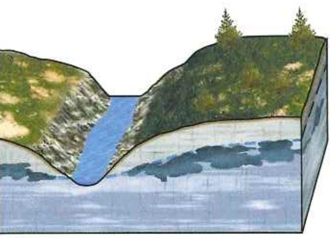
Caves originally form at or near the water table. As the water table drops, caves empty of most water and become filled with air. In many locations, groundwater drips from the ceiling of a cave or flows along its walls. As the water evaporates and loses its acidity, new calcite precipitates. Over time, this calcite builds into cave formations, or speleothems, such as stalactites, stalagmites, columns, and flowstone.

Distinctive landscapes, called karst landscapes, develop at the Earth's surface over limestone bedrock. In such regions, the ground may be rough where rock has dissolved along joints; where the roofs of caves collapse, sinkholes develop. If a surface stream flows into a cave network, we say that the stream is "disappearing." The water from such streams may reemerge elsewhere as a spring. In some places, the collapse of subsurface openings leaves behind natural bridges.

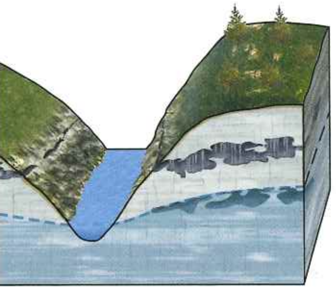
southern China.

The landscape is treeless today, a consequence of industrialization policies in the 1950s.

d a karst landscape.



ter table in an uplifted sequence



vers the water table, and the caves

Life in Caves

Despite their lack of light, caves are not sterile, lifeless environments. Caves that are open to the air provide a refuge for bats as well as for various insects and spiders. Similarly, fish and crustaceans enter caves where streams flow in or out. Species living in caves have evolved some unusual characteristics. For example, cave fish lose their pigment and in some cases their eyes. Recently, explorers discovered caves in Mexico in which warm, mineral-rich groundwater currently flows. Colonies of bacteria metabolize sulfur-containing minerals in this water and create thick mats of living ooze in the complete darkness of the cave. Long gobs of this bacteria slowly drip from the ceiling. Because of the mucus-like texture of these drips, they have come

ANOTHER VIEW Swamps are swamps because the land surface lies just below the water table. The bald cypress trees of this swamp in southern Illinois have adapted to life in soggy ground. During dry seasons, the water table sinks below the ground surface and the land dries out.

water rises on its own. Pumping water out of a well too fast causes drawdown, yielding a cone of depression. At a spring, groundwater exits the ground on its own.

- Hot springs and geysers release hot water to the Earth's surface. This water may have been heated by residing very deep in the crust, or by the proximity of a magma chamber.
- Groundwater is a precious resource, used for municipal water supplies, industry, and agriculture. In recent years, some regions have lost their groundwater supply because of overuse or contamination.
- When limestone dissolves just below the water table, underground caves develop. Soluble beds and joints determine the location and orientation of caves. If the water table drops, caves empty out. Limestone then precipitates out of water dripping from cave roofs, and creates speleothems.
- Regions where abundant caves have collapsed to form sinkholes are called karst landscapes. These terrains can contain sinkholes, natural bridges, and disappearing streams.

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ordinary well (p. 480)
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stalagmite (p. 488)
water table (p. 477)
well (p. 480)

5. How does the chemical composition of groundwater change with time? What is "hard water"?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- Visual problems on water tables, aquifers, and aquitards.
- A labeling exercise on karst landscapes.
- A What a Geologist Sees exercise on identifying sources of groundwater contamination.

10. Is groundwater a renewable or nonrenewable resource?
11. Describe some of the ways in which human activities can adversely affect the water table.
12. What are some sources of groundwater contamination? How can contamination be prevented?
13. Describe the process leading to the formation of caves and the speleothems within caves.
14. Describe the various features of a karst landscape, and explain how they evolve.

On Further Thought

15. The population of Desert Paradise (a fictitious town in the southwestern United States) has been doubling every seven years. Most of the new inhabitants are "snowbirds," people escaping the cold winters of more northerly latitudes. There are no permanent streams or lakes anywhere near DP. In fact, the only standing water in the town occurs in the ponds of golf courses. The water in these ponds needs to be replenished almost constantly, for without supplementing it, the water seeps into the ground quickly and the ponds dry up. The golf courses and yards of the suburban-style developments all have lawns of green grass. DP has been growing on a flat, gravel-filled basin between two small mountain ranges. Where does the water supply of DP come from? What do you predict will happen to the water table of the area in coming years, and how might the land surface change as a consequence? Is there a policy that you might suggest to the residents of DP that could slow the process of change?

SEE FOR YOURSELF P. . . Groundwater and Karst Landscapes

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet P of our **Geotours Workbook**.

Sinkholes in Central Florida
Latitude 28°37′50.59″N,
Longitude 81°23′13.60″W
Several sinkholes, that range from about 100 to 800 m across can be seen from an elevation of 20 km. These lie

Karst landscape in Puerto Rico
Latitude 18°23′53.04″N,
Longitude 66°25′49.43″W
From an elevation of 7 km, we see a karst terrain in central Puerto Rico.