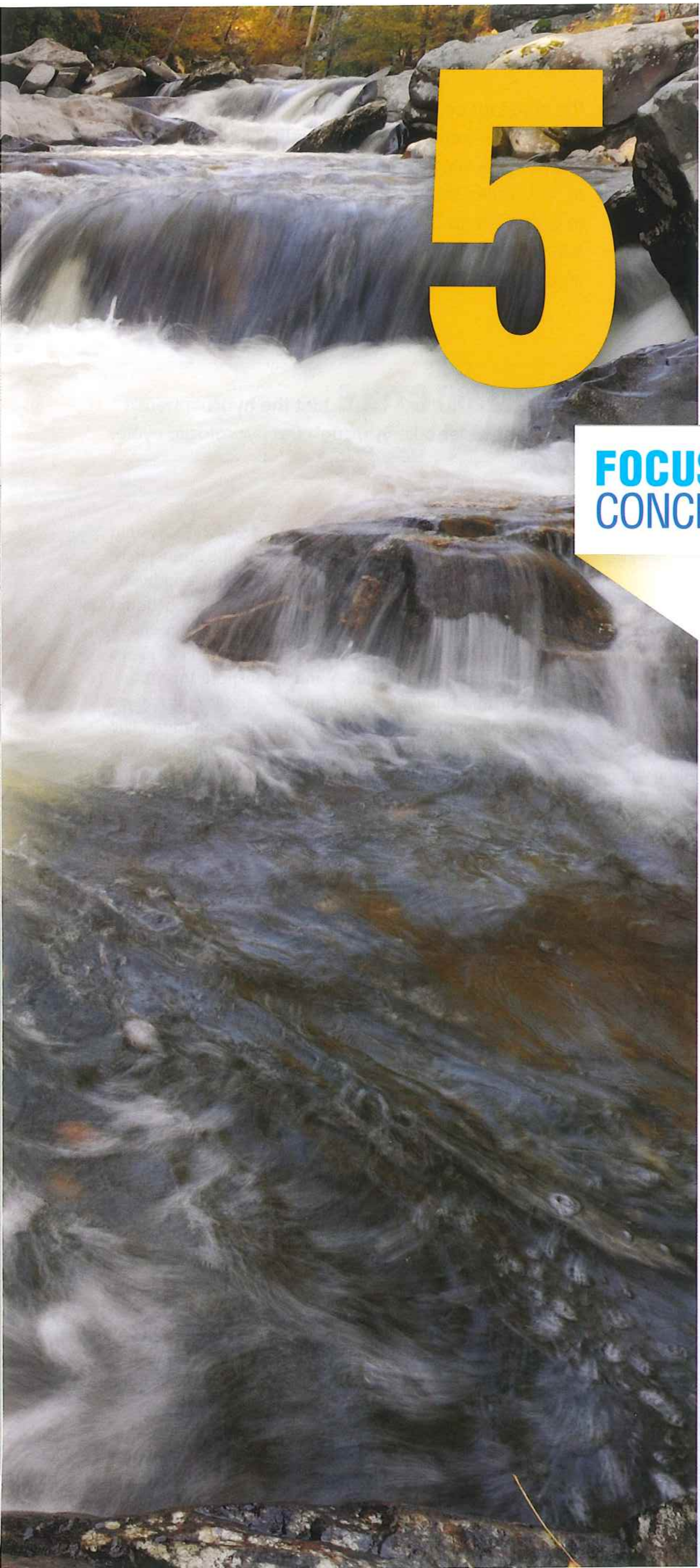
5

Running Water and Groundwater



Turbulent flow in the Little River in northeastern Alabama.

(Photo by Michael Collier)

FOCUS ON CONCEPTS

Each statement represents the primary **LEARNING OBJECTIVE** for the corresponding major heading within the chapter. After you complete the chapter, you should be able to:

5.1 List the hydrosphere's major reservoirs and describe the different paths that water takes through the hydrologic cycle.

5.2 Describe the nature of drainage basins and river systems. Sketch four basic drainage patterns.

5.3 Discuss streamflow and the factors that cause it to change.

5.4 Outline the ways in which streams erode, transport, and deposit sediment.

5.5 Contrast bedrock and alluvial stream channels. Distinguish between two types of alluvial channels.

5.6 Contrast narrow V-shaped valleys, broad valleys with floodplains, and valleys that display incised meanders.

5.7 Discuss the formation of deltas, natural levees, and alluvial fans.

5.8 Discuss the causes of floods and some common flood control measures.

5.9 Discuss the importance of groundwater and describe its distribution and movement.

5.10 Compare and contrast springs, wells, and artesian systems.

5.11 List and discuss three important environmental problems associated with groundwater.

5.12 Explain the formation of caverns and the development of karst topography.

Water is continually on the move, from the ocean to the land and back again, in an endless cycle. This chapter deals with the part of the hydrologic cycle that returns water to the sea. Some water travels quickly via a rushing stream, and some moves more slowly below the surface. When viewed as part of the Earth system, streams and groundwater represent basic links in the constant cycling of the planet's water. In this chapter, we examine the factors that influence the distribution and movement of water, as well as look at how water sculpts the landscape. To a great extent, the Grand Canyon, Niagara Falls, Old Faithful, and Mammoth Cave all owe their existence to the action of water on its way to the sea.

5.1 EARTH AS A SYSTEM: THE HYDROLOGIC CYCLE

List the hydrosphere's major reservoirs and describe the different paths that water takes through the hydrologic cycle.

Water is constantly moving among Earth's different spheres—the *hydrosphere*, the *atmosphere*, the *geosphere*, and the *biosphere*. This unending circulation of water is called the **hydrologic cycle**. Earth is the only planet in the solar system that has a global ocean and a hydrologic cycle.

Earth's Water

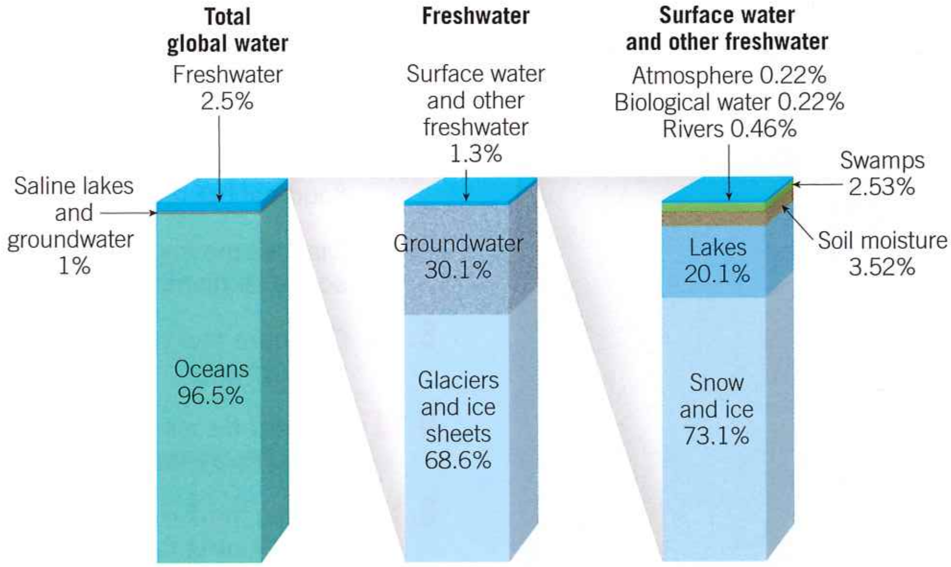
Water is almost everywhere on Earth—in the oceans, glaciers, rivers, lakes, air, soil, and living tissue. All these "reservoirs" constitute Earth's hydrosphere. In all, the water content of the hydrosphere is an estimated 1.36 billion cubic kilometers (326 million cubic miles). The vast bulk of it, about 96.5 percent, is stored in the global ocean. Ice sheets and glaciers account for an additional 1.76 percent, leaving just slightly more than 2 percent to be divided among lakes, streams, groundwater, and the atmosphere (**FIGURE 5.1**). Although the percentage of Earth's total water found in each of the latter sources is just a small fraction of the total inventory, the absolute quantities are great.

Water's Paths

The hydrologic cycle is a gigantic, worldwide system powered by energy from the Sun, in which the atmosphere provides a vital link between the oceans and continents (**FIGURE 5.2**). **Evaporation**, the process by which liquid water changes into water vapor (gas), is how water enters the atmosphere from the ocean and, to a much lesser extent, from the continents. Winds transport this moisture-laden air, often great distances. Complex processes of cloud formation eventually result in precipitation. The precipitation that falls into the ocean has completed its cycle and is ready to begin another. The water that falls on the continents, however, must make its way back to the ocean.

What happens to precipitation once it has fallen on land? A portion of the water soaks into the ground (called **infiltration**), slowly moving downward, then moving laterally, and finally seeping into lakes, streams, or directly into the ocean. When the rate of rainfall exceeds Earth's ability to absorb it, the surplus water flows over the surface into lakes and streams, a process called **runoff**. Much of the water that infiltrates or runs off eventually returns to the atmosphere because of evaporation from the soil, lakes, and streams. Also, some of the water that soaks into the ground is absorbed by plants, which then release it into the atmosphere. This process is called **transpiration**. Because both evaporation and transpiration involve the transfer of water from the surface directly to the atmosphere, they are often considered together as the combined process of **evapotranspiration**.

FIGURE 5.1 Distribution of Earth's Water



Storage in Glaciers

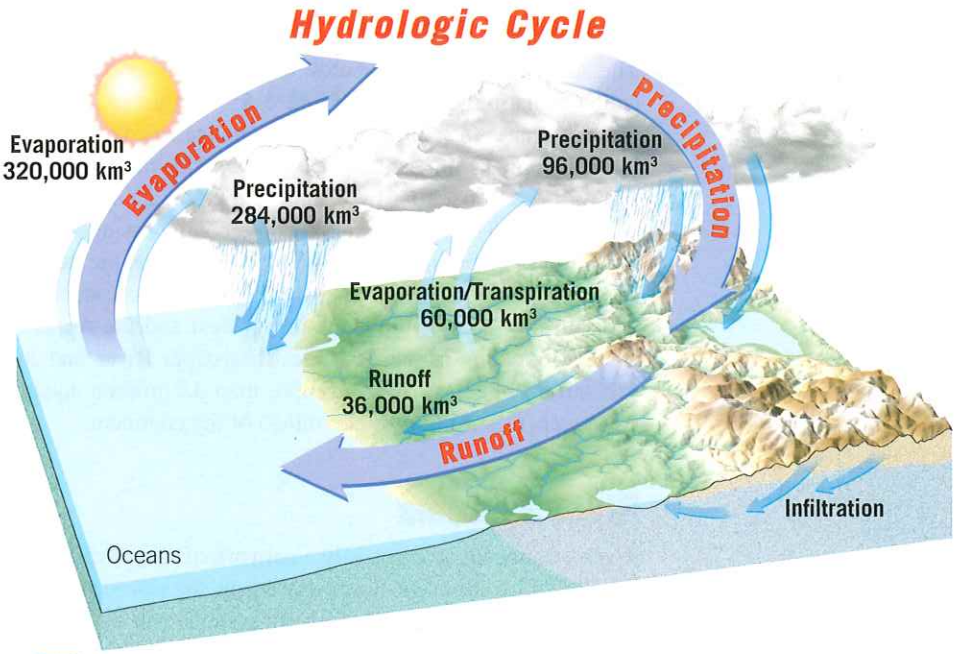
When precipitation falls in very cold places—at high elevations or high latitudes—the water may not immediately soak in, run off, or evaporate. Instead, it may become part of a snowfield or a glacier. In this way, glaciers store large quantities of water on land. If present-day glaciers were to melt and release all their water, sea level would rise by several dozen meters. Such a rise would submerge many heavily populated coastal areas. As you will see in Chapter 6, over the past 2 million years, huge ice sheets have formed and melted on several occasions, each time affecting the balance of the hydrologic cycle.

Water Balance

Figure 5.2 also shows Earth's overall *water balance*, or the volume that passes through each part of the cycle annually. The amount of water vapor in the air at any one time is just a tiny fraction of Earth's total water supply. But the *absolute* quantities that are cycled through the atmosphere over a 1-year period are immense—some 380,000 cubic kilometers (91,000 cubic miles)—enough to cover Earth's entire surface to a depth of about 1 meter (39 inches).

It is important to know that the hydrologic cycle is *balanced.* Because the total amount of water vapor in the atmosphere remains about the same, the average annual precipitation worldwide must be equal to the quantity of water evaporated. However, for all the continents taken together, precipitation exceeds evaporation. Conversely, over the oceans, evaporation exceeds precipitation. Because the level of the world ocean is not dropping, the system must be in balance. In Figure 5.2, the 36,000 cubic kilometers (8600 cubic miles) of water that annually makes its way from the land to the ocean causes enormous erosion. In fact, this immense volume of moving water is *the single most important agent sculpting Earth's land surface.*

In the rest of this chapter, we will observe the work of water running over the surface, including floods, erosion, and the formation of valleys. Then we will look underground at the slow labors of groundwater as it forms springs and caverns and provides drinking water on its long migration to the sea.



SmartFigure 5.2 The Hydrologic Cycle The primary movement of water through the cycle is shown by the large arrows. A number refers to the annual amount of water taking a particular path.

5.1 CONCEPT CHECKS

1 Describe or sketch the movement of water through the hydrologic cycle. Once precipitation has fallen on land, what paths might it take?
2 What is meant by the term *evapotranspiration*?
3 Over the oceans, evaporation exceeds precipitation, yet sea level does not drop. Explain why.

5.2 RUNNING WATER Describe the nature of drainage basins and river systems. Sketch four basic drainage patterns.

Much of the precipitation that falls on land either enters the soil (infiltration) or remains at the surface, moving downslope as runoff. The amount of water that runs off rather than soaking into the ground depends on several factors: (1) the intensity and duration of rainfall, (2) the amount of water already in the soil, (3) the nature of the surface material, (4) the slope of the land, and (5) the extent and type of vegetation. When the surface material is highly impermeable, or when it becomes saturated, runoff is the dominant process. Runoff is also high in urban areas because large areas are covered by impermeable buildings, roads, and parking lots.

Runoff initially flows in broad, thin sheets. This unconfined flow eventually develops threads of current that form tiny channels called rills. Rills meet to form gullies, which join to form streams. At first streams are small, but as one intersects another, larger and larger ones form. Eventually rivers develop that carry water from a broad region.

Drainage Basins

The land area that contributes water to a river system is called a **drainage basin** (**FIGURE 5.3**). The drainage basin of one stream is separated from the drainage basin of another by an imaginary line called a **divide**. Divides range in scale from a ridge separating two small gullies on a hillside to a *continental divide*, which splits whole continents into enormous drainage basins. The Mississippi River has the largest drainage basin in North America (**FIGURE 5.4**). Extending between the Rocky Mountains in the west and the Appalachian Mountains in the east, the Mississippi River and its tributaries collect water from more than 3.2 million square kilometers (1.2 million square miles) of the continent.

River Systems

River systems involve not only a network of stream channels but the entire drainage basin. Based on the dominant processes operating within them, river systems can be divided into three zones: *sediment production*—where erosion dominates, *sediment transport*, and *sediment deposition* (**FIGURE 5.5**). It is important to recognize that sediment is being eroded, transported, and deposited along the entire length of a stream, regardless of which process is dominant within each zone.

Sediment Production The zone of *sediment production*, where most of the sediment is derived, is located in the headwater region of the river system. Much of the sediment carried by streams begins as bedrock that is subsequently broken down by weathering and then transported downslope by mass wasting and overland flow. Bank erosion can also contribute significant amounts of sediment. In addition,

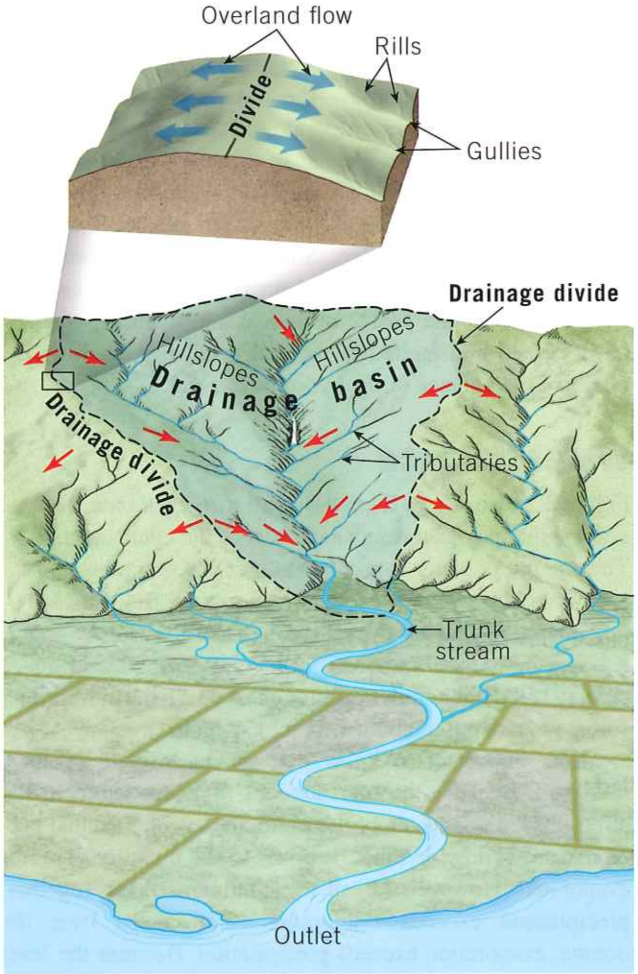
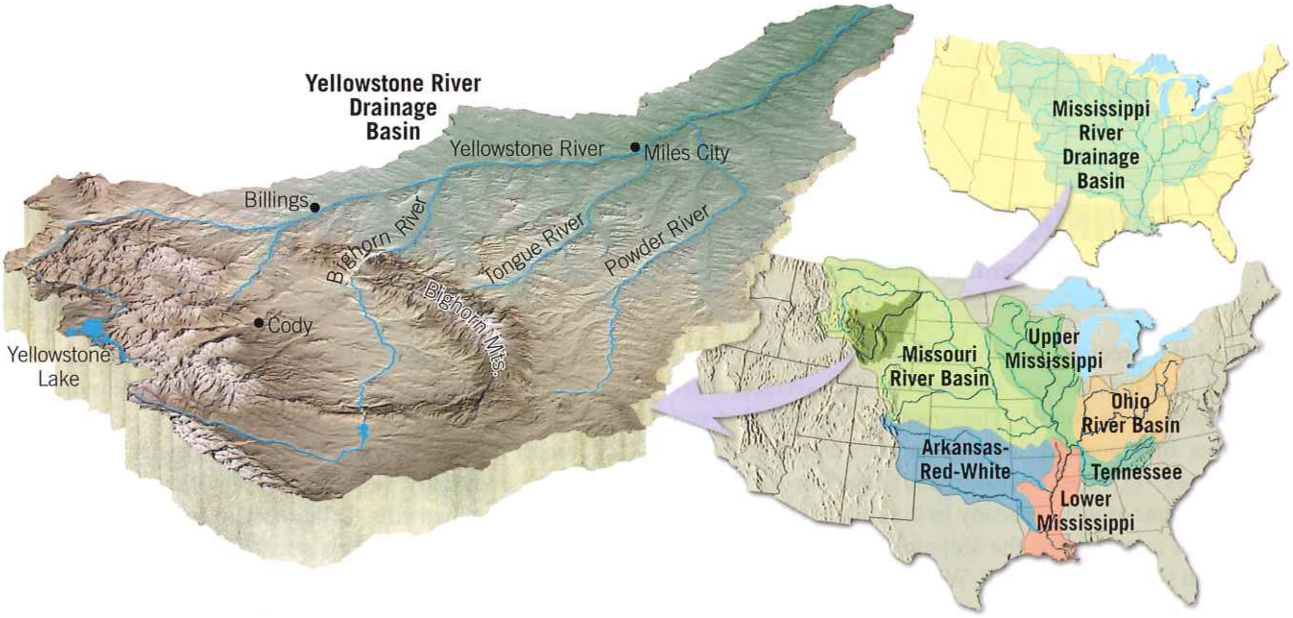


FIGURE 5.3 Drainage Basin and Divide A drainage basin is the area drained by a stream and its tributaries. Boundaries between basins are called divides.



SmartFigure 5.4 Mississippi River Drainage Basin The drainage basin of the Mississippi River, North America's largest, covers about 3 million square kilometers (almost 1.2 million square miles) and consists of many smaller drainage basins. The drainage basin of the Yellowstone River is one of many that contribute water to the Missouri River, which, in turn, is one of many that make up the drainage basin of the Mississippi River.

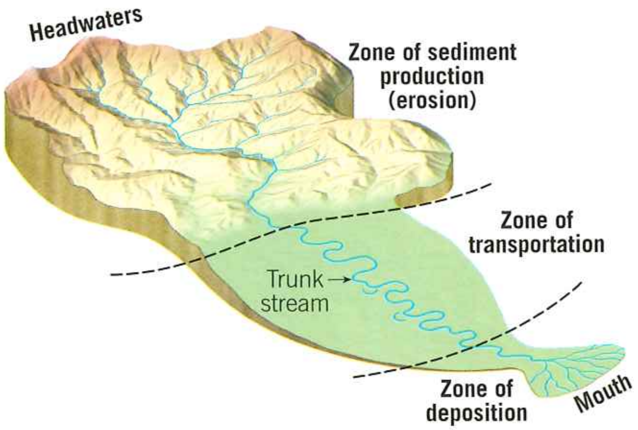


FIGURE 5.5 Zones of a River Each of the three zones is based on the dominant process that is operating in that part of the river system.

scouring of the channel bed deepens the channel and adds to the stream's sediment load.

Sediment Transport

Sediment acquired by a stream is transported through the channel network along sections referred to as *trunk streams*. When trunk streams are in balance, the amount of sediment eroded from their banks equals the amount deposited elsewhere in the channel. Although trunk streams rework their channels over time, they are not a source of sediment, nor do they accumulate or store it.

Sediment Deposition

When a river reaches the ocean, or another large body of water, it slows, and the energy to transport sediment is greatly reduced. Most of the sediments either accumulate at the mouth of the river to form a delta, are reconfigured by wave action to form a variety of coastal features, or are moved far offshore by ocean currents. Because coarse sediments tend to be deposited upstream, it is primarily the fine sediments (clay, silt, and fine sand) that eventually reach the ocean. Taken together, erosion, transportation, and deposition are the processes by which rivers move Earth's surface materials and sculpt landscapes.

Drainage Patterns

Drainage systems are networks of streams that together form distinctive patterns. The nature of a drainage pattern can vary greatly from one type of terrain to another, primarily in response to the kinds of rock on which the streams developed and/or the structural pattern of faults and folds. **FIGURE 5.6** illustrates four drainage patterns.

The most commonly encountered drainage pattern is the **dendritic pattern**. This pattern of irregularly branching tributary streams resembles the branching pattern of a deciduous tree. In fact, the word *dendritic* means "treelike." The dendritic pattern forms where the underlying material is relatively uniform. Because the surface material is essentially uniform in its resistance to erosion, it does not control the pattern of streamflow. Rather, the pattern is determined chiefly by the direction of slope of the land.

When streams diverge from a central area like spokes from the hub of a wheel, the pattern is said to be **radial**. This pattern typically develops on isolated volcanic cones and domal uplifts.

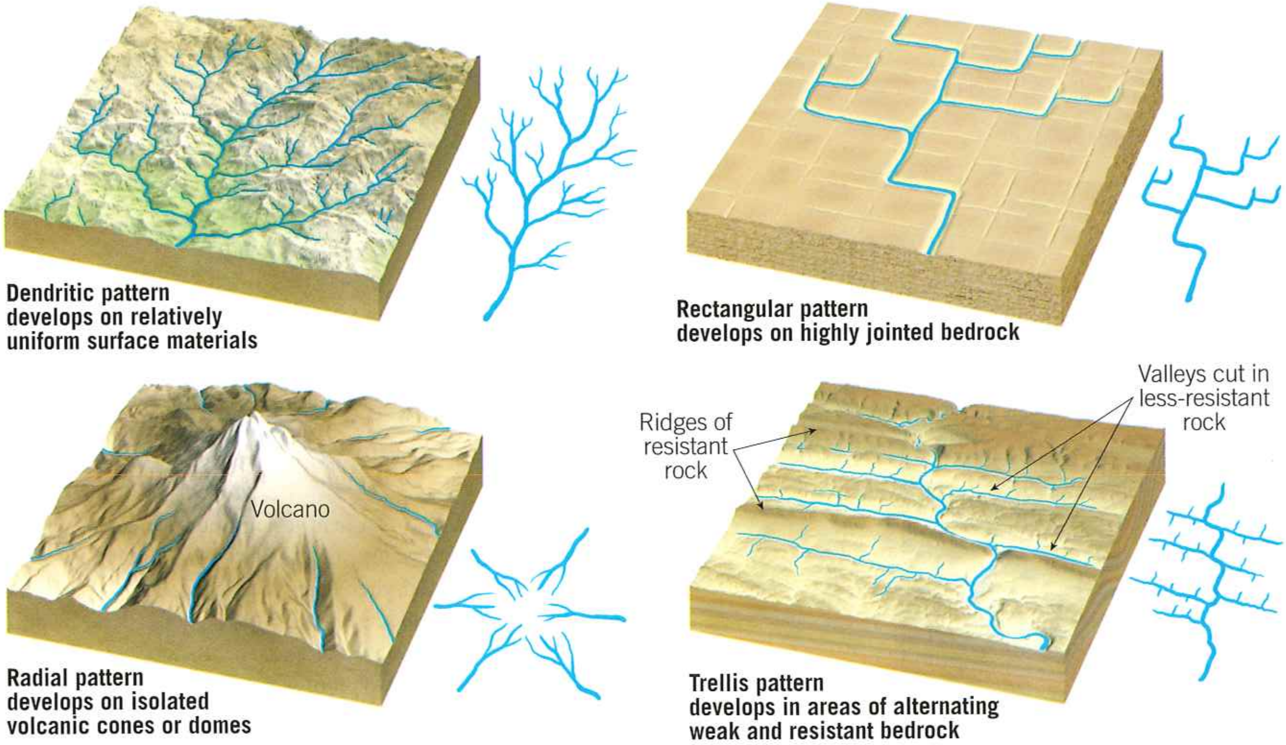


FIGURE 5.6 Drainage Patterns Networks of streams form a variety of patterns.

A **rectangular pattern** exhibits many right-angle bends. This pattern develops when the bedrock is crisscrossed by a series of joints and/or faults. Because these structures are eroded more easily than unbroken rock, their geometric pattern guides the directions of valleys.

A **trellis pattern** is a rectangular drainage pattern in which tributary streams are nearly parallel to one another and have the appearance of a garden trellis. This pattern forms in areas underlain by alternating bands of resistant and less-resistant rock.

5.2 CONCEPT CHECKS

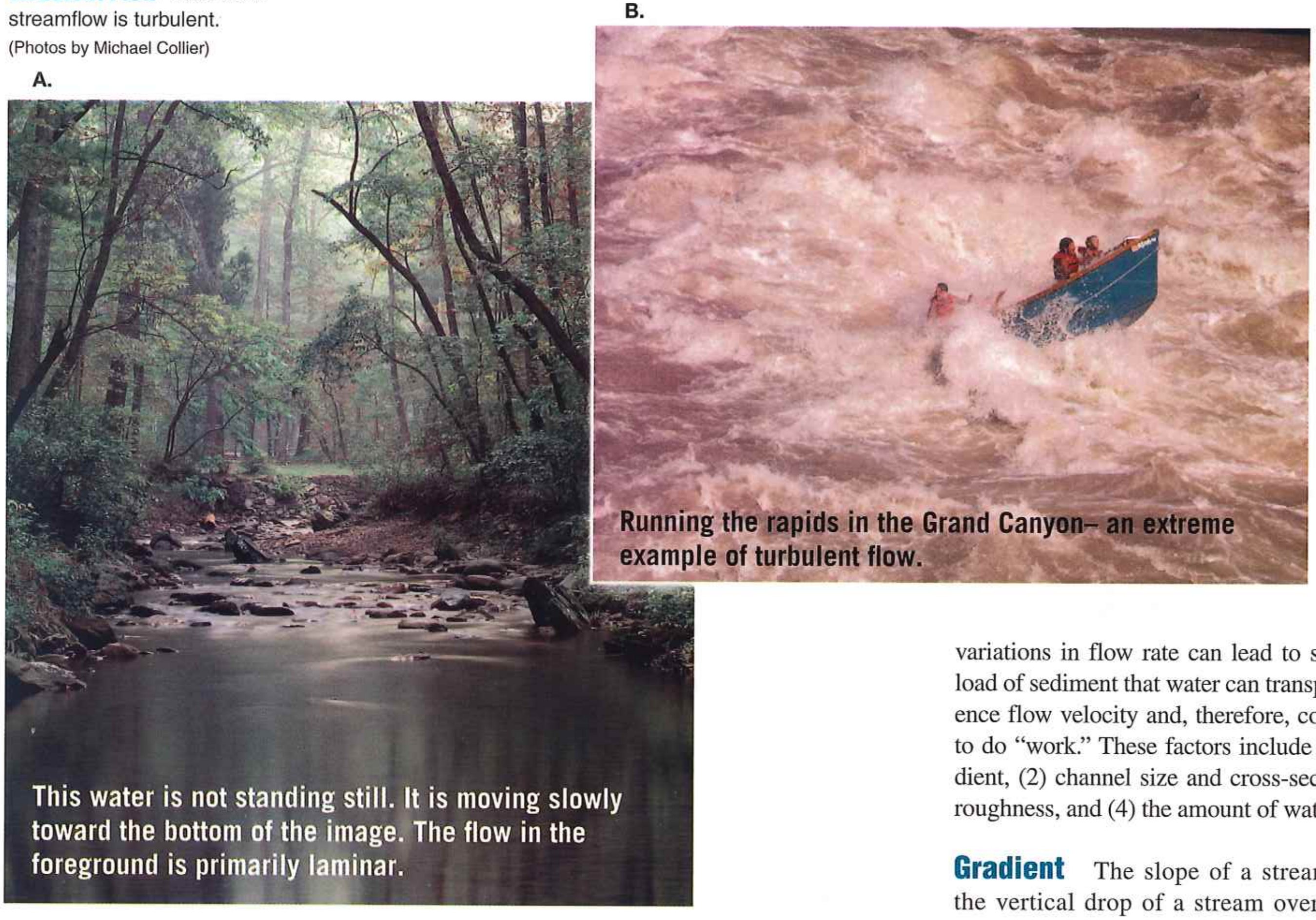
1. List several factors that influence infiltration.
2. Draw a simple sketch of a drainage basin and divide and label each.
3. What are the three main parts (zones) of a river system?
4. Prepare a sketch of the four drainage patterns discussed in this section.

5.3 STREAMFLOW

Discuss streamflow and the factors that cause it to change.

Water may flow in one of two ways, either as **laminar flow** or **turbulent flow**. In slow-moving streams, the flow is often laminar, which means that the water moves in roughly straight-line paths that parallel the stream channel. However, streamflow is usually turbulent, with the water moving in an erratic fashion that can be characterized as a swirling motion. Strong, turbulent flow may be seen in whirlpools and eddies, as well as rolling whitewater rapids (**FIGURE 5.7**). Even streams that appear smooth on the surface often exhibit turbulent flow near the bottom and sides of the channel. Turbulence contributes to a stream's ability to erode its channel because it acts to lift sediment from the streambed.

FIGURE 5.7 Laminar and Turbulent Flow Most often streamflow is turbulent. (Photos by Michael Collier)



Running the rapids in the Grand Canyon– an extreme example of turbulent flow.

This water is not standing still. It is moving slowly toward the bottom of the image. The flow in the foreground is primarily laminar.

An important factor influencing stream turbulence is the water's flow velocity. As the velocity of a stream increases, the flow becomes more turbulent. Flow velocities can vary significantly from place to place along a stream, as well as over time, in response to variations in the amount and intensity of precipitation. If you have ever waded into a stream, you may have noticed that the strength of the current increased as you moved into deeper parts of the channel. This is related to the fact that frictional resistance is greatest near the banks and bed of the stream channel.

Factors Affecting Flow Velocity

The ability of a stream to erode and transport material is directly related to its flow velocity. Even slight variations in flow rate can lead to significant changes in the load of sediment that water can transport. Several factors influence flow velocity and, therefore, control a stream's potential to do "work." These factors include (1) channel slope or gradient, (2) channel size and cross-sectional shape, (3) channel roughness, and (4) the amount of water flowing in the channel.

Gradient The slope of a stream channel expressed as the vertical drop of a stream over a specified distance is the **gradient**. Portions of the lower Mississippi River have very low gradients of 10 centimeters per kilometer or less. By contrast, some mountain stream channels decrease in elevation at a rate of more than 40 meters per kilometer, a gradient 400 times steeper than the lower Mississippi. Gradient varies not only among different streams but also over a particular stream's length. The steeper the gradient, the more energy available for streamflow. If two streams were identical in every respect except gradient, the stream with the higher gradient would have the greater velocity.

Channel Shape, Size, and Roughness A stream's channel is a conduit that guides the flow of water, but the water encounters friction as it flows. The shape, size, and roughness of the channel affect the amount of friction. Larger channels have more efficient flow because a smaller proportion of water is in contact with the channel. A smooth channel promotes a more uniform flow, whereas an irregular channel filled with boulders creates enough turbulence to slow the stream significantly.

Discharge Streams vary in size from small headwater creeks less than 1 meter wide to large rivers as wide as several kilometers. The size of a stream channel is largely determined by the amount of water supplied from the drainage basin. The measure most often used to compare the sizes of streams is **discharge**—the volume of water flowing past a certain point in a given unit of time. Discharge, usually measured in cubic meters per second or cubic feet per second, is determined by multiplying a stream's cross-sectional area by its velocity.

The largest river in North America, the Mississippi, discharges an average of 17,300 cubic meters (611,000 cubic feet) per second. Although this is a huge quantity of water, it is dwarfed by the mighty Amazon in South America, the world's largest river. Fed by a vast rainy region that is nearly three-fourths the size of the conterminous United States, the Amazon discharges 12 times more water than the Mississippi.

The discharges of most rivers are far from constant. This is true because of variables such as rainfall and snowmelt. In areas with seasonal variations in precipitation, streamflow will tend to be highest during the wet season or during spring snowmelt, and it will be lowest during the dry season or during periods when high temperatures increase water losses through evaporation. However, not all channels maintain a continuous flow of water. Streams that exhibit flow only during wet periods are referred to as *intermittent streams.* In arid climates, many streams carry water only occasionally, after a heavy rainstorm, and are called *ephemeral streams.*

Changes from Upstream to Downstream

One useful way of studying a stream is to examine its **longitudinal profile**. Such a profile is simply a cross-sectional view of a stream from its source area (called the *head* or *headwaters*) to its *mouth*, the point downstream where it empties into another water body—a river, a lake, or an ocean. As shown in **FIGURE 5.8**, the most obvious feature of a typical longitudinal profile is its concave shape—a result of the decrease in slope that occurs from the headwaters to the mouth. In addition, local irregularities exist in the profiles of most streams; the flatter sections may be associated with lakes or reservoirs, and the steeper sections are sites of rapids or waterfalls.

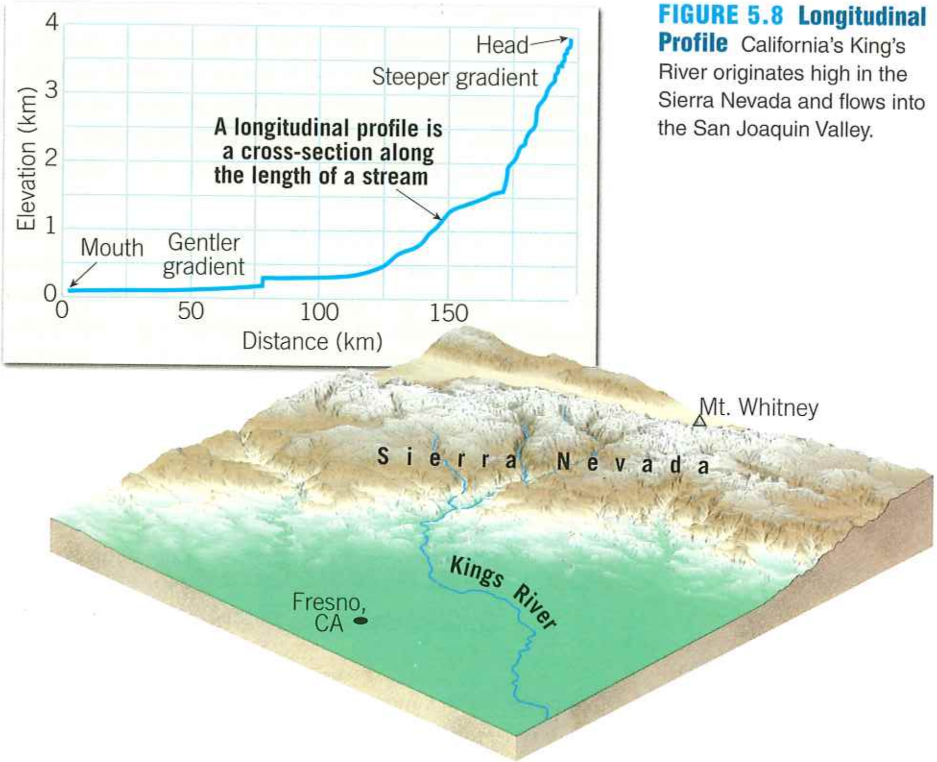
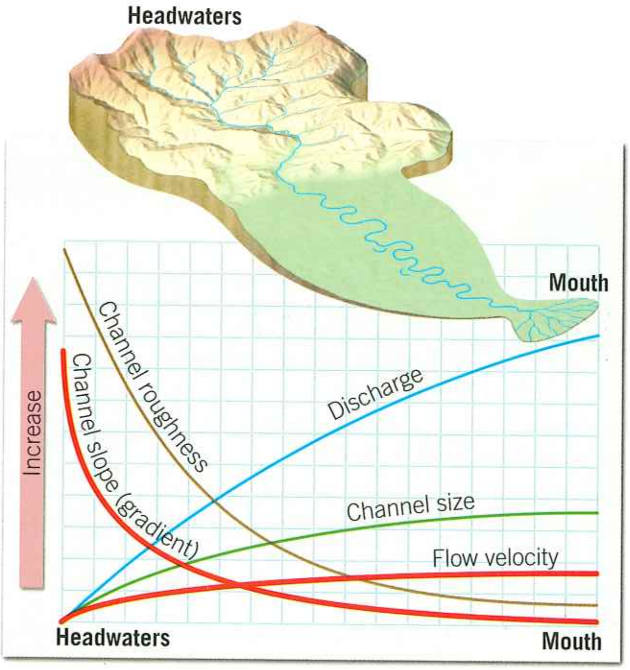


FIGURE 5.8 Longitudinal Profile California's King's River originates high in the Sierra Nevada and flows into the San Joaquin Valley.

The change in slope observed on most stream profiles is usually accompanied by an increase in discharge and channel size, as well as a reduction in sediment particle size (**FIGURE 5.9**). For example, data from successive gaging



SmartFigure 5.9 Channel Changes from Head to Mouth Although the gradient decreases toward the mouth, increases in discharge and channel size and decreases in roughness more than offset the decrease in slope. Consequently, flow velocity usually increases toward the mouth.

stations along most rivers show that, in humid regions, discharge increases toward the mouth. This should come as no surprise because, as we move downstream, more and more tributaries contribute water to the main channel. In the case of the Amazon, for example, about 1000 tributaries join the main river along its 6500-kilometer (more than 4000-mile) course across South America.

In order to accommodate the growing volume of water, channel size typically increases downstream as well. Recall that flow velocities are higher in large channels than in small channels. Furthermore, observations show a general decline in sediment size downstream, making the channel smoother and more efficient.

Although the gradient decreases toward a stream's mouth, the flow velocity generally increases. This fact contradicts our intuitive assumptions of swift, narrow headwater streams and wide, placid rivers flowing across more subtle topography. Increases in channel size and discharge, and decreases in channel roughness that occur downstream, compensate for the decrease in slope—thereby making the stream more efficient.

5.3 CONCEPT CHECKS

1. Contrast laminar flow and turbulent flow.
2. Summarize the factors that influence flow velocity.
3. What is a longitudinal profile?
4. What typically happens to channel width, channel depth, flow velocity, and discharge between the head and mouth of a stream? Briefly explain why these changes occur.

5.4 THE WORK OF RUNNING WATER

Outline the ways in which streams erode, transport, and deposit sediment.

Streams are Earth's most important erosional agents. Not only do they have the ability to downcut and widen their channels, but streams also have the capacity to transport the enormous quantities of sediment that are delivered to the stream by sheetflow, mass wasting, and groundwater. Eventually much of this material is deposited to create a variety of landforms.

Stream Erosion

A stream's ability to accumulate and transport soil and weathered rock is aided by the work of raindrops, which knock sediment particles loose (see Figure 4.19, page 112). When the ground is saturated, rainwater cannot infiltrate, so it flows downslope, transporting some of the material it has dislodged. On barren slopes the sheetflow will often erode small channels, or *rills*, which in time may evolve into larger *gullies* (see Figure 4.20 on page 112).

Once flow is confined in a channel, the erosional power of a stream is related to its slope and discharge. When the flow of water is sufficiently strong, it can dislodge particles from the channel and lift them into the moving water. In this manner, the force of running water swiftly erodes poorly consolidated materials on the bed and sides of a stream channel. On occasion, the banks of the channel may be undercut, dumping even more loose debris into the water to be carried downstream.

In addition to eroding unconsolidated materials, the hydraulic force of streamflow can also cut a channel into solid bedrock. A stream's ability to erode bedrock is greatly enhanced by the particles it carries. These particles can be any size, from large boulders in very fast-flowing waters to sand and gravel-size particles in somewhat slower flow. Just as the particles of grit on sandpaper can wear away a piece of wood, so too can the sand and gravel carried by a stream abrade a bedrock channel. Moreover, pebbles caught

EYE ON EARTH

The White River in Arkansas is a tributary of the Mississippi River. As you can see in this aerial image, this part of the river has many twists and turns called meanders. There is more about meanders later in the chapter.

QUESTION 1 *The color of the White River is brown. What part of the stream's load gives it this color?*

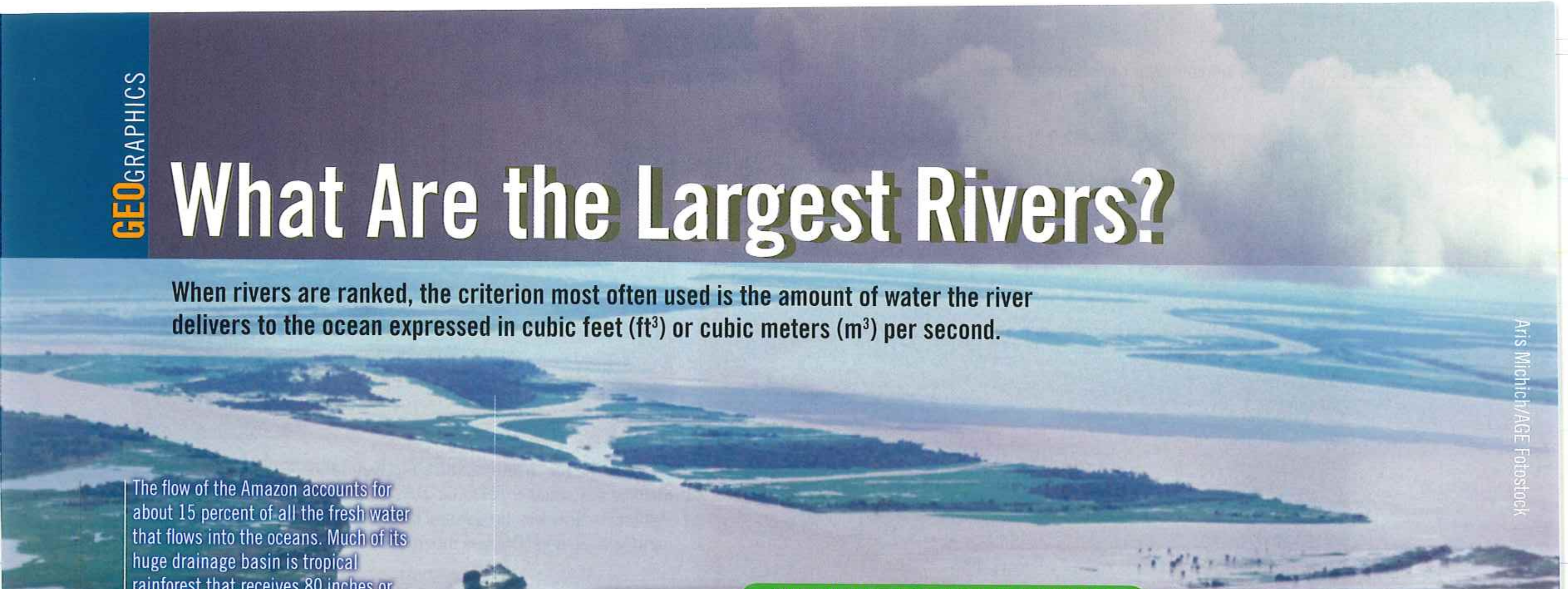
QUESTION 2 *If a channel were created across the narrow neck of land shown by the arrow, how would the river's gradient change?*

QUESTION 3 *How would the flow velocity be affected by the formation of such a channel?*

Michael Collier

What Are the Largest Rivers?

When rivers are ranked, the criterion most often used is the amount of water the river delivers to the ocean expressed in cubic feet (ft^3) or cubic meters (m^3) per second.



Aris Michich/AGE Fotostock

The flow of the Amazon accounts for about 15 percent of all the fresh water that flows into the oceans. Much of its huge drainage basin is tropical rainforest that receives 80 inches or more of rainfall each year.

WORLD'S 10 LARGEST RIVERS

The size of the drainage basin and the amount of rainfall it receives are the primary factors influencing discharge.

The drainage basin of the "Mighty Mississippi" covers about 40 percent of the lower 48 states and includes all or parts of 31 states and 2 Canadian provinces. The discharge of North America's largest river is just one-twelfth that of the Amazon.

LARGEST U.S. RIVERS

RANK	RIVER	DRAINAGE BASIN (1000 mi^2)	AVERAGE DISCHARGE AT MOUTH (1000 ft^3/sec)
1	Mississippi	1,150	593
2	St. Lawrence	396	348
3	Ohio	203	281
4	Columbia	258	265
5	Yukon	328	225
6	Missouri	529	76
7	Tennessee	41	68

Guido Alberto Rossi/AGE Fotostock

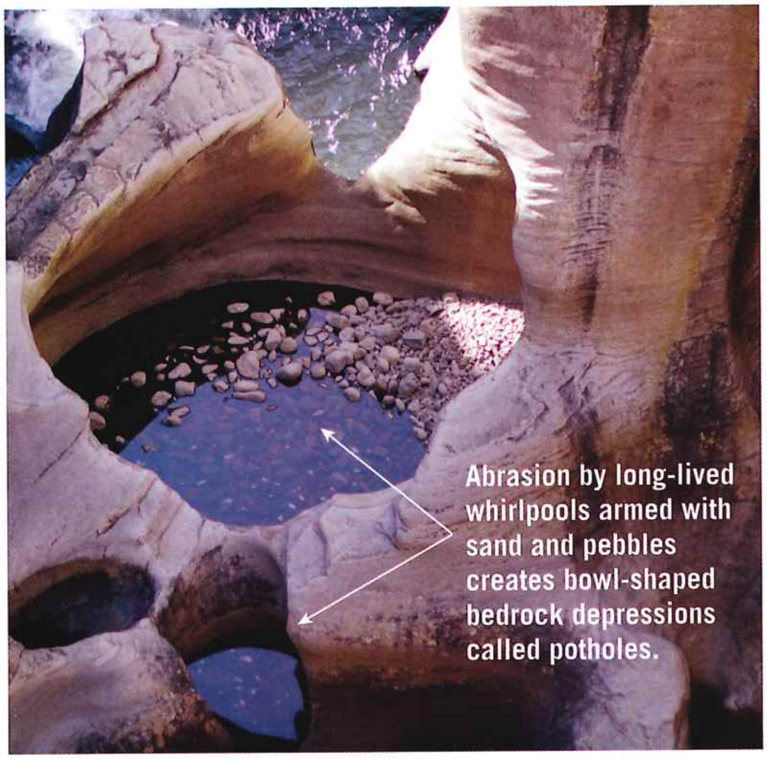


FIGURE 5.10 Potholes The rotational motion of swirling pebbles acts like a drill, creating potholes. (Photo by Elmari Joubert/Alamy)

in swirling eddies can act like "drills" and bore circular **potholes** into the channel floor (**FIGURE 5.10**).

Transportation of Sediment

All streams, regardless of size, transport some weathered rock material (**FIGURE 5.11**). Streams also sort the solid sediment they transport because finer, lighter material is carried more readily than larger, heavier particles. Streams transport their load of sediment in three ways: (1) in solution (**dissolved load**), (2) in suspension (**suspended load**), and (3) sliding or rolling along the bottom (**bed load**).

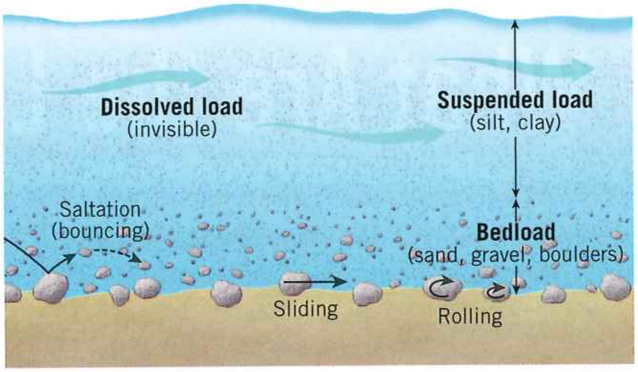


FIGURE 5.11 Transportation of Sediment Streams transport their load of sediment in three ways. The dissolved and suspended loads are carried in the general flow. The bed load includes coarse sand, gravel, and boulders that move by rolling, sliding, and saltation.

Dissolved Load

Most of the dissolved load is brought to a stream by groundwater and is dispersed throughout the flow. When water percolates through the ground, it acquires soluble soil compounds. Then it seeps through cracks and pores in bedrock, dissolving additional mineral matter. Eventually much of this mineral-rich water finds its way into streams.

The velocity of streamflow has essentially no effect on a stream's ability to carry its dissolved load; material in the solution goes wherever the stream goes. Precipitation of the dissolved mineral matter occurs when the chemistry of the water changes, when organisms create hard parts, or when the water enters an inland "sea," located in an arid climate where the rate of evaporation is high.

Suspended Load

Most streams carry the largest part of their load in *suspension*. Indeed, the muddy appearance created by suspended sediment is the most obvious portion of a stream's load (**FIGURE 5.12**). Usually only fine particles consisting of silt and clay can be carried this way, but during a flood, larger particles are transported as well. During a flood, the total quantity of material carried in suspension increases dramatically, as people whose homes have been sites for the deposition of this material can attest.

The type and amount of material carried in suspension are controlled by two factors: the flow velocity and the settling velocity of each sediment grain. **Settling velocity** is defined as the speed at which a particle falls through a still fluid. The larger the particle, the more rapidly it settles toward the stream bed. In addition to size, the shape and

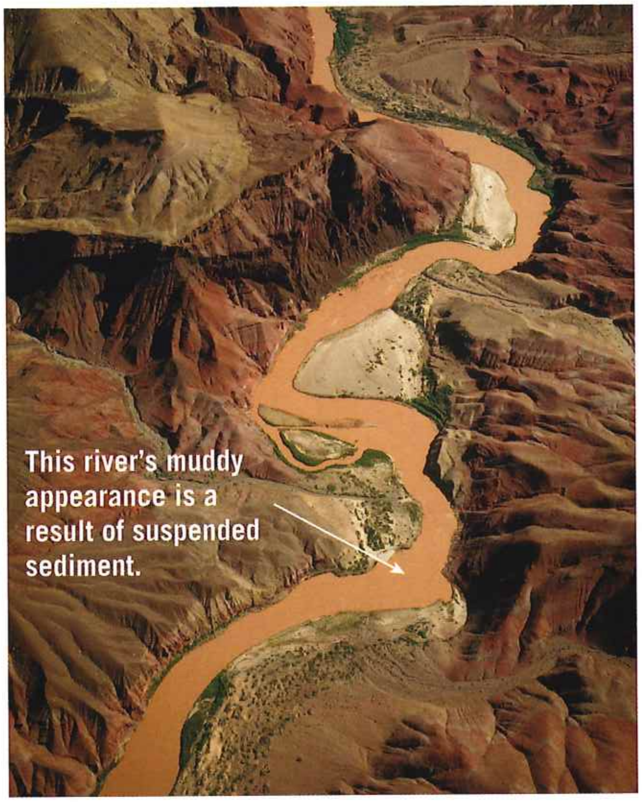


FIGURE 5.12 Suspended Load An aerial view of the Colorado River in the Grand Canyon. Heavy rains washed sediment into the river. (Photo by Michael Collier)

specific gravity of particles also influence settling velocity. Flat grains sink through water more slowly than do spherical grains, and dense particles fall toward the bottom more rapidly than do less dense particles. The slower the settling velocity and the higher the flow velocity, the longer a sediment particle will stay in suspension, and the farther it will be carried downstream.

Bed Load A portion of a stream's load of solid material consists of sediment that is too large to be carried in suspension. These coarser particles move along the bottom (bed) of the stream and constitute the *bed load*. In terms of the erosional work accomplished by a downcutting stream, the grinding action of the bed load is of great importance.

The particles that make up the bed load move by rolling, sliding, and saltation. Sediment moving by **saltation** (*saltare* = to leap) appears to jump or skip along the stream bed. This occurs as particles are propelled upward by collisions or lifted by the current and then carried downstream a short distance until gravity pulls them back to the bed of the stream. Particles that are too large or heavy to move by saltation either roll or slide along the bottom, depending on their shapes.

Compared with the movement of suspended load, the movement of bed load through a stream network tends to be less rapid and more localized. A study conducted on a glacially fed river in Norway determined that suspended sediments took only a day to exit the drainage basin, while the bed load required several decades to travel the same distance. Depending on the discharge and slope of the channel, coarse gravels may only be moved during times of high flow, while boulders move only during exceptional floods. Once set in motion, large particles are usually carried short distances. Along some stretches of a stream, bed load cannot be carried at all until it is broken into smaller particles.

Competence and Capacity A stream's ability to carry solid particles is described using two criteria: *capacity* and *competence*. **Capacity** is the maximum load of solid particles a stream can transport per unit of time. The greater the discharge, the greater the stream's capacity for hauling sediment. Consequently, large rivers with high flow velocities have large capacities.

Competence is a measure of a stream's ability to transport particles based on size rather than quantity. Flow velocity is the key: Swift streams have greater competencies than slow streams, regardless of channel size. A stream's competence increases proportionately to the square of its velocity. Thus, if the velocity of a stream doubles, the impact force of the water increases four times; if the velocity triples, the force increases nine times, and so forth. Hence, large boulders that are often visible during low water and seem immovable can, in fact, be transported during exceptional floods because of the stream's increased competence.

By now it should be clear why the greatest erosion and transportation of sediment occur during floods. The increase in discharge results in greater capacity, and the increased velocity produces greater competency. Rising velocity makes the water more turbulent, and larger particles are set in motion. In just a few days, or perhaps a few hours, a stream at flood stage can erode and transport more sediment than it does during many months of normal flow.

Deposition of Sediment

Deposition occurs whenever a stream slows, causing a reduction in competence. Put another way, particles are deposited when flow velocity is less than the settling velocity; as a stream's flow velocity decreases, sediment begins to settle, largest particles first. In this manner, stream transport provides a mechanism by which solid particles of various sizes are separated. This process, called **sorting**, explains why particles of similar size are deposited together.

The general term for sediment deposited by streams is **alluvium**. Many different depositional features are composed of alluvium. Some occur within stream channels, some occur on the valley floor adjacent to a channel, and some are found at the mouth of a stream. We will consider the nature of these features later in the chapter.

5.4 CONCEPT CHECKS

1. List two ways in which streams erode their channels.
2. In what three ways does a stream transport its load? Which part of the load moves slowest?
3. What is the difference between capacity and competency?
4. What is settling velocity? What factors influence settling velocity?

5.5 STREAM CHANNELS

Contrast bedrock and alluvial stream channels. Distinguish between two types of alluvial channels.

A basic characteristic of streamflow that distinguishes it from sheetflow is that it is usually confined to a channel. A stream channel can be thought of as an open conduit that consists of the streambed and banks that act to confine the flow, except during floods.

Although somewhat oversimplified, we can divide stream channels into two types. *Bedrock channels* are those in which the streams are actively cutting into solid rock. In contrast, when the bed and banks are composed mainly of unconsolidated sediment or alluvium, the channel is called an *alluvial channel*.

Bedrock Channels

As the name suggests, bedrock channels are cut into the underlying strata and typically form in the headwaters of river systems where streams have steep slopes. The energetic flow tends to transport coarse particles that actively abrade the bedrock channel. Potholes are often visible evidence of the erosional forces at work.

Steep bedrock channels often develop a sequence of *steps* and *pools*. Steps are steep segments where bedrock is exposed. These steep areas contain rapids or, occasionally, waterfalls. Pools are relatively flat segments where alluvium tends to accumulate.

The channel pattern exhibited by streams cutting into bedrock is controlled by the underlying geologic structure. Even when flowing over rather uniform bedrock, streams tend to exhibit winding or irregular patterns rather than flowing in straight channels. Anyone who has gone white-water rafting has observed the steep, winding nature of a stream flowing in a bedrock channel.

Alluvial Channels

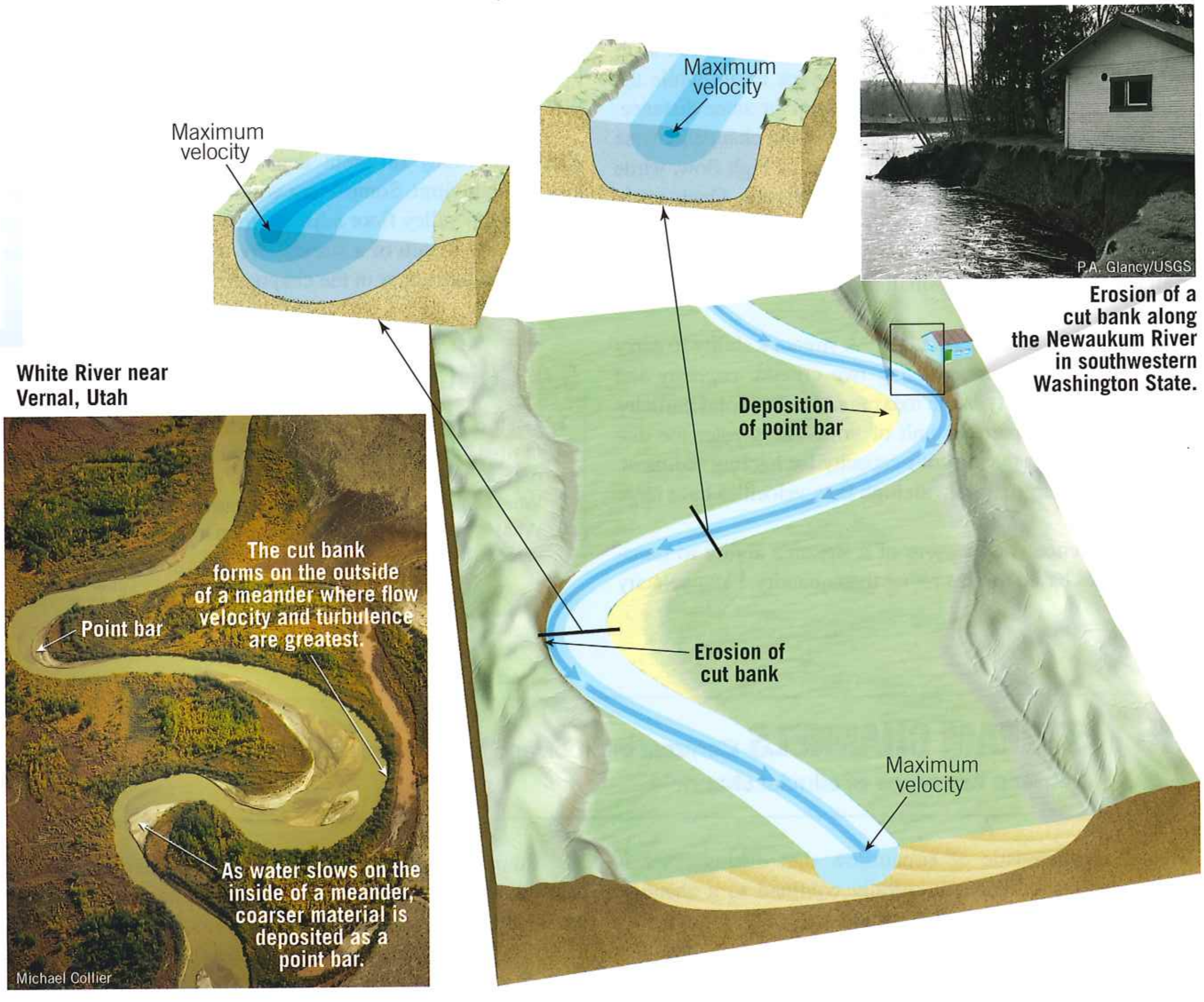
Many stream channels are composed of loosely consolidated sediment (alluvium) and therefore can undergo significant changes in shape because the sediments are continually being eroded, transported, and redeposited. The major factors affecting the shapes of these channels are the average size of the sediment being transported, the channel gradient, and the discharge.

Alluvial channel patterns reflect a stream's ability to transport its load at a uniform rate, while expending the least amount of energy. Thus, the size and type of sediment being carried help determine the nature of the stream channel. Two common types of alluvial channels are *meandering channels* and *braided channels*.

Meandering Streams

Streams that transport much of their load in suspension generally move in sweeping bends called **meanders**. These streams flow in relatively deep, smooth channels and transport mainly mud (silt and clay), sand, and occasionally fine gravel. The lower Mississippi River exhibits a channel of this type.

Meandering channels evolve over time as individual meanders migrate across the floodplain. Most of the erosion is focused at the outside of the meander, where velocity and turbulence are greatest. In time, the outside bank is undermined, especially during periods of high water. Because the outside of a meander is a zone



White River near Vernal, Utah

Erosion of a cut bank along the Newaukum River in southwestern Washington State.

SmartFigure 5.13 Formation of Cut Banks and Point Bars By eroding its outer bank and depositing material on the inside of the bend, a stream is able to shift its channel.

of active erosion, it is often referred to as the **cut bank** (**FIGURE 5.13**). Debris acquired by the stream at the cut bank moves downstream, where the coarser material is generally deposited as **point bars** on the insides of meanders. In this manner, meanders migrate laterally by eroding the outside of the bends and depositing sediment on the inside without appreciably changing their shape.

In addition to migrating laterally, the bends in a channel also migrate down the valley. This occurs because erosion is more effective on the downstream (downslope) side of the meander. Sometimes the downstream migration of a meander is slowed when it reaches a more resistant bank material. This allows the next meander upstream to gradually erode the material between the two meanders, as shown in **FIGURE 5.14**. Eventually, the river may erode through the narrow neck of land, forming a new, shorter channel segment called a **cutoff**. Because of its shape, the abandoned bend is called an **oxbow lake**.

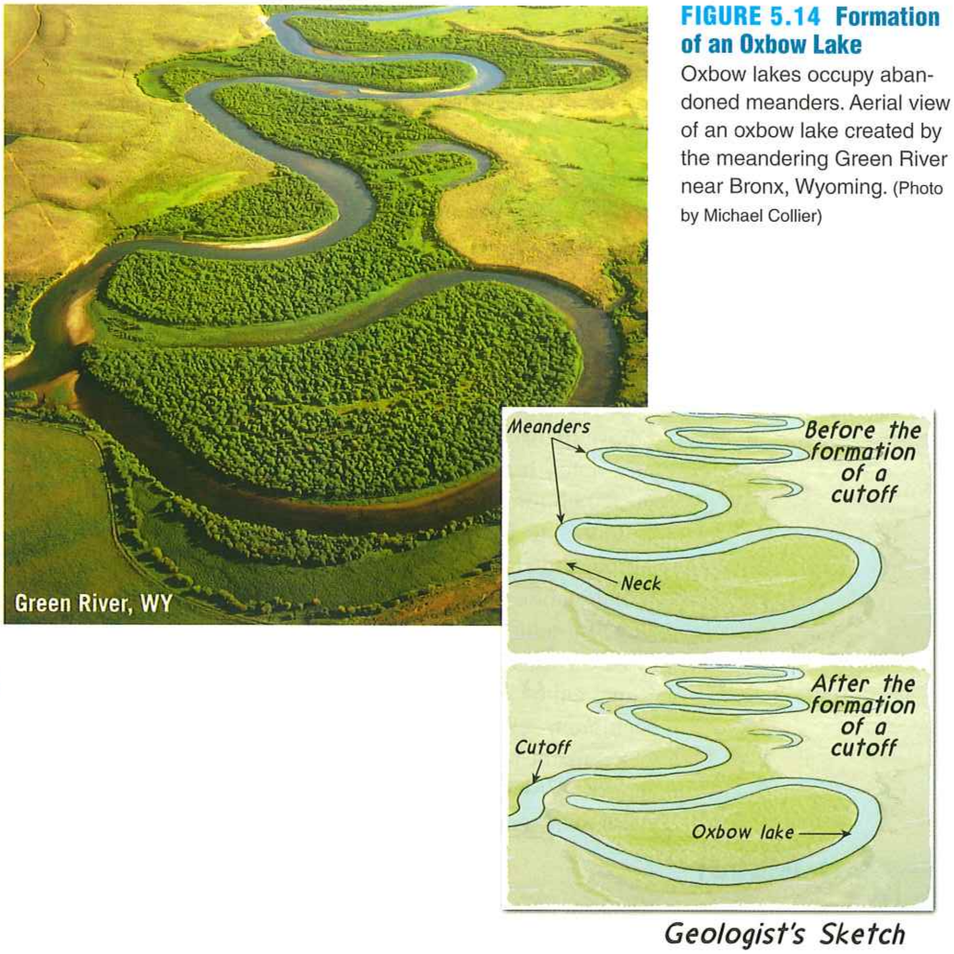


FIGURE 5.14 Formation of an Oxbow Lake Oxbow lakes occupy abandoned meanders. Aerial view of an oxbow lake created by the meandering Green River near Bronx, Wyoming. (Photo by Michael Collier)

Braided Streams Some streams consist of a complex network of converging and diverging channels that thread their way among numerous islands or gravel bars (**FIGURE 5.15**). Because these channels have an interwoven appearance, these streams are said to be **braided channels**. Braided channels form where a large proportion of the stream's load consists of coarse material (sand and gravel) and the stream has a highly variable discharge. Because the bank material is readily erodible, braided channels are wide and shallow.

One setting in which braided streams form is at the end of a glacier where there is a large seasonal variation in discharge. During the summer, large amounts of ice-eroded sediment are dumped into the meltwater streams flowing away from the glacier. However, when flow is sluggish, the stream is unable to move all the sediment and therefore deposits the coarsest material as bars that force the flow to split and follow several paths. Usually the laterally shifting channels completely rework most of the surface sediments each year, thereby transforming the entire streambed. In some braided streams, however, the bars have built up to form islands that are anchored by vegetation.

In summary, meandering channels develop where the load consists largely of fine-grained particles that are transported as suspended load in deep, relatively smooth channels. By contrast, wide, shallow braided channels develop where coarse-grained material is transported as bed load.

FIGURE 5.15 Braided Stream The Knik River is a classic braided stream with multiple channels separated by migrating gravel bars. The Knik is choked with sediment from four melting glaciers in the Chugach Mountains north of Anchorage, Alaska. (Photo by Michael Collier)

5.5 CONCEPT CHECKS

1. Are bedrock channels more likely to be found near the head or the mouth of a stream?
2. Describe or sketch the development of a meander, including how an oxbow lake forms.
3. Describe a situation that might cause a stream to become braided.

5.6 SHAPING STREAM VALLEYS Contrast narrow V-shaped valleys, broad valleys with floodplains, and valleys that display incised meanders.

Streams, with the aid of weathering and mass wasting, shape the landscape through which they flow. As a result, streams continuously modify the valleys they occupy.

A **stream valley** consists of not only the channel but also the surrounding terrain that directly contributes water to the stream. Thus, it includes the valley bottom, which is the lower, flatter area that is partially or totally occupied by the stream channel, and the sloping valley walls that rise above the valley bottom on both sides. Most stream valleys are much broader at the top than their channels are wide at the bottom. This would not be the case if the only agent responsible for eroding valleys were the streams flowing through them. The sides of most valleys are shaped by a combination of weathering, overland flow, and mass wasting. In some arid regions, where weathering is slow and where rock is particularly resistant, narrow valleys (sometimes called *slot canyons*) that have nearly vertical walls are common.

Stream valleys can be divided into two general types—narrow V-shaped valleys and wide valleys with flat floors, with many gradations between.

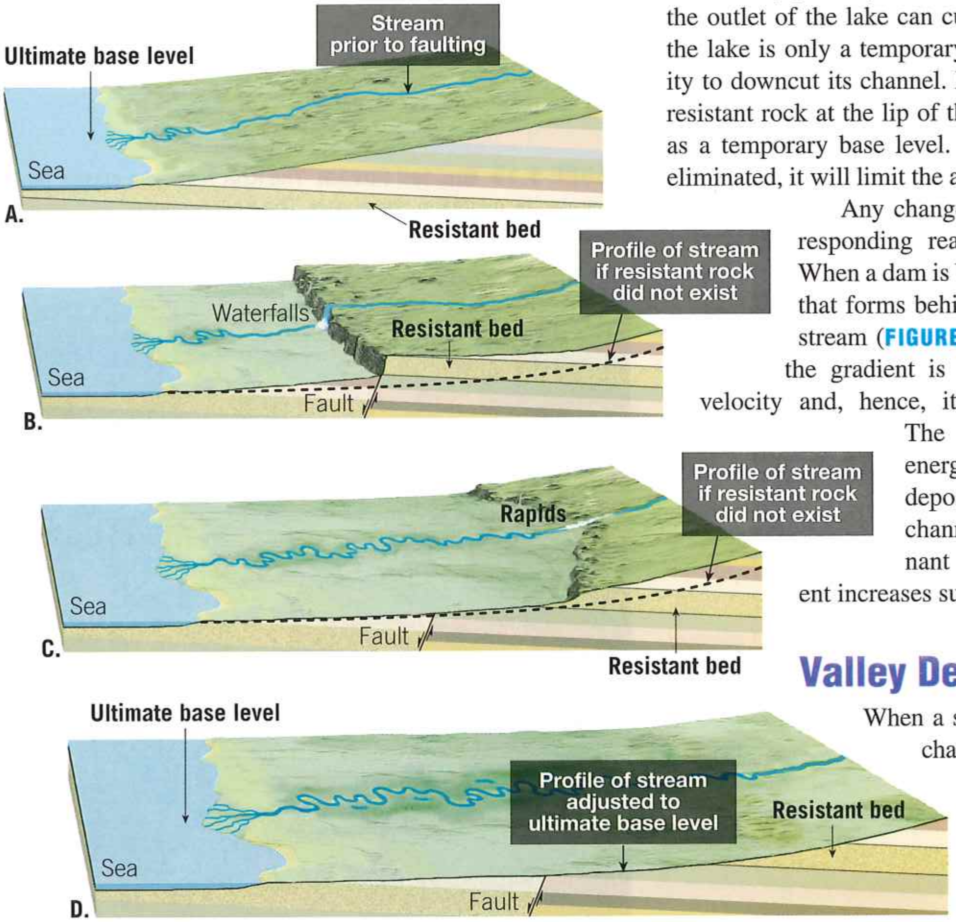


FIGURE 5.16 Temporary Base Level This series of diagrams illustrates what would happen if a fault raised a layer of resistant rock across the path of a stream. **A**. Stream course with a smooth profile prior to faulting. **B**. After faulting, the resistant layer acts as a temporary base level and forms a waterfall. Because of the steep gradient, the stream's erosive energy is focused on the resistant bed. **C**. The waterfall evolves to rapids. **D**. Eventually the river reestablishes a smooth profile.

Base Level and Stream Erosion

Streams cannot endlessly erode their channels deeper and deeper. There is a lower limit to how deep a stream can erode, and that limit is called **base level**. Although the idea is relatively straightforward, it is nevertheless a key concept in the study of stream activity. Base level is defined as the lowest elevation to which a stream can erode its channel. Essentially this is the level at which the mouth of a stream enters the ocean, a lake, or another stream. Base level accounts for the fact that most stream profiles have low gradients near their mouths, because the streams are approaching the elevation below which they cannot erode their beds.

Two general types of base level are recognized. Sea level is considered the *ultimate base level* because it is the lowest level to which stream erosion could lower the land. *Temporary*, or *local*, *base levels* include lakes, resistant layers of rock, and main streams that act as base levels for their tributaries. For example, when a stream enters a lake, its velocity quickly approaches zero, and its ability to erode ceases. Thus, the lake prevents the stream from eroding below its level at any point upstream from the lake. However, because the outlet of the lake can cut downward and drain the lake, the lake is only a temporary hindrance to the stream's ability to downcut its channel. In a similar manner, the layer of resistant rock at the lip of the waterfall in **FIGURE 5.16** acts as a temporary base level. Until the ledge of hard rock is eliminated, it will limit the amount of downcutting upstream.

Any change in base level will cause a corresponding readjustment of stream activities. When a dam is built along a stream, the reservoir that forms behind it raises the base level of the stream (**FIGURE 5.17**). Upstream from the dam the gradient is reduced, lowering the stream's velocity and, hence, its sediment-transporting ability. The stream, now having too little energy to transport its entire load, will deposit sediment. This builds up its channel. Deposition will be the dominant process until the stream's gradient increases sufficiently to transport its load.

Valley Deepening

When a stream's gradient is steep and the channel is well above base level, downcutting is the dominant activity. Abrasion caused by bed load sliding and rolling along the bottom, and the hydraulic power of fast-moving water, slowly lower the streambed. The result is usually a V-shaped valley with steep sides. A classic example of a V-shaped valley is the section of Yellowstone River shown in **FIGURE 5.18**.

The most prominent features of a V-shaped valley are *rapids* and *waterfalls*. Both occur where the stream's gradient increases significantly, a situation usually caused by variations in the erodibility of the bedrock into which a stream channel is cutting. Resistant beds create rapids by acting as a temporary base level upstream while allowing downcutting to continue downstream. In time, erosion usually eliminates the resistant rock. Waterfalls are places where the stream makes an abrupt vertical drop.

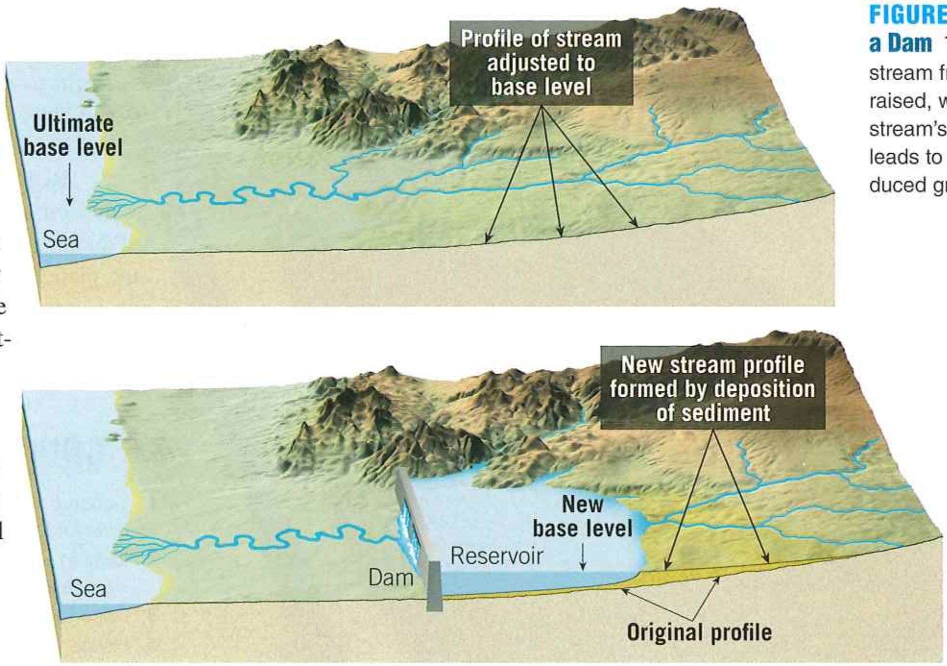


FIGURE 5.17 Building a Dam The base level upstream from the reservoir is raised, which reduces the stream's flow velocity and leads to deposition and a reduced gradient.

Valley Widening

Once a stream has cut its channel closer to base level, downward erosion becomes less dominant. At this point, the stream's channel takes on a meandering pattern, and more of the stream's energy is directed from side to side. The result is a widening of the valley as the river cuts away first at one bank and then at the other (**FIGURE 5.19**). The continuous lateral erosion caused by shifting of the stream's meanders produces an increasingly broader, flat valley floor covered with alluvium. This feature, called a **floodplain**, is appropriately named because when a river overflows its banks during flood stage, it inundates the floodplain.

Over time the floodplain will widen to the point that the stream is actively eroding the valley walls only in a few places. In fact, in large rivers such as the lower Mississippi River Valley, the distance from one valley wall to another can exceed 160 kilometers (100 miles).

Changing Base Level and Incised Meanders

We usually expect a stream with a highly meandering course to be on a floodplain in a wide valley. However, certain rivers exhibit meandering channels that flow in steep, narrow valleys. Such meanders are called **incised** (*incisum* = to cut into) **meanders** (**FIGURE 5.20**). How do such features form?

Originally, the meanders probably developed on the floodplain of a stream that was relatively near base level. Then, a change in base level caused the stream to begin downcutting. One of two events could have occurred: Either base level dropped or the land on which the river was flowing was uplifted.

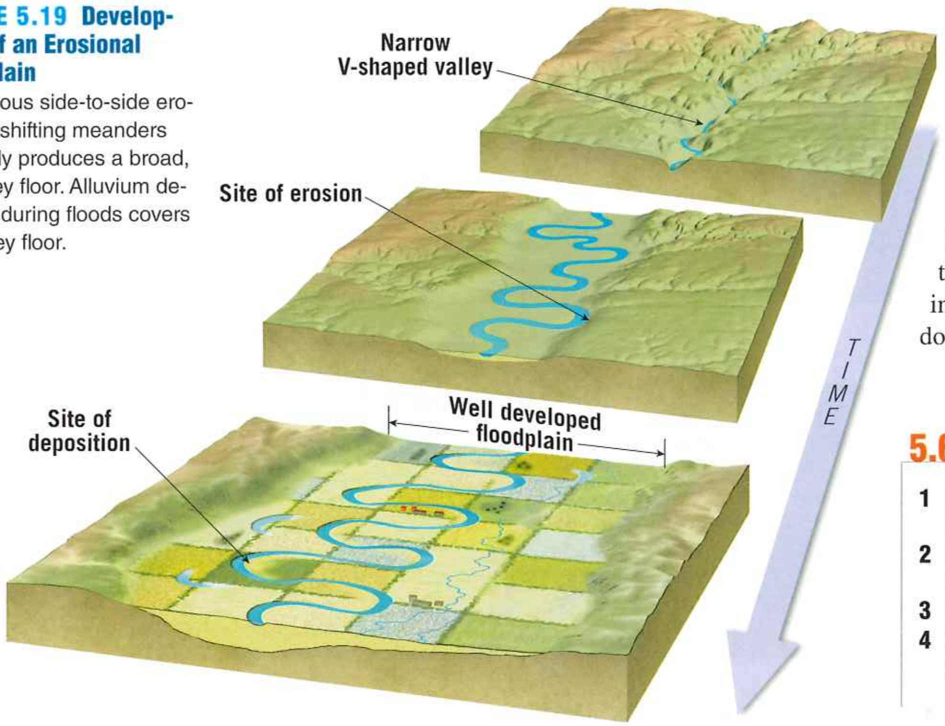
An example of the first circumstance happened during the Ice Age, when large quantities of water were withdrawn from the ocean and locked up in glaciers on land.

FIGURE 5.18 Yellowstone River The V-shaped valley, rapids, and waterfalls indicate that the river is vigorously downcutting. (Photo by Charles A. Blakeslee/AGE Fotostock)

The result was that sea level (the ultimate base level) dropped, causing rivers flowing into the ocean to begin to downcut. Of course, this activity ceased at the close of the Ice Age, when ice sheets melted and sea level rose.

Regional uplift of the land, the second cause of incised meanders, is exemplified by the Colorado Plateau in the southwestern United States. Here, as the plateau was gradually uplifted, numerous meandering rivers adjusted to being higher above base level by downcutting.

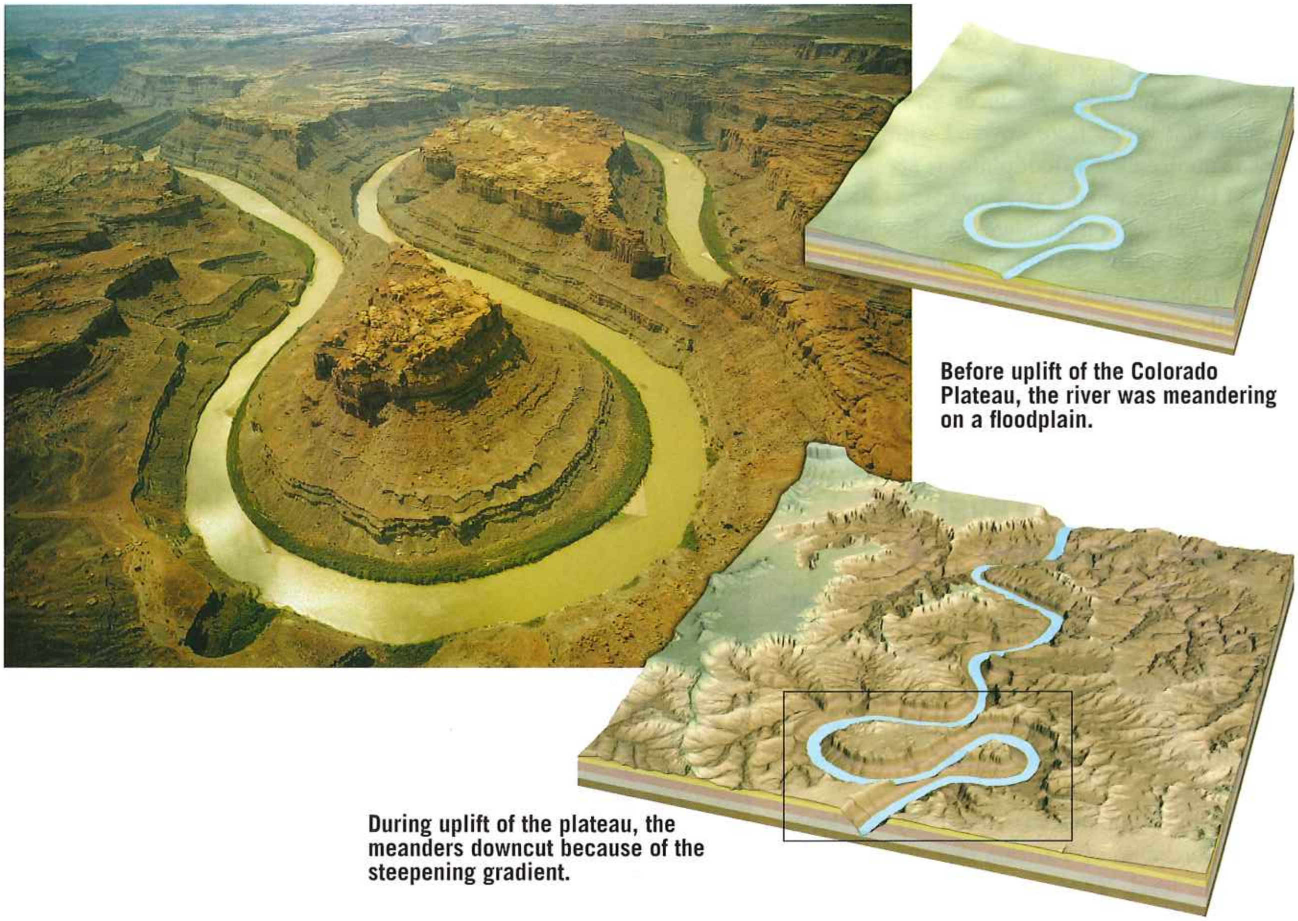
FIGURE 5.19 Development of an Erosional Floodplain Continuous side-to-side erosion by shifting meanders gradually produces a broad, flat valley floor. Alluvium deposited during floods covers the valley floor.



5.6 CONCEPT CHECKS

1 Define *base level* and distinguish between ultimate base level and temporary base level.
2 Explain why V-shaped valleys often contain rapids and waterfalls.
3 Describe or sketch how an erosional floodplain develops.
4 Relate the formation of incised meanders to changes in base level.

SmartFigure 5.20 Incised Meanders Aerial view of incised meanders of the Colorado River on the Colorado Plateau. (Photo by Michael Collier)



Before uplift of the Colorado Plateau, the river was meandering on a floodplain.

During uplift of the plateau, the meanders downcut because of the steepening gradient.

5.7 DEPOSITIONAL LANDFORMS

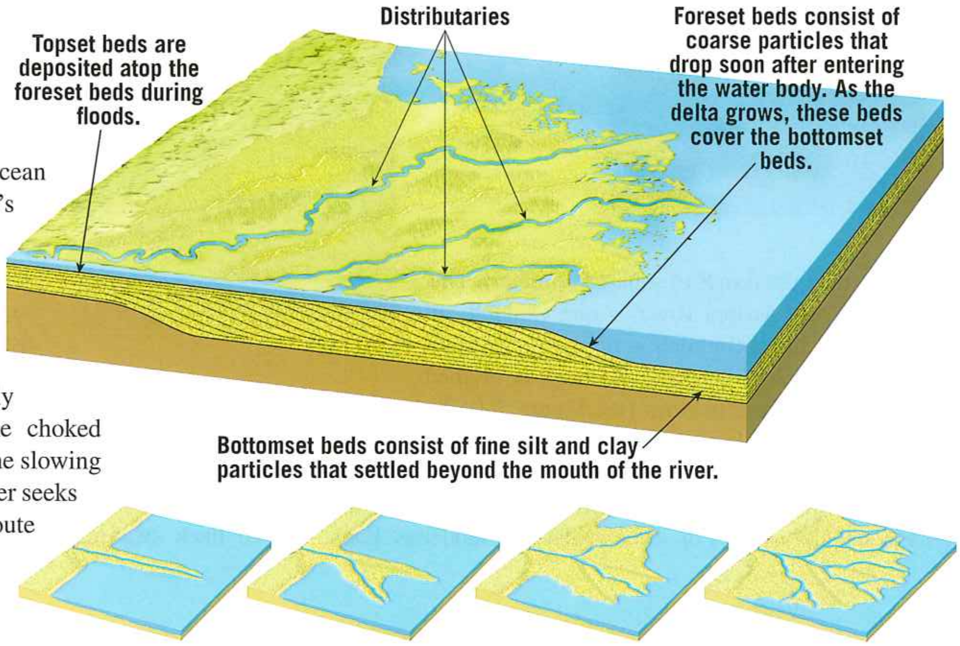
Discuss the formation of deltas, natural levees, and alluvial fans.

Recall that streams continually pick up sediment in one part of their channel and deposit it downstream. These small-scale channel deposits are most often composed of sand and gravel and are commonly referred to as **bars**. Such features, however, are only temporary because the material will be picked up again and eventually carried to the ocean. In addition to sand and gravel bars, streams also create other depositional features that have a somewhat longer life span. These include *deltas*, *natural levees*, and *alluvial fans*.

Deltas

A **delta** forms where a sediment-charged stream enters the relatively still waters of a lake, an inland sea, or the ocean (**FIGURE 5.21**). As the stream's forward motion slows, sediments are deposited by the dying current. As the delta grows outward, the stream's gradient continually lessens. This circumstance eventually causes the channel to become choked with sediment deposited from the slowing water. As a consequence, the river seeks a shorter, higher-gradient route to base level, as illustrated in Figure 5.21. This illustration shows the main channel dividing into several smaller ones, called **distributaries**. Most deltas are characterized by these shifting channels that act in an opposite way to that of tributaries.

Rather than carry water into the main channel, distributaries carry water away from the main channel. After numerous shifts of the channel, a delta may grow into a roughly triangular shape like the Greek letter delta (Δ), for which it is named. Note, however, that many deltas do not exhibit the idealized shape. Differences in the configurations of shorelines and variations in the nature and strength of wave activity result in many shapes. Many large rivers have deltas



As the stream extends its channel, the gradient is reduced. During flood stage some of the flow is diverted to a shorter, higher-gradient route forming a new distributary.

FIGURE 5.21 Formation of a Simple Delta Structure and growth of a simple delta that forms in relatively quiet waters.

EYE ON EARTH

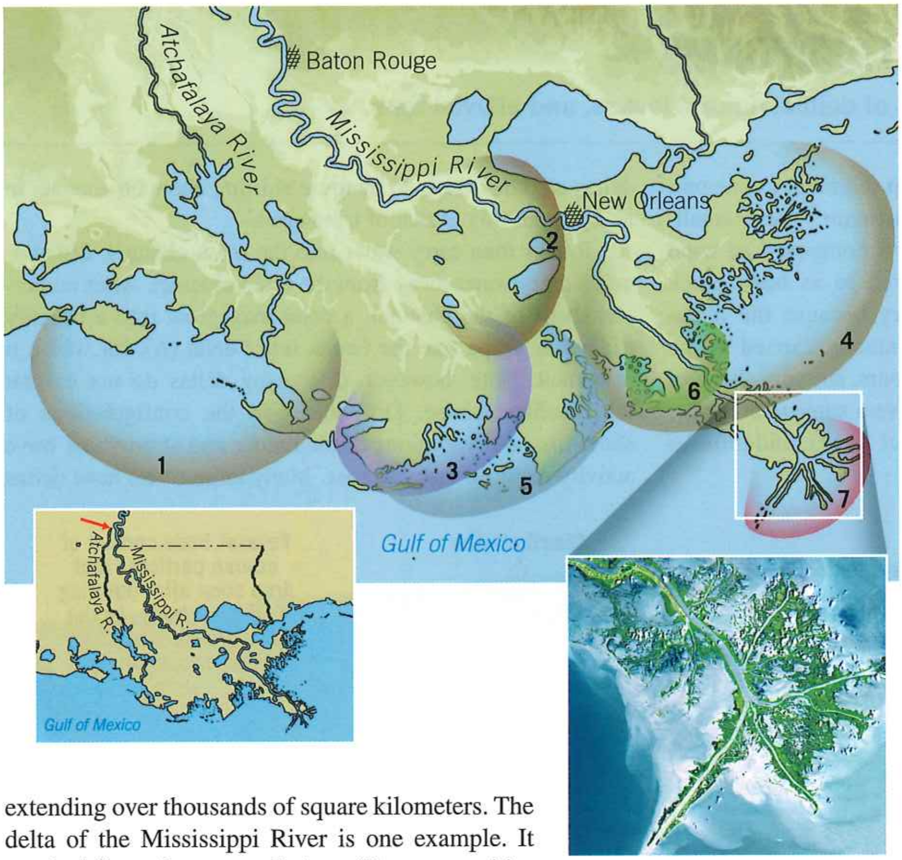
This satellite image shows the delta of the Yukon River. The river originates in northern British Columbia. It flows through the Yukon Territory and across the tundra of Alaska before entering the Bering Sea, a distance of nearly 3200 kilometers (about 2000 miles).

QUESTION 1 *Explain why the river breaks into numerous channels as it crosses the delta.*

QUESTION 2 *What term is applied to the channels that radiate across the delta?*

QUESTION 3 *Notice the cloud of sediment in the water surrounding the delta. Are these sediments more likely sand and gravel or silt and clay? Explain.*

FIGURE 5.22 Growth of the Mississippi River Delta During the past 6000 years, the river has built a series of seven coalescing subdeltas. The numbers indicate the order in which the subdeltas were deposited. The present bird-foot delta (number 7) represents the activity of the past 500 years. The left inset shows the point where the Mississippi may sometime break through (arrow) and the shorter path it would take to the Gulf of Mexico. (Image courtesy of JPL/Cal Tech/NASA)



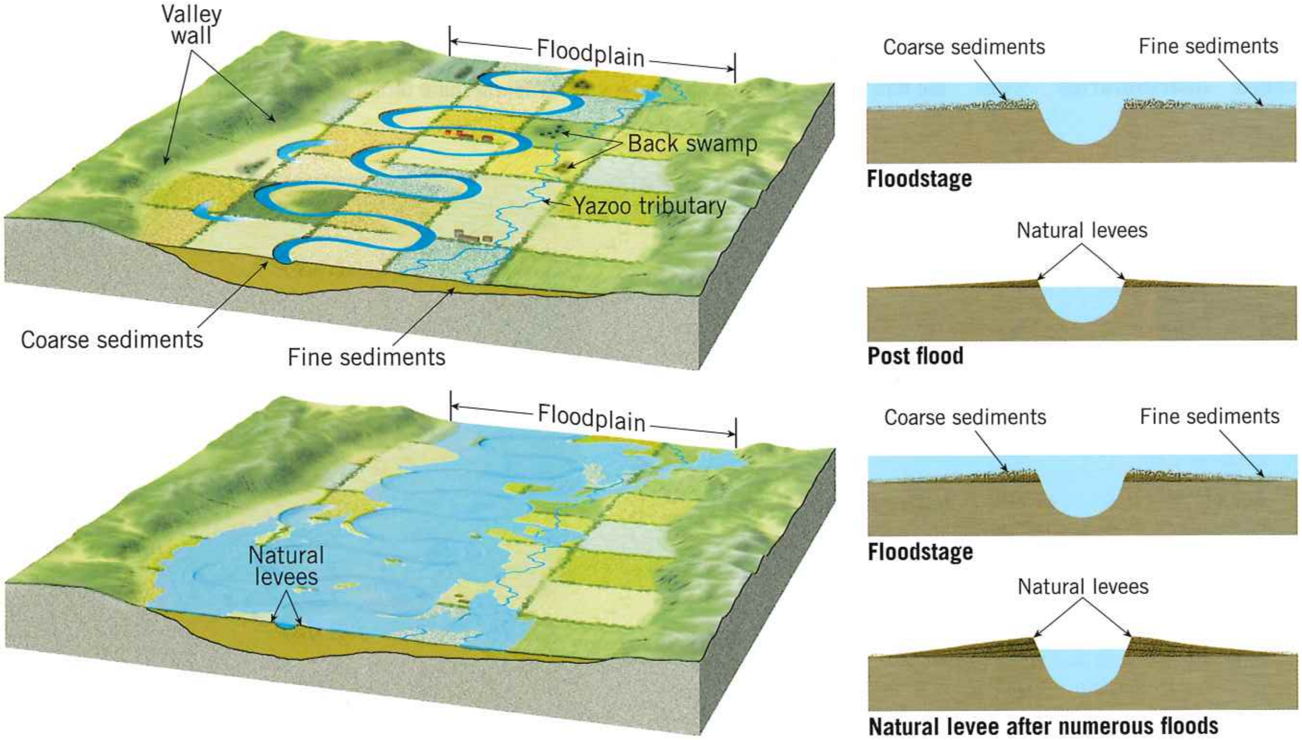
extending over thousands of square kilometers. The delta of the Mississippi River is one example. It resulted from the accumulation of huge quantities of sediment derived from the vast region drained by the river and its tributaries (see Figure 5.4). Today, New Orleans rests where there was ocean less than 5000 years ago. **FIGURE 5.22** shows that portion of the Mississippi delta that has been built over the past 6000 years. As you can see, the delta is actually a series of seven coalescing subdeltas. Each formed when the river left its existing channel in favor of a shorter, more direct path to the Gulf of Mexico. The individual subdeltas interfinger and partially cover one another, producing a very complex structure. The present subdelta, called a *bird-foot* delta because of the configuration of its distributaries, has been built by the Mississippi in the past 500 years.

Natural Levees

Some rivers occupy valleys with broad floodplains and build **natural levees** that parallel their channels on both banks (**FIGURE 5.23**). Natural levees are built by successive floods over many years. When a stream overflows its banks, its velocity immediately diminishes, leaving coarse sediment deposited in strips bordering the channel. As the water spreads out over the valley, a lesser amount of fine sediment is deposited over the valley floor. This uneven distribution of material produces the very gentle slope of the natural levee.

The natural levees of the lower Mississippi rise 6 meters (20 feet) above the floodplain. The area behind the levee is characteristically poorly drained for the obvious reason that water cannot flow up the levee and into the river. Marshes called **back swamps** result. A tributary stream that cannot

FIGURE 5.23 Formation of a Natural Levee These gently sloping structures that parallel a river channel are created by repeated floods. Because the ground next to the channel is higher than the adjacent floodplain, back swamps and yazoo tributaries may develop.



enter a river because levees block the way often has to flow parallel to the river until it can breach the levee. Such streams are called **yazoo tributaries**, after the Yazoo River, which parallels the Mississippi for more than 300 kilometers (about 190 miles).

Alluvial Fans

Alluvial fans typically develop where a high-gradient stream leaves a narrow valley in mountainous terrain and comes out suddenly onto a broad, flat plain or valley floor (see Figure 6.33, page 196). Alluvial fans form in response to the abrupt drop in gradient combined with the change from a narrow channel of a mountain stream to less confined channels at the base of the mountains. The sudden drop in velocity causes the stream to dump its load of sediment quickly in a distinctive cone- or fan-shaped accumulation. As illustrated by Figure 6.33, the surface of the fan slopes outward in a broad arc from an apex at the mouth of the steep valley. Usually, coarser material is dropped near the apex of the fan, while finer material is carried toward the base of the deposit.

5.7 CONCEPT CHECKS

1. What feature may form where a stream enters the relatively still waters of a lake, an inland sea, or the ocean?
2. What are distributaries, and why do they form?
3. Briefly describe the formation of a natural levee. How is this feature related to back swamps and yazoo tributaries?
4. How does an alluvial fan differ from a delta?

5.8 FLOODS AND FLOOD CONTROL

Discuss the causes of floods and some common flood control measures.

A **flood** occurs when the flow of a stream becomes so great that it exceeds the capacity of its channel and overflows its banks. Among the most deadly and most destructive of all geologic hazards, floods are, nevertheless, simply part of the *natural* behavior of streams.

Causes of Floods

Rivers flood because of the weather. Rapid melting of snow in the spring and/or major storms that bring heavy rains over a large region cause most floods. Exceptional rains caused the devastating floods in the upper Mississippi River Valley during the summer of 1993 (**FIGURE 5.24**).

Unlike the extensive *regional floods* just mentioned, *flash floods* are more limited in extent. Flash floods occur with little warning and can be deadly because they produce a rapid rise in water levels and can have a devastating flow velocity. Several factors influence flash flooding. Among them are rainfall intensity and duration, topography, and surface conditions. Mountainous areas are susceptible because steep slopes can quickly funnel runoff into narrow canyons. Urban areas are susceptible to flash floods because a high percentage of the surface area is composed of impervious surfaces such as roofs, streets, and parking lots, where runoff is very rapid.

Human interference with a stream system can worsen or even cause floods. A prime example is the failure of a dam or an artificial levee. These structures are built for flood protection. They are designed to contain floods of a certain magnitude. If a larger flood occurs, the dam or levee is overtopped. If the dam or levee fails or is washed out, the water behind it is released and becomes a flash flood. The bursting of a dam in 1889 on the Little Conemaugh River caused the devastating Johnstown, Pennsylvania, flood that took some 3000 lives. A second dam failure occurred there in 1977, causing 77 fatalities.

Flood Control

Several strategies have been devised to eliminate or lessen the catastrophic effects of floods. Engineering efforts include the construction of artificial levees, the building of flood-control dams, and river channelization.

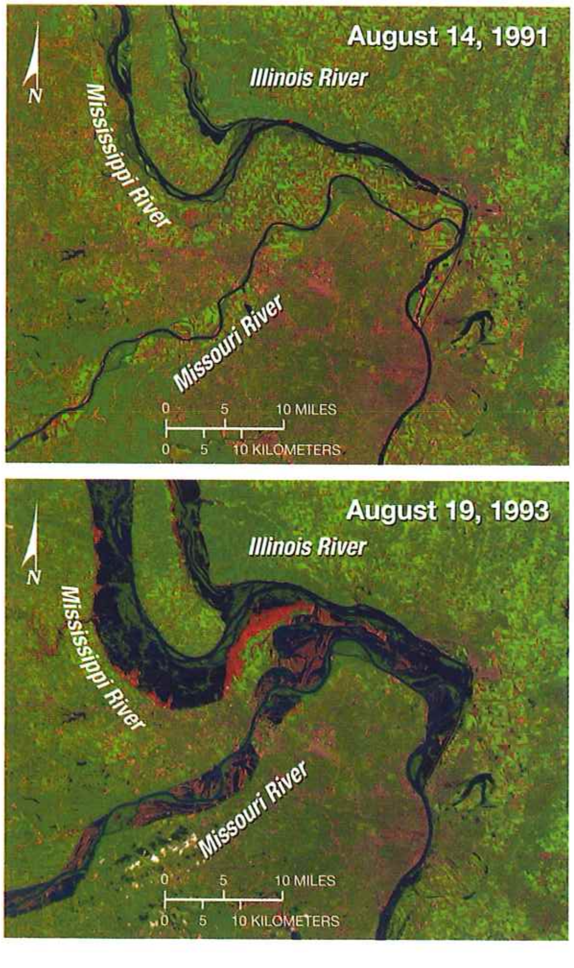


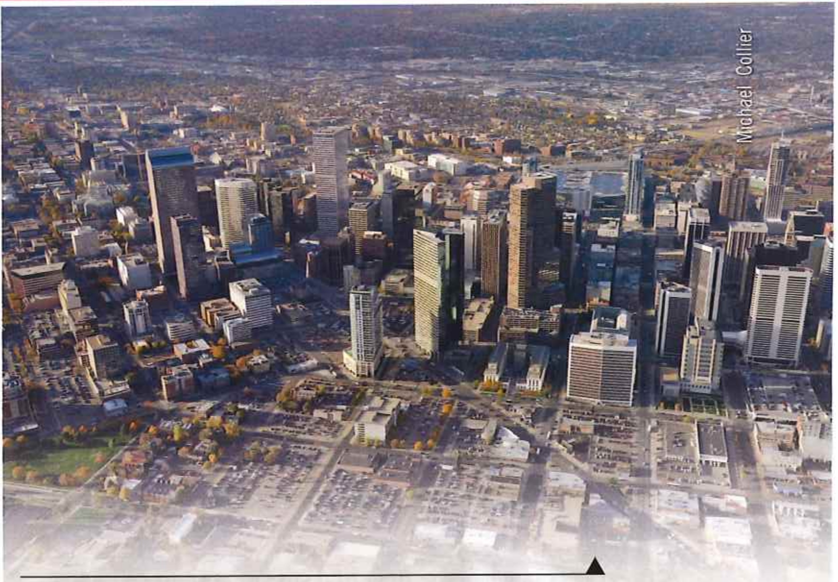
FIGURE 5.24 The Great Flood of 1993 These satellite images show the St. Louis area where the Mississippi, Illinois, and Missouri Rivers join. The upper image shows the rivers during a relatively normal period in August 1991. The lower image shows the peak of the 1993 flood. In all, nearly 14 million acres were inundated, displacing at least 50,000 people. (Courtesy of NASA)

Flash floods

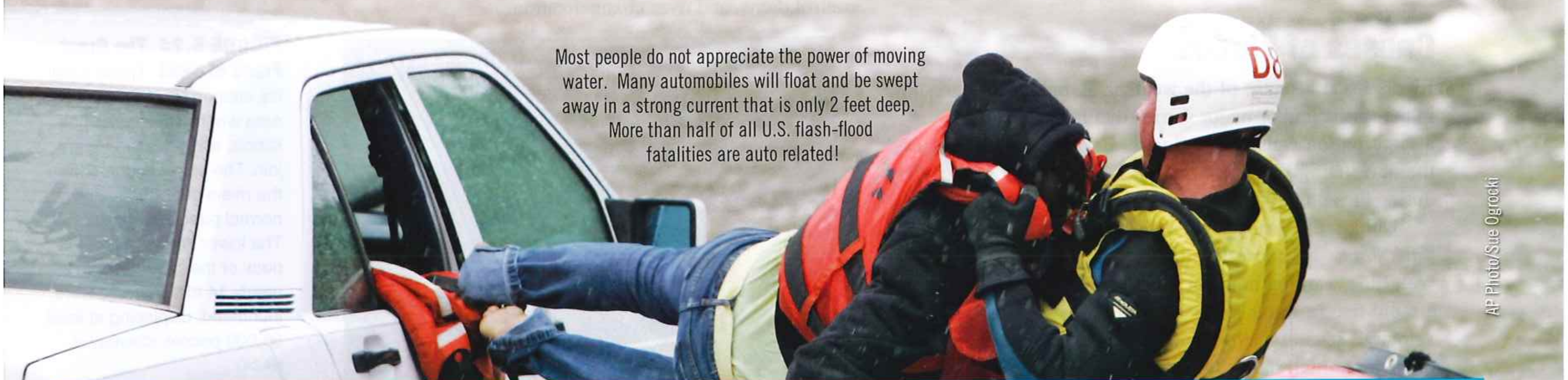
Flash floods are local floods of great volume and short duration. The rapidly rising surge of water usually occurs with little advance warning and can destroy roads, bridges, homes, and other substantial structures.


USGS

The power of a flash flood is illustrated by the Big Thompson River flood of July 31, 1976, in Colorado. During a four-hour span more than 30 centimeters (12 inches) of rain fell on portions of the river's small drainage basin. This amounted to nearly three-quarters of the average yearly total. The flash flood in the narrow canyon lasted only a few hours, but cost 139 people their lives.


Michael Collier

Urban development increases runoff. As a result, peak discharge and flood frequency increase. A recent study indicated that the area of impervious surfaces in the 48 contiguous United States is roughly equal to the area of the state of Ohio (44,000 mi²).

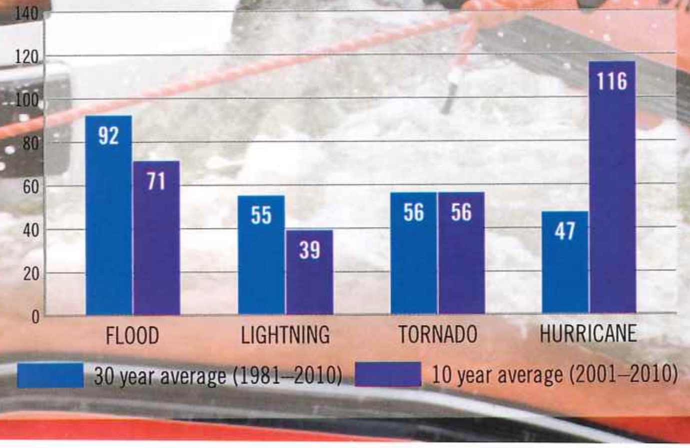


AP Photo/Sue Ogrocki

Most people do not appreciate the power of moving water. Many automobiles will float and be swept away in a strong current that is only 2 feet deep. More than half of all U.S. flash-flood fatalities are auto related!

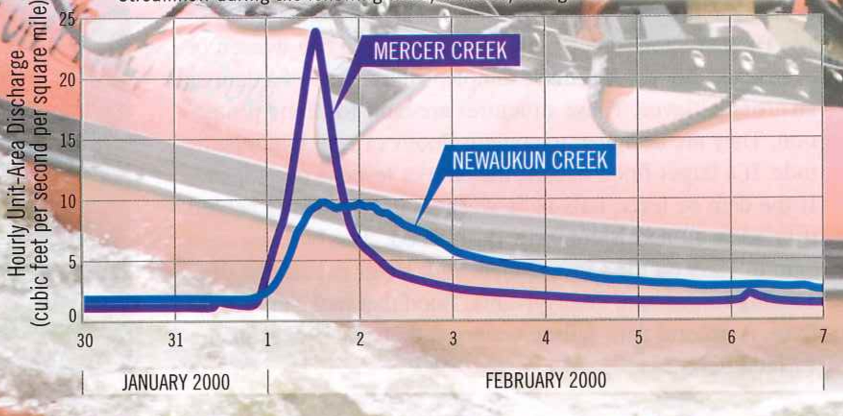
Average Annual Storm-Related Deaths in the United States

In most years floods are responsible for the greatest number of storm-related deaths. The average number of hurricane deaths was dramatically affected by Hurricane Katrina in 2005 (more than 1000). For all other years on this graph, hurricane fatalities numbered fewer than 20.



Effect of Urban Development on Flooding

Streamflow in Mercer Creek, an urban stream in western Washington, increases more quickly, reaches a higher peak discharge, and has a larger volume during a one-day storm on February 1, 2000, than streamflow in Newaukum Creek, a nearby rural stream. Streamflow during the following week, however, was greater in Newaukum Creek.



Artificial Levees *Artificial levees* are earthen mounds built on the banks of a river to increase the volume of water the channel can hold. Levees, used since ancient times, are the most commonly used stream-containment structures.

Artificial levees are usually easy to distinguish from natural levees because their slopes are much steeper. In some locations, especially urban areas, concrete floodwalls are sometimes constructed that serve the same purpose as artificial levees.

Many artificial levees were not built to withstand periods of extreme flooding. For example, levee failures were numerous in the Midwest during the summer of 1993, when the upper Mississippi and many of its tributaries experienced record floods (**FIGURE 5.25**). During that same event, floodwalls at St. Louis, Missouri, created a bottleneck for the river that led to increased flooding upstream of the city.

Flood-Control Dams *Flood-control dams* are built to store floodwater and then let it out slowly. This lowers the flood crest by spreading it out over a longer time span. Since the 1920s, thousands of dams have been built on nearly every major river in the United States. Many dams have significant non-flood-related functions, such as providing water for irrigated agriculture and for hydroelectric power generation. Many reservoirs are also major regional recreational facilities.

Although dams may reduce flooding and provide other benefits, building these structures also has significant costs and consequences. For example, reservoirs created by dams may cover fertile farmland, useful forests, historic sites, and scenic valleys. Of course, dams trap sediment. Therefore, deltas and floodplains downstream erode because they are no longer replenished with silt during floods. Large dams can also cause significant ecological damage to river environments that took thousands of years to establish.

Building a dam is not a permanent solution to flooding. Sedimentation behind a dam causes the volume of its reservoir to gradually diminish, reducing the effectiveness of this flood-control measure.

Channelization *Channelization* involves altering a stream channel in order to speed the flow of water to prevent it from reaching flood height. This may simply involve clearing a channel of obstructions or dredging a channel to make it wider and deeper.

Another alteration involves straightening a channel by creating *artificial cutoffs*. The idea is that by shortening the stream, the gradient and hence the flow velocity are both increased. By increasing velocity, the larger discharge associated with flooding can be dispersed more rapidly.

Since the early 1930s, the U.S. Army Corps of Engineers has created many artificial cutoffs on the Mississippi for the purpose of increasing the efficiency of the channel and reducing the threat of flooding. In all, the river has been shortened more than 240 kilometers (150 miles). These efforts have been somewhat successful in reducing the height of the river in flood stage. However, channel shortening led to higher gradients and accelerated erosion of riverbank material, both of which necessitated further intervention. Following the creation of artificial cutoffs, massive riverbank protection to reduce erosion was installed along several stretches of the lower Mississippi.

A Nonstructural Approach All of the flood-control measures described so far have involved structural solutions aimed at "controlling" a river. These solutions are expensive

Mobile Field Trip 5.25 Broken Levee Water from the swollen Mississippi River rushes through a break in an artificial levee in Monroe County, Illinois. During the record-breaking 1993 Midwest floods, many artificial levees could not withstand the force of the floodwaters. Sections of many weakened structures were overtopped or collapsed. (Photo by AP Photo/ James A. Finley) and often give people residing on the floodplain a false sense of security.

Today, many scientists and engineers advocate a nonstructural approach to flood control. They suggest that an alternative to artificial levees, dams, and channelization is sound floodplain management. By identifying high-risk areas, appropriate zoning regulations can be implemented to minimize development and promote more appropriate land use.

5.8 CONCEPT CHECKS

1. Contrast regional floods and flash floods. Which type of flood is more deadly?
2. List and briefly describe three basic flood-control strategies. What are some drawbacks of each?
3. What is meant by a *nonstructural approach* to flood control?

5.9 GROUNDWATER: WATER BENEATH THE SURFACE

Discuss the importance of groundwater and describe its distribution and movement.

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 groundwater is hidden from view except in caves and mines, and the impressions people gain from these subsurface openings are often misleading. Observations on the land surface give an impression that Earth is "solid." This view is not changed very much 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." But actual rivers underground are extremely rare. In reality, most of the subsurface environment is not "solid" at all. Rather, 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. Groundwater collects and moves in these tiny openings.

The Importance of Groundwater

Of the entire hydrosphere, or all of Earth's water, only a small percentage 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 freshwater are considered, the significance of groundwater becomes more apparent.

Take a look back at Figure 5.1, which shows the distribution of freshwater in the hydrosphere. Clearly, the largest volume of freshwater is in the form of glacial ice. Second in rank is groundwater, with slightly more than 30 percent of the total. However, when ice is excluded and just liquid water is considered, nearly 96 percent is groundwater. Without question, *groundwater represents the largest reservoir of freshwater that is readily available to humans.* Its value in terms of economics and human well-being is incalculable.

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, it is 40 percent of the water for irrigation, and it provides more than 25 percent of industry's needs. In some areas, however, overuse of this basic resource has caused serious problems, including streamflow depletion, land subsidence, and increased pumping costs. In addition, groundwater contamination resulting from human activities is a real and growing threat in many places.

Groundwater's Geologic Roles

Geologically, groundwater is important as an erosional agent. The dissolving action of groundwater slowly removes rock, allowing surface depressions known as sinkholes to form and creating subterranean caverns (**FIGURE 5.26**). 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. When we see water flowing in a river during a dry period, it is water from rain that fell at some earlier time and was stored underground.

Distribution of Groundwater

When rain falls, some of the water runs off, some returns to the atmosphere through evaporation and transpiration, and the remainder soaks into the ground. This last path is the primary source of practically all groundwater. The amount of water that takes each of these paths, however, varies greatly from time to time and place to place. Influential factors include the steepness of the slope, the nature of the surface material, the intensity of the rainfall, and the 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 on more gradual slopes composed of materials that are more easily penetrated by water, a much larger percentage of the water soaks into the ground.

Underground Zones 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 *belt 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 for life functions and transpiration. Some of this water also evaporates directly back into the atmosphere.

Water that is not held as soil moisture penetrates downward until it reaches a zone where all the open spaces in sediment and rock are completely filled with water. This is the **zone of saturation**. Water within it is called **groundwater**. The upper limit of this zone is known as the **water table**. The area above the water table where the soil, sediment, and rock are not saturated is called the **unsaturated zone** (**FIGURE 5.27**). 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

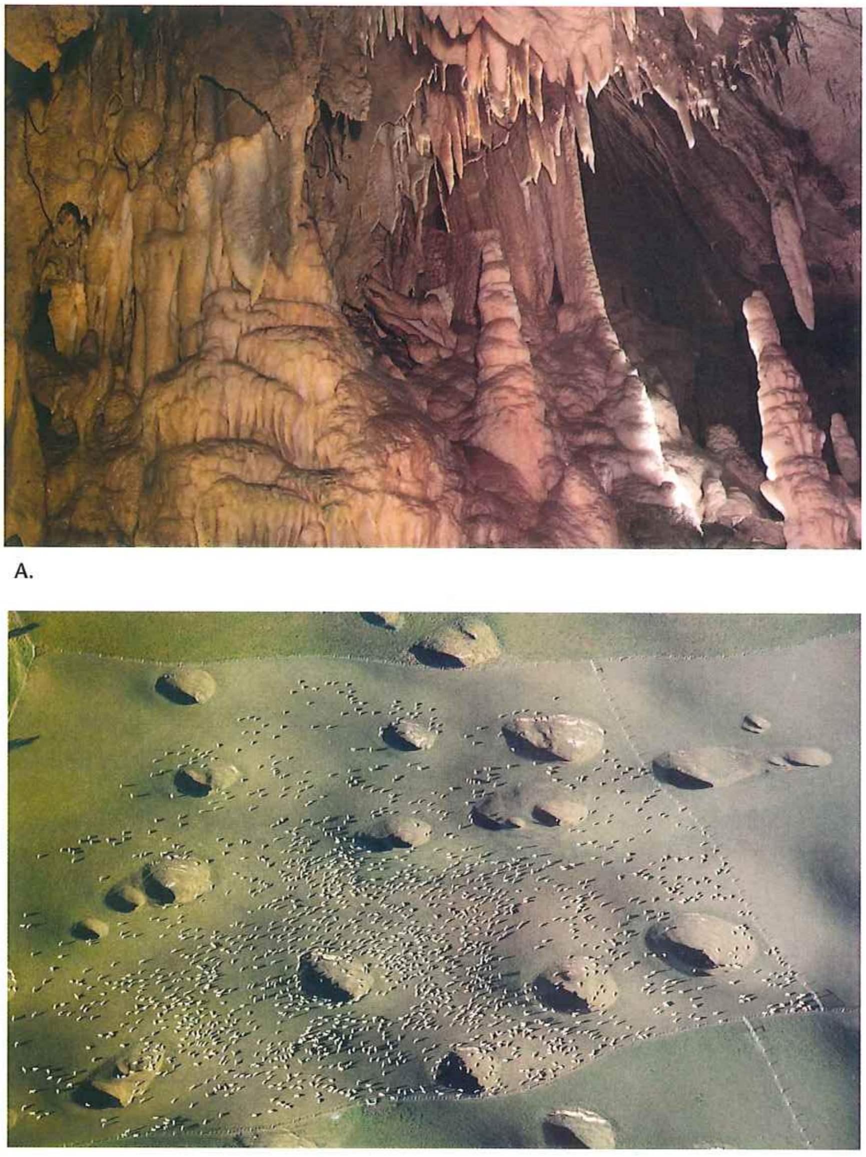


FIGURE 5.26 Caverns and Sinkholes **A.** A view of the interior of New Mexico's Carlsbad Caverns. The dissolving action of acidic groundwater created the caverns. Later, groundwater deposited the limestone decorations. (Photo by Clint Farlinger/Alamy)
B. Groundwater was responsible for creating these depressions, called sinkholes, west of Timaru on New Zealand's South Island. The white dots in this photo are grazing sheep. (Photo by David Wall/Alamy)

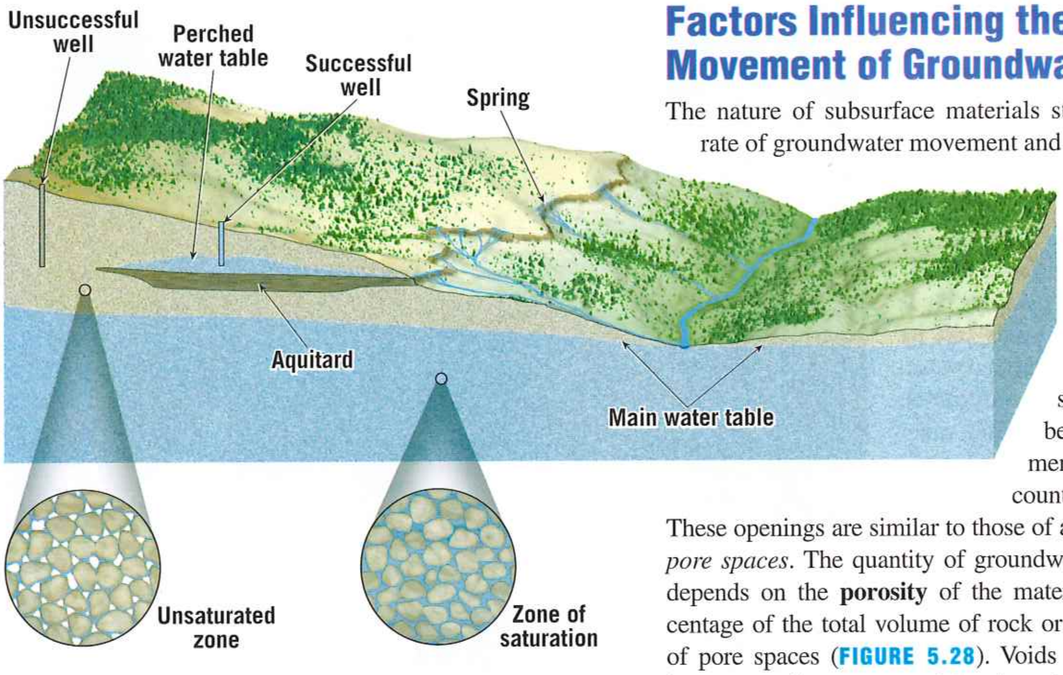
EYE ON EARTH

Marshes and swamps are characterized by saturated, poorly drained soils. This wetland is located southwest of Fort McMurray, Alberta, Canada. (Photo by Michael Collier)

QUESTION 1 *Describe the position of the water table in this image.*

QUESTION 2 *Suggest two situations that might cause this marsh to disappear. Include one natural cause and one cause related to human activities.*

FIGURE 5.27 Water Beneath the Surface This diagram illustrates the relative positions of many features associated with subsurface water.



wells, thus permitting groundwater to be withdrawn for use. We will examine wells more closely later in the chapter.

Water Table 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, reaching its highest elevations beneath hills and decreasing in height toward valleys (see Figure 5.27). The water table of a wetland (swamp) 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. Because of this, water tends to "pile up" beneath high areas between stream valleys. If rainfall were to cease completely, these water "hills" would slowly subside and gradually approach the level of the adjacent valleys. However, new supplies of rainwater are usually added often enough to prevent this. Nevertheless, in times of extended drought, the water table may drop enough to dry up shallow wells. Other causes for the uneven water table are variations in rainfall and permeability of Earth materials from place to place.

FIGURE 5.28 Porosity Demonstration Porosity is the percentage of the total volume of rock or sediment that consists of pore spaces.

The beaker on the left is filled with 1000 ml of sediment. The beaker on the right is filled with 1000 ml of water.

The sediment-filled beaker now contains 500 ml of water. Pore spaces (porosity) must represent 50 percent of the volume of the sediment.

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 called *pore 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 (**FIGURE 5.28**). 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 percent 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. Most igneous and metamorphic rocks, as well as some sedimentary rocks, are composed of tightly interlocking crystals, so the voids between grains may be negligible. In these rocks, fractures must provide the voids.

Permeability Porosity alone cannot measure a material's capacity to yield groundwater. Rock or sediment may be very porous and still prohibit water from moving through it. The **permeability** of a material indicates its ability to *transmit* a fluid. Groundwater moves by twisting and turning through interconnected small openings. The smaller the pore spaces, the slower the groundwater moves. If the spaces between particles are too small, water cannot move at all. For example, clay's ability to store water can be great, due to its high porosity, but its pore spaces are so small that water is unable to move through it. Thus, we say that clay is *impermeable.*

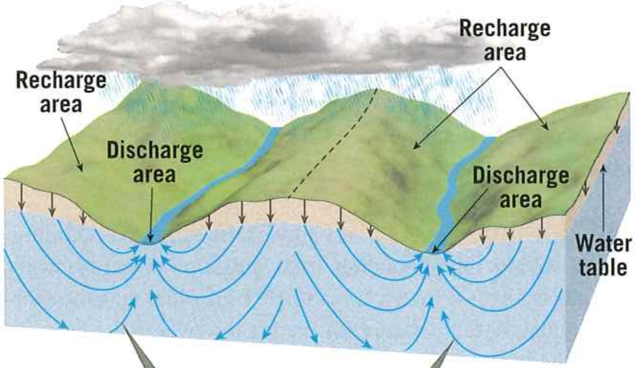
Aquitards and Aquifers Impermeable layers such as clay that hinder or prevent water movement are termed **aquitards** (*aqua* = water, *tard*

= slow). In contrast, larger particles, such as sand or gravel, have larger pore spaces. Therefore, water moves with relative ease. Permeable rock strata or sediments that transmit groundwater freely are called **aquifers** ("water carriers"). Aquifers are important because they are the water-bearing layers sought after by well drillers.

Groundwater Movement

The movement of most groundwater is exceedingly slow, from pore to pore. A typical rate is a few centimeters per day. The energy that makes the water 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. This means that water usually gravitates toward a stream channel, lake, or spring. Although some water takes the most direct path down the slope of the water table, much of the water follows long, curving paths toward the zone of discharge.

FIGURE 5.29 shows how water percolates 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 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.



The looping flow lines result from the downward pull of gravity and the tendency of groundwater to move toward areas of reduced pressure.

FIGURE 5.29 Groundwater Movement Arrows show paths of groundwater movement through uniformly permeable material.

5.9 CONCEPT CHECKS

1 About what percentage of freshwater is groundwater? How does this change if glacial ice is excluded?
2 What are two geologic roles for groundwater?
3 When it rains, what factors influence the amount of water that soaks in?
4 Define *groundwater* and relate it to the water table.
5 Distinguish between porosity and permeability. Contrast aquifer and aquitard.
6 What factors cause water to follow the paths shown in Figure 5.29?

5.10 SPRINGS, WELLS, AND ARTESIAN SYSTEMS

Compare and contrast springs, wells, and artesian systems.

A great deal of groundwater eventually makes its way to the surface. Sometimes this occurs as a naturally flowing spring or as a spectacularly erupting geyser. Much of the groundwater that people use is brought to the surface by pumping it from a well. To understand these phenomena, it is necessary to understand Earth's sometimes complex underground "plumbing."

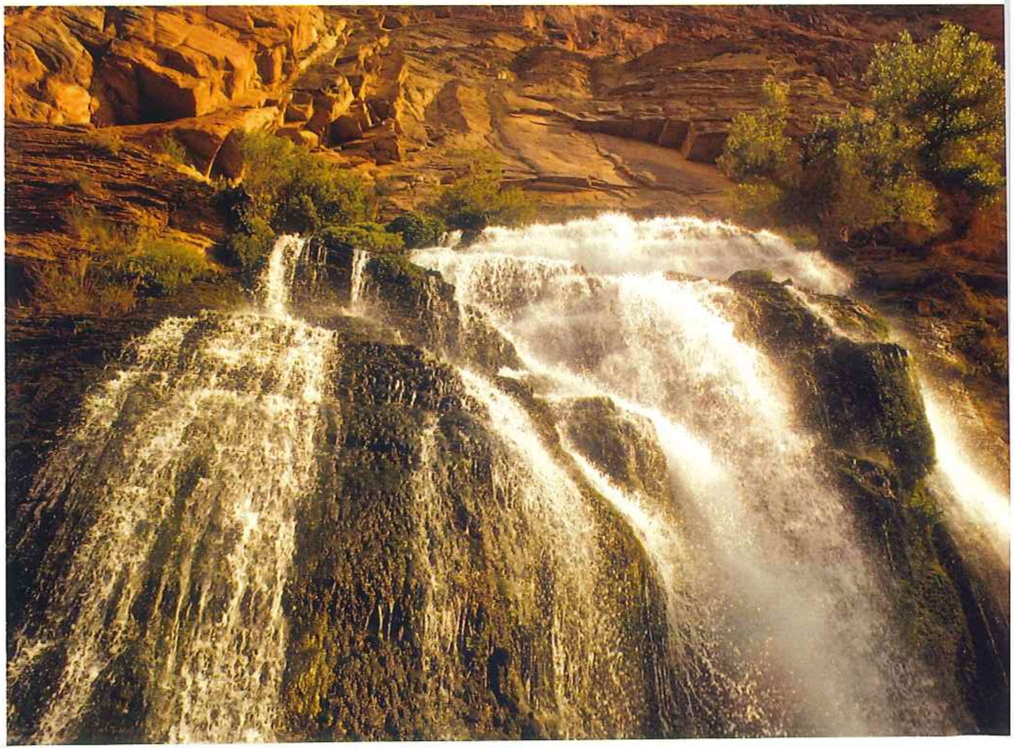
Springs

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 water is flowing freely from the ground in all kinds of weather, in seemingly inexhaustible supply but with no obvious source. Today, we know that the 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 the ground surface, a natural flow of groundwater results, which we call a **spring** (**FIGURE 5.30**). Many springs form when an aquitard blocks the downward movement of groundwater and forces it to move laterally. When the permeable bed (aquifer) outcrops in a valley, one or more springs result.

Another situation that can produce a spring is illustrated in Figure 5.27. Here an aquitard is situated above the main water table. As water percolates downward, a portion

FIGURE 5.30 Thunder Spring Water gushes from a bedrock wall in the Grand Canyon. (Photo by Michael Collier)



accumulates above the aquitard to create 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.

Hot Springs There is no universally accepted definition of **hot spring**. One frequently used definition is that the water in a hot spring is 6° to 9°C (10° to 15°F) warmer than the average annual air temperature for the locality where it occurs. In the United States alone, there are well over 1000 such springs.

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), a figure known as the *geothermal gradient*. Therefore, when groundwater circulates at great depths, it becomes heated. If the hot water rises rapidly to the surface, it may emerge as a hot spring. The water of some hot springs in the eastern United States is heated in this manner. The springs at Hot Springs National Park in Arkansas are one example. Water temperatures of these springs average about 60°C (140°F).

The great majority (more than 95 percent) of the hot springs (and geysers) in the United States are found in the West. The reason for this distribution is that the sources of heat for most hot springs are magma bodies and hot igneous rocks, and it is in the West that igneous activity has occurred most recently. The hot springs and geysers of the Yellowstone region are well-known examples.

FIGURE 5.31 Old Faithful This geyser in Wyoming's Yellowstone National Park is one of the most famous in the world. Contrary to popular legend, it does not erupt every hour on the hour. Time spans between eruptions vary from about 65 minutes to more than 90 minutes and have generally increased over the years, thanks to changes in the geyser's plumbing. (Photo by Jeff Vanuga/Corbis RF)

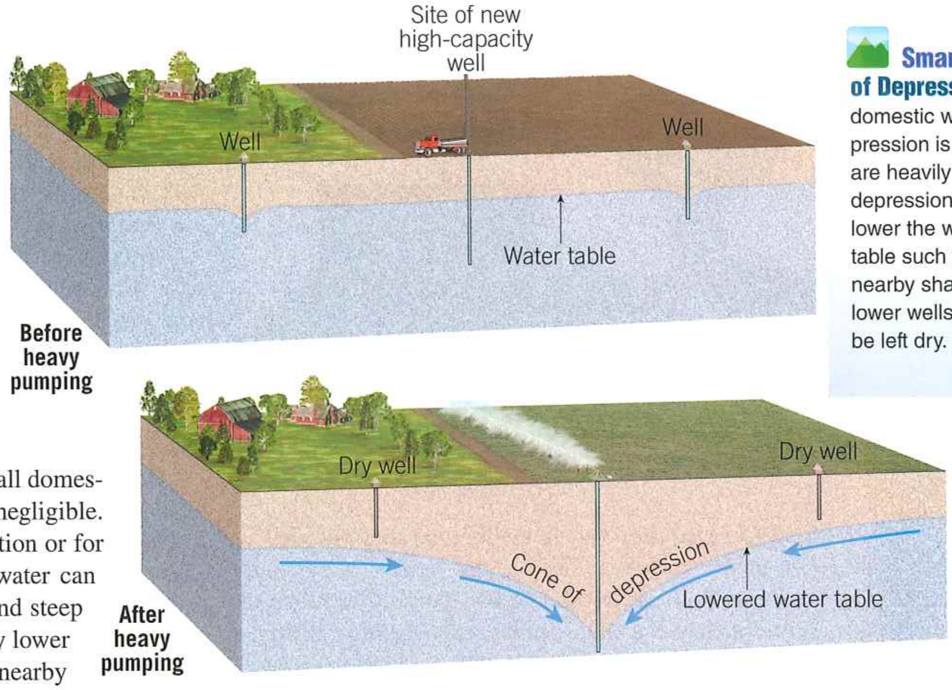
Geysers Intermittent fountains in which columns of hot water and steam are ejected with great force, often rising 30 to 60 meters (100 to 200 feet) into the air, are called **geysers**. After the jet of water ceases, a column of steam rushes out, often with a thunderous roar. Perhaps the most famous geyser in the world is Old Faithful in Yellowstone National Park (**FIGURE 5.31**). 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. In fact, the Icelandic word *geysa*, meaning "to gush," gives us the name *geyser.*

Geysers occur where extensive underground chambers exist within hot igneous rocks. As relatively cool groundwater enters the chambers, it is heated by the surrounding rock. At the bottom of the chamber, 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, at the bottom of a 300-meter (1000-foot) water-filled chamber, water must attain a temperature of nearly 230°C (450°F) before it will boil. The heating causes the water to expand, and as a result, some of the water 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. As a result, a portion of the water deep within the chamber quickly turns to an expanding mass of steam, which causes the geyser to erupt. Following the eruption, cool groundwater again seeps into the chamber, and the cycle begins anew.

Wells The most common method for removing groundwater is to use a **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. According to the National Groundwater Association, there are about 16 million water wells for various purposes in the United States. Private household wells constitute the largest share—more than 13 million. About 500,000 new residential wells are drilled each year.

By far the single greatest use of well 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 by homes in cities and rural areas.

The water table level may fluctuate considerably during the course of a year, dropping during dry seasons and rising following periods of precipitation. Therefore, to ensure a continuous supply of water, a well must penetrate below the water table. Whenever a substantial amount of 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 5.32**). For most small domestic wells, the cone of depression is negligible. However, when wells are used for irrigation or for industrial purposes, the withdrawal of water can be great enough to create a very wide and steep cone of depression that may substantially lower the water table in an area and cause nearby shallow wells to become dry. Figure 5.32 illustrates this situation.

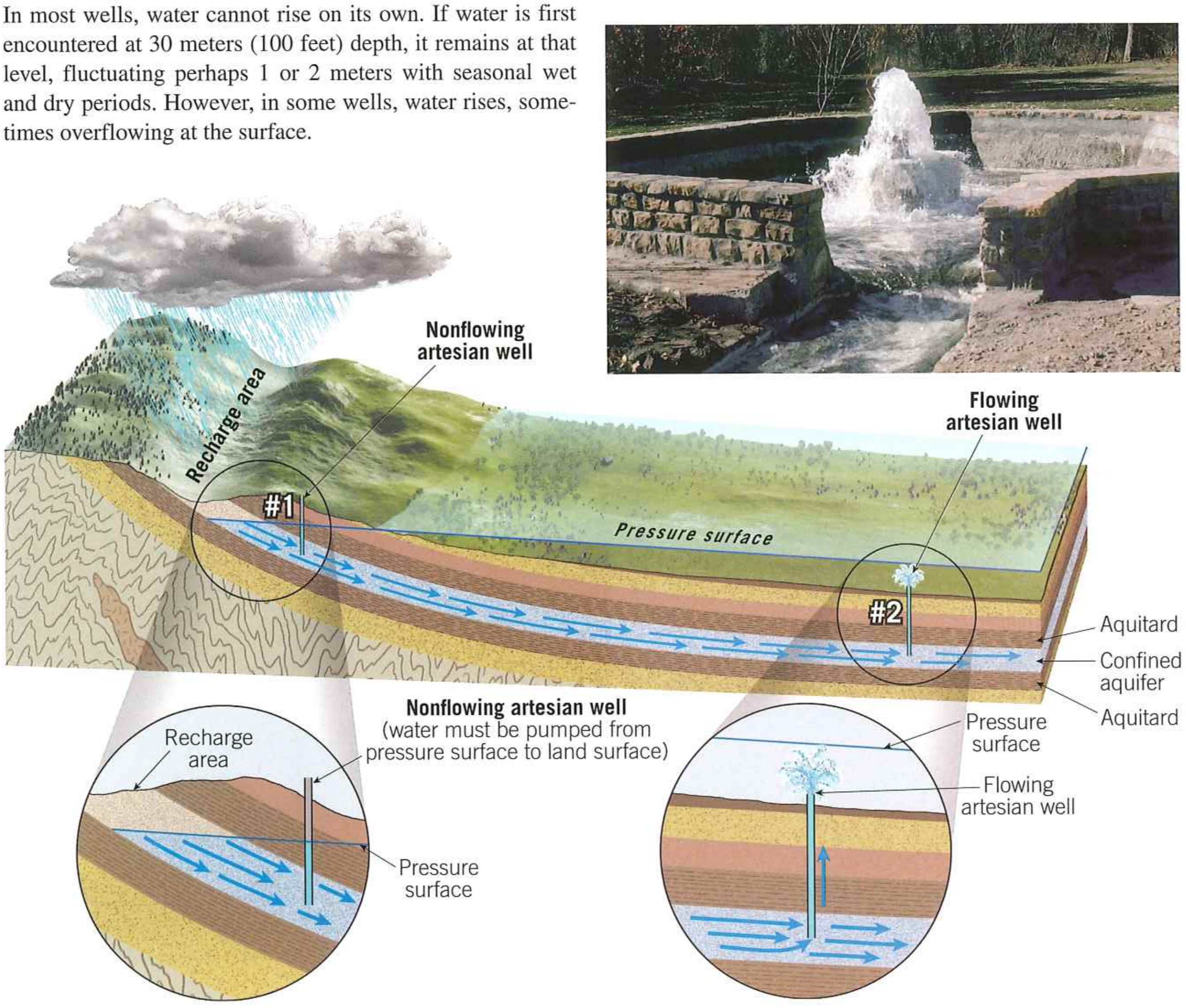


SmartFigure 5.32 Cone of Depression For most small domestic wells, the cone of depression is negligible. When wells are heavily pumped, the cone of depression can be large and may lower the water table such that nearby shallower wells may be left dry.

Artesian Systems

In most wells, water cannot rise on its own. If water is first encountered at 30 meters (100 feet) depth, it remains at that level, fluctuating perhaps 1 or 2 meters with seasonal wet and dry periods. However, in some wells, water rises, sometimes overflowing at the surface.

Artesian system refers to a situation in which groundwater rises in a well above the level where it was initially encountered. For such a situation to occur, two conditions must exist (**FIGURE 5.33**): (1) Water must be



SmartFigure 5.33 Artesian Systems These groundwater systems occur where an inclined aquifer is surrounded by impermeable beds (aquitards). Such aquifers are called *confined aquifers*. The photo shows a flowing artesian well. (Photo by James E. Patterson)

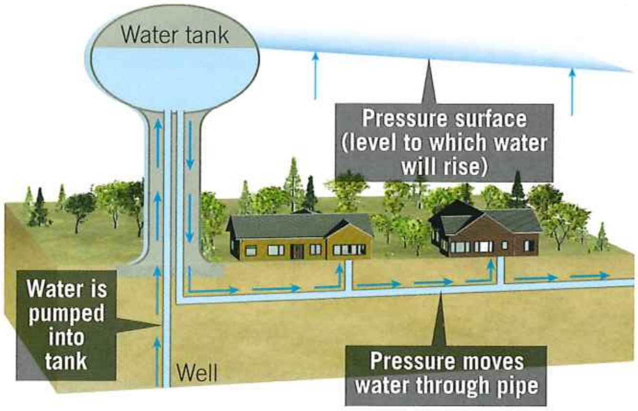


FIGURE 5.34 City Water Systems City water systems can be considered to be artificial artesian systems.

confined to an aquifer that is inclined so that one end is exposed at the surface, where it 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 this pressure surface. The greater the distance from the recharge area (the area where water enters the inclined aquifer), the greater the friction and the smaller the rise of water.

In Figure 5.33, 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 in Figure 5.33). Not all artesian systems are wells. *Artesian springs* also exist. In such situations, 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 oases.

Artesian systems act as "natural pipelines," transmitting water from remote areas of recharge great distances to the points of discharge. In this manner, water that fell in central Wisconsin years ago is now taken from the ground and used by communities many kilometers to the south, in Illinois. In South Dakota, such a system brings water from the western Black Hills eastward across the state.

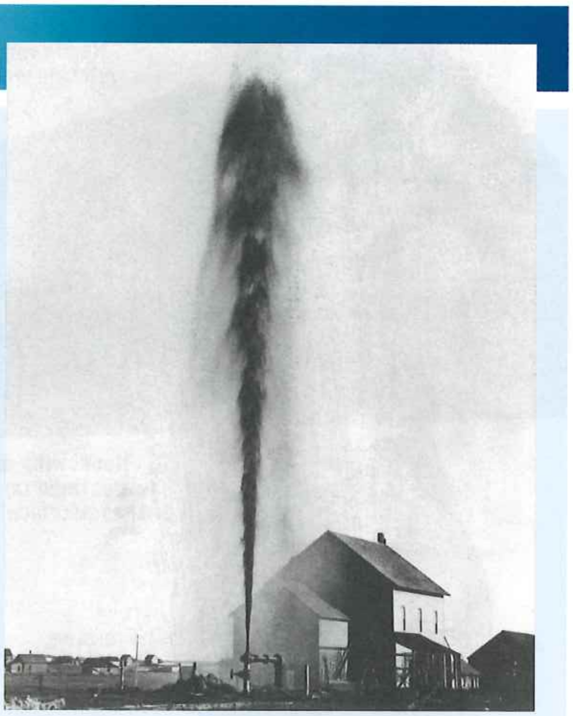
On a different scale, city water systems may be considered examples of artificial artesian systems (**FIGURE 5.34**). A water tower, into which water is pumped, may be considered the area of recharge, the pipes the confined aquifer, and the faucets in homes the flowing artesian wells.

5.10 CONCEPT CHECKS

1. Describe the circumstances that created the spring in Figure 5.27.
2. What is the source of heat for most hot springs and geysers?
3. Describe what occurs to cause a geyser to erupt.
4. Relate drawdown to cone of depression.
5. In Figure 5.27, two wells are at the same level. Why is one successful and the other not?
6. Sketch a simple cross section of an artesian system with a flowing artesian well. Label aquitards, the aquifer, and the pressure surface.

EYE ON EARTH

In 1900, when this well was drilled near Woonsocket in eastern South Dakota, a "gusher" of water resulted. The stream of water from a 3-inch pipe reached a height of nearly 30 meters (100 feet). Thousands of additional wells now tap the same aquifer. (Photo by N.H. Darton/USGS)



QUESTION 1 *Describe or sketch the subsurface geologic situation that was responsible for this fountain of water.*

QUESTION 2 *What term is applied to a well such as this?*

QUESTION 3 *Today wells that tap this aquifer do not flow freely at the surface but must be pumped. Suggest a likely reason.*

5.11 ENVIRONMENTAL PROBLEMS OF GROUNDWATER

List and discuss three important environmental problems associated with groundwater.

Like many of our other 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 their groundwater supply.

Treating Groundwater as a Nonrenewable Resource

For many, groundwater appears to be an endlessly renewable resource, for 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 amount of water available to recharge the aquifer is significantly less than the amount being withdrawn.

The High Plains, a relatively dry region that extends from South Dakota to western Texas, is one example of an extensive agricultural economy that is largely dependent on irrigation using groundwater (**FIGURE 5.35**). Underlying about 111 million acres (450,000 square kilometers [174,000 square miles]) in parts of eight states, the High Plains aquifer is one of the largest and most agriculturally significant aquifers in the United States. It accounts for about 30 percent of all groundwater withdrawn for irrigation in the country. In the southern part of this region, which includes the Texas panhandle, the natural recharge of the aquifer is very slow, and the problem of declining groundwater levels is acute. In fact, in years of average or below-average precipitation, recharge is negligible because all or nearly all of the meager rainfall is returned to the atmosphere by evaporation and transpiration.

Therefore, where intense irrigation has been practiced for an extended period, depletion of groundwater can be severe. Declines in the water table at rates as great as 1 meter (3 feet) per year have led to an overall drop of between 15 and 60 meters (50 and 200 feet) in some areas. Under these circumstances, it can be said that the groundwater is literally being "mined." Even if pumping were to cease immediately, it would take thousands of years for the groundwater to be fully replenished.

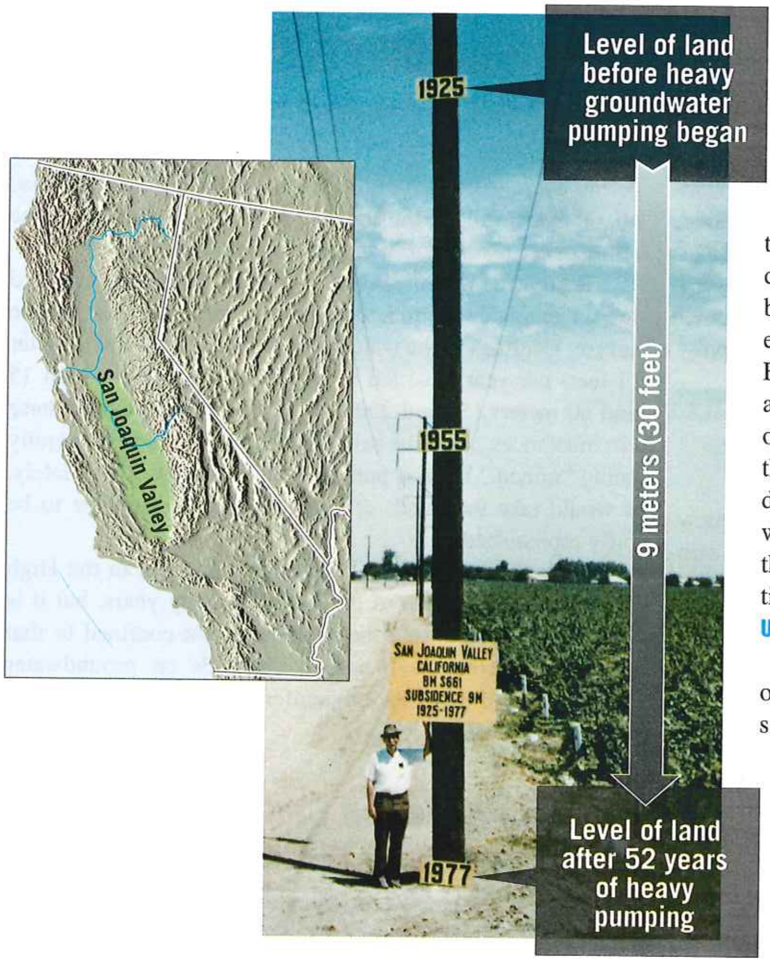
Groundwater depletion has been a concern in the High Plains and other areas of the West for many years, but it is worth pointing out that the problem is not confined to that part of the country. Increased demands on groundwater resources have overstressed aquifers in many areas, not just in arid and semiarid regions.

Land Subsidence Caused by Groundwater Withdrawal

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 loose sediments. As water is withdrawn, the water pressure drops, and the weight of the overburden is transferred to the sediment. The greater pressure packs

FIGURE 5.35 Mining Groundwater **A.** The High Plains aquifer is one of the largest aquifers in the United States. **B.** In parts of the High Plains aquifer, water is pumped from the ground faster than it is replenished. In such instances, groundwater is being treated as a nonrenewable resource. This aerial view shows circular crop fields irrigated by center-pivot irrigating systems in semiarid eastern Colorado. (Photo by James L. Amos/CORBIS). **C.** Groundwater provides more than 54 billion gallons per day in support of agriculture in the United States. (Photo by Michael Collier)

FIGURE 5.36 That Sinking Feeling! The San Joaquin Valley, an important agricultural area, relies heavily on irrigation. Between 1925 and 1975, this part of the valley subsided almost 9 meters (30 feet) due to the withdrawal of groundwater and the resulting compaction of sediments. (Photo courtesy of U.S. Geological Survey, Denver)



the sediment grains more tightly together, and the ground subsides.

Many areas can be used to illustrate such land subsidence. A classic example in the United States occurred in the San Joaquin Valley of California (**FIGURE 5.36**). Other well-known cases of land subsidence resulting from groundwater pumping in the United States include Las Vegas, Nevada; New Orleans and Baton Rouge, Louisiana; portions of southern Arizona; and the Houston–Galveston area of Texas. In the low-lying coastal area between Houston and Galveston, land subsidence ranges from 1.5 to 3 meters (5 to 10 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, a portion of which is built on a former lake bed. In the first half of the twentieth century, thousands of wells were sunk into the water-saturated sediments beneath the city. As water was withdrawn, portions of the city subsided by 6 meters (20 feet) or more.

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 farm wastes and inadequate or broken sewer systems.

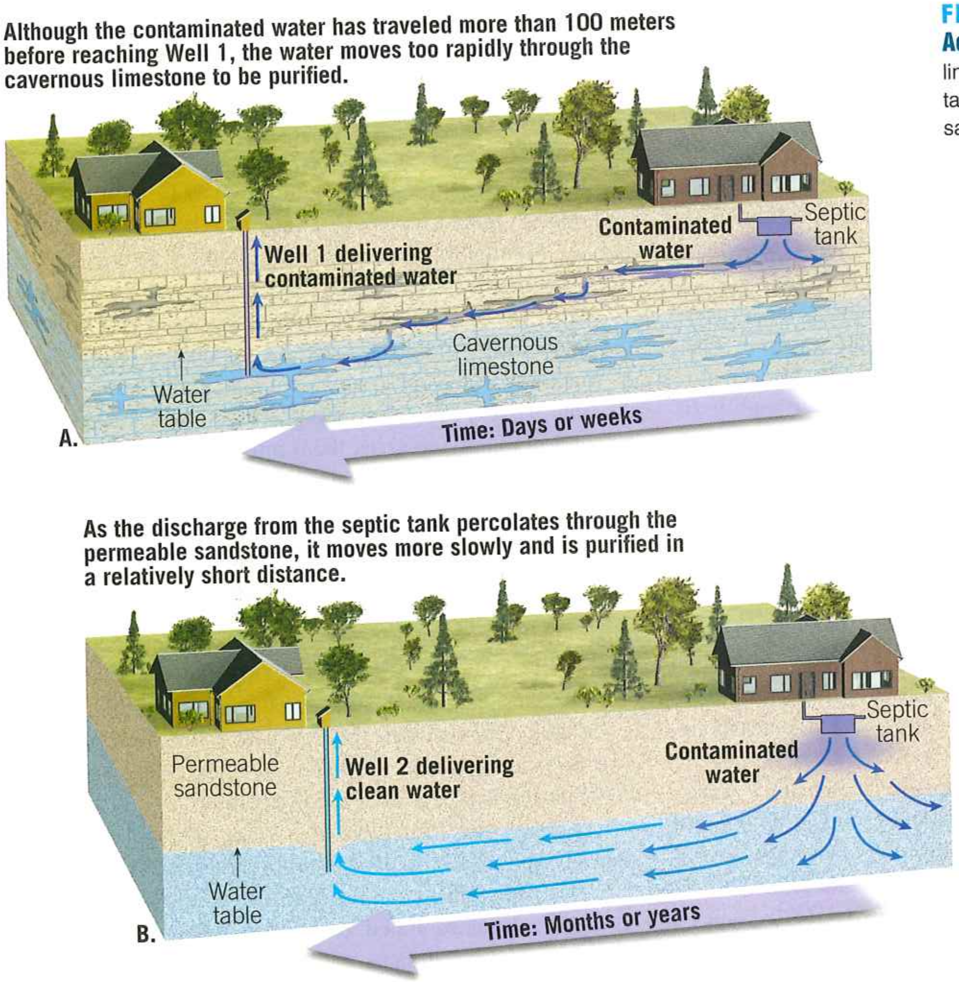
If sewage water that is contaminated with bacteria enters the groundwater system, it may become purified through natural processes. The harmful bacteria can be mechanically filtered by the sediment through which the water percolates, destroyed by chemical oxidation, and/or assimilated by other organisms. 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 5.37A**.

Conversely, when the aquifer is composed of sand or permeable sandstone, the water 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 5.37B**).

Other sources and types of contamination also threaten groundwater supplies (**FIGURE 5.38**). 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. As rainwater oozes through the refuse, it may dissolve a variety of potential contaminants. If the leached material reaches the water table, it will mix with the groundwater and contaminate the supply.

Because groundwater movement is usually slow, polluted water might 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 might 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



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.

As the discharge from the septic tank percolates through the permeable sandstone, it moves more slowly and is purified in a relatively short distance.

FIGURE 5.37 Comparing Two Aquifers In this example, the limestone aquifer allowed the contamination to reach a well but the sandstone aquifer did not.

FIGURE 5.38 Potential Sources of Groundwater Contamination Sometimes leaking gasoline storage tanks and materials leached from landfills contaminate aquifers. (Storage tank photo by Earth Gallery Environment/ Alamy; landfill photo by Picsfive/ Shutterstock)

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 freshwater is pumped back in. This process is costly and time-consuming, and it may be risky because there is no way to be certain that all the contamination has been removed. Clearly, the most effective solution to groundwater contamination is prevention.

5.11 CONCEPT CHECKS

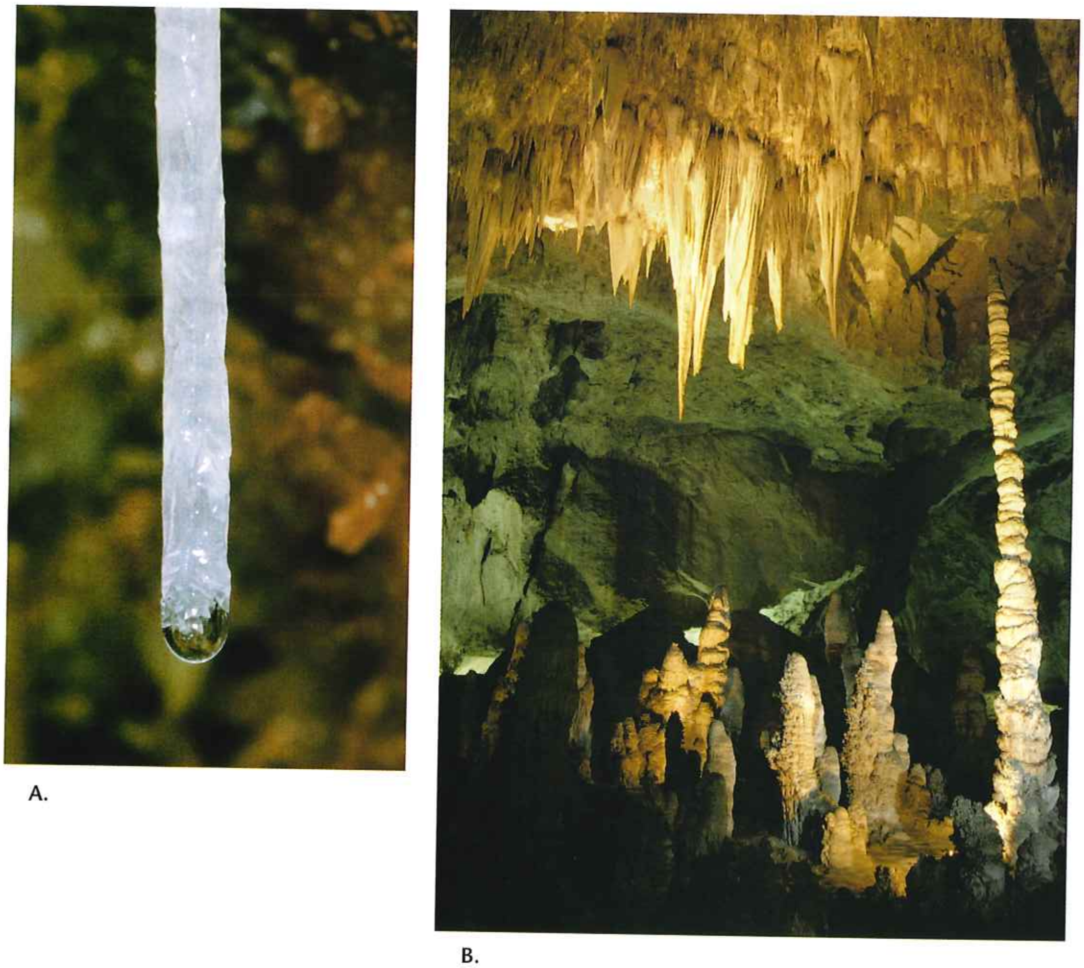
1. Describe the problem associated with pumping groundwater for irrigation in parts of the High Plains.
2. Explain why ground may subside after groundwater is pumped to the surface.
3. Which aquifer would be most effective in purifying polluted groundwater: coarse gravel, sand, or cavernous limestone?

5.12 THE GEOLOGIC WORK OF GROUNDWATER

Explain the formation of caverns and the development of karst topography.

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 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. Most natural water contains this weak acid 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 calcite in the rocks to form calcium bicarbonate, a soluble material that is then carried away in solution.

FIGURE 5.39 Cave Decorations A. Close-up of a delicate live soda-straw stalactite in Chinn Springs Cave, Independence County, Arkansas. (Photo by Dante Fenolio/Science Source) B. Stalagmites and stalactites in Carlsbad Caverns National Park, New Mexico. (Photo by Fritz Poelking/Glow Images)



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. Although most are relatively small, some have spectacular dimensions. Carlsbad Caverns in southeastern New Mexico and Mammoth Cave in Kentucky are famous examples. One chamber in Carlsbad Caverns has an area equivalent to 14 football fields and enough height to accommodate the U.S. Capitol Building. At Mammoth Cave, the total length of interconnected caverns extends for more than 540 kilometers (340 miles).

Most caverns are created at or 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.

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 caverns in which they reside, but depositional features. They are 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. This commonly occurs as nearby streams cut their valleys deeper, lowering the water table as the elevation of the rivers drops. As soon as the chamber is filled with air, the conditions are right for the decoration phase of cavern building to begin.

Of the various dripstone features found in caverns, perhaps the most familiar are **stalactites**. These icicle-like pendants hang from the ceiling of a cavern and form where water seeps through cracks above. When water reaches air in the cave, some of the dissolved carbon dioxide escapes from the drop, and calcite begins to precipitate. 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 5.39A**). 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 deposit along the outside of the tube. As deposition continues, the stalactite takes on the more common conical shape.

Formations that develop on the floor of a cavern and reach upward toward the ceiling are

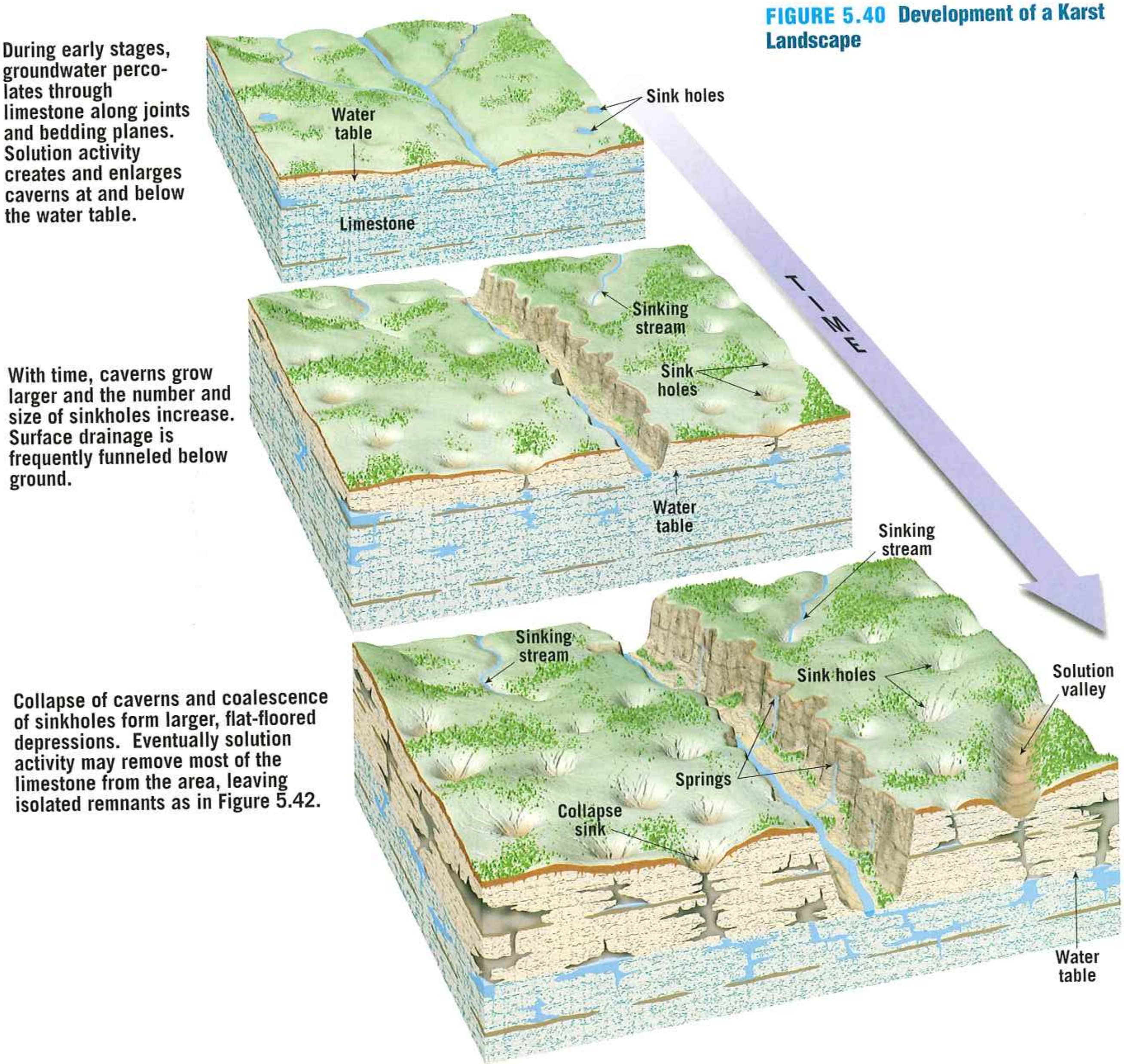


FIGURE 5.40 **Development of a Karst Landscape**

called **stalagmites** (**FIGURE 5.39B**). 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 more 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 *Krs* region in the border area between Slovenia and Italy, 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 (**FIGURE 5.40**). Generally, arid and semiarid areas do not develop karst topography because there is insufficient groundwater. When karst features exist in such regions, they are likely to be remnants of a time when rainier conditions prevailed.

Sinkholes Karst areas typically have irregular terrain punctuated with many depressions called **sinkholes** or, simply, **sinks** (see Figure 5.26). In the limestone areas of Florida, Kentucky, and southern Indiana, literally tens of thousands of these depressions vary in depth from just 1 to 2 meters (3 to 6 feet) to a maximum of more than 50 meters (165 feet).

Sinkholes commonly form in one of 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-seeping rainwater that is freshly charged with carbon dioxide. These

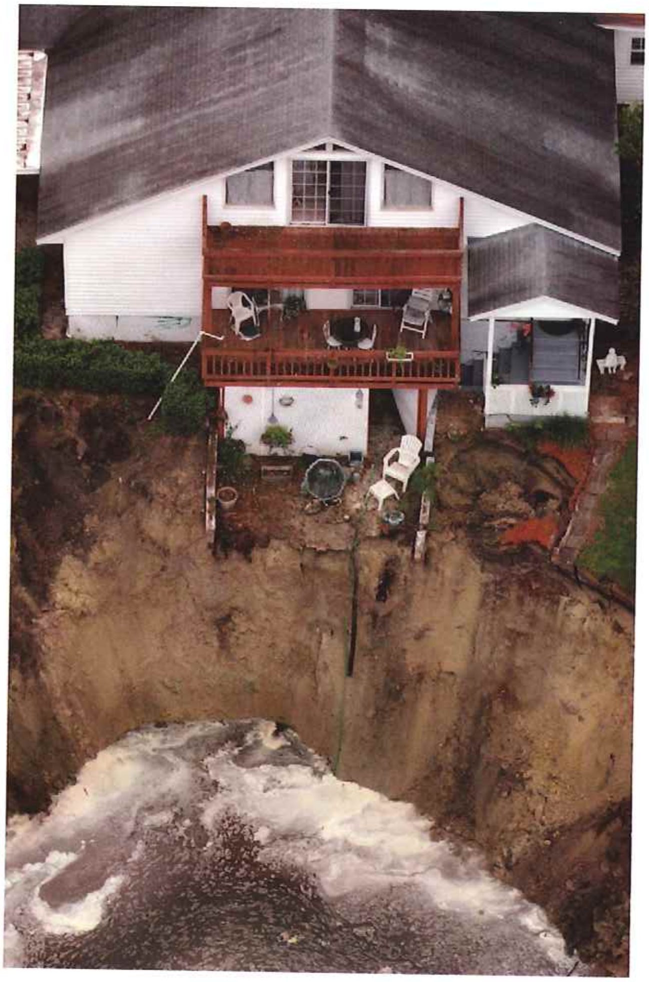


FIGURE 5.41 Sinkholes Can Be Geologic Hazards This sinkhole formed suddenly in the backyard of a home in Lake City, Florida. Sinkholes such as this one form when the roof of a cavern collapses. (AP Photo/*The Florida Times-Union*, Jon M. Fletcher)

depressions are usually not deep and are characterized by relatively gentle slopes. By contrast, sinkholes can also form suddenly 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 serious geologic hazard. Such a situation is clearly the case in **FIGURE 5.41**.

In addition to a surface pockmarked by sinkholes, karst regions characteristically show a striking lack of surface drainage (streams). Following a rainfall, 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. The Mammoth Cave area of Kentucky, for example, is home to Sinking Creek, Little Sinking Creek, and Sinking Branch. Some sinkholes become plugged with clay and debris, creating small lakes or ponds.

Tower Karst Landscapes Some regions of karst development exhibit landscapes that look very different from the sinkhole-studded terrain depicted in Figure 5.40. One striking example is an extensive region in southern China that is described as exhibiting *tower karst*. As **FIGURE 5.42** 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. In such settings, groundwater dissolves large volumes of limestone, leaving only these residual towers. Karst development occurs more rapidly in tropical climates due to the abundant rainfall and 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.

5.12 CONCEPT CHECKS

1. How does groundwater create caverns?
2. How do stalactites and stalagmites form?
3. Describe two ways in which sinkholes form.

FIGURE 5.42 Tower Karst Landscape in China One of the best-known and most distinctive regions of tower karst development is along the Li River in the Guilin District of southeastern China. (Photo by Philippe Michel/AGE Fotostock)

5 CONCEPTS IN REVIEW

Running Water and Groundwater

5.1 EARTH AS A SYSTEM: THE HYDROLOGIC CYCLE

List the hydrosphere's major reservoirs and describe the different paths that water takes through the hydrologic cycle.

KEY TERMS: hydrologic cycle, evaporation, infiltration, runoff, transpiration, evapotranspiration

- Water moves through the hydrosphere's many reservoirs by evaporating, condensing into clouds, and falling as precipitation. Once it reaches the ground, rain can either soak in, evaporate, be returned to the atmosphere by plant transpiration, or run off. Running water is the most important agent sculpting Earth's varied landscapes.

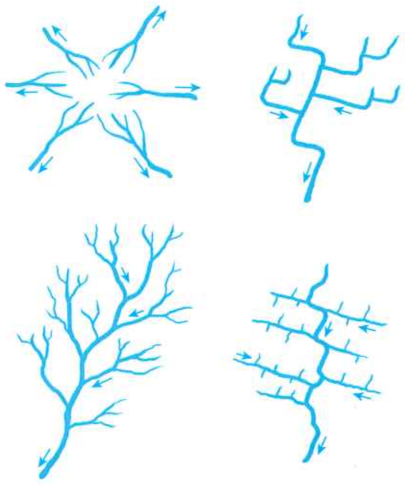
5.2 RUNNING WATER

Describe the nature of drainage basins and river systems. Sketch four basic drainage patterns.

KEY TERMS: drainage basin, divide, dendritic pattern, radial pattern, rectangular pattern, trellis pattern

- The land area that contributes water to a stream is its drainage basin. Drainage basins are separated by imaginary lines called divides.
- As a generalization, river systems tend to erode at the upstream end, transport sediment through the middle section, and deposit sediment at the downstream end.

Q Identify each of the drainage patterns depicted in the accompanying sketch.



5.3 STREAMFLOW

Discuss streamflow and the factors that cause it to change.

KEY TERMS: laminar flow, turbulent flow, gradient, discharge, longitudinal profile

- The flow of water in a stream may be laminar or turbulent. A stream's flow velocity is influenced by channel gradient; size, shape, and roughness of the channel; and discharge.
- A cross-sectional view of a stream from head to mouth is a longitudinal profile. Usually the gradient and roughness of the stream channel decrease going downstream, whereas the size of the channel, stream discharge, and flow velocity increase in the downstream direction.

Q Sketch a typical longitudinal profile. Where does most erosion happen? Where is sediment transport the dominant process?

5.4 THE WORK OF RUNNING WATER

Outline the ways in which streams erode, transport, and deposit sediment.

KEY TERMS: pothole, dissolved load, suspended load, bed load, settling velocity, saltation, capacity, competence, sorting, alluvium

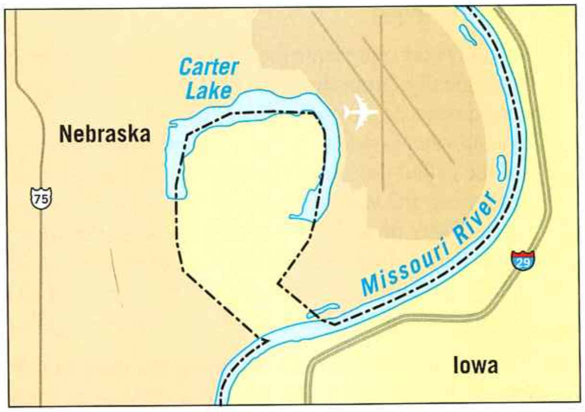
- Streams erode when turbulent water lifts loose particles from the streambed. The focused "drilling" of the stream armed with swirling particles also creates potholes in solid rock.
- Streams transport their load of sediment in solution, in suspension, and along the bottom (bed) of the channel. A stream's ability to transport solid particles is described using two criteria: Capacity refers to how much sediment a stream is transporting, and competence refers to the particle sizes the stream is capable of moving.
- Streams deposit sediment when velocity slows and competence is reduced. This results in sorting, the process by which like-size particles are deposited together.

5.5 STREAM CHANNELS

Contrast bedrock and alluvial stream channels. Distinguish between two types of alluvial channels.

KEY TERMS: meander, cut bank, point bar, cutoff, oxbow lake, braided channel

- Bedrock channels are cut into solid rock and are most common in headwaters areas where gradients are steep. Rapids and waterfalls are common features.
- Alluvial channels are dominated by streamflow through alluvium previously deposited by the stream. A floodplain usually covers the valley floor, with the river meandering or moving through braided channels.
- Meanders change shape through erosion at the cut bank (the outer edge of the meander) and deposition of sediment on point bars (the inside of a meander). A meander may become cut off and form an oxbow lake.



Q The town of Carter Lake is the *only* place in the state of Iowa that is west of the Missouri River. Examine the map and hypothesize how this unusual situation could have occurred.

5.6 SHAPING STREAM VALLEYS

Contrast narrow V-shaped valleys, broad valleys with floodplains, and valleys that display incised meanders.

KEY TERMS: stream valley, base level, floodplain, incised meander

- A stream valley includes the channel itself, the adjacent floodplain, and the relatively steep valley walls. Streams erode downward until they approach base level, the lowest point to which a stream can erode its channel. A river flowing toward the ocean (the ultimate base level) may encounter several local base levels along its route. These could be lakes or resistant rock layers that retard downcutting by the stream.
- A stream valley is widened through the meandering action of the stream, which erodes the valley walls and widens the floodplain. If base level were to drop or if the land were uplifted, a meandering stream might start downcutting and develop incised meanders.

Q Meanders are associated with a river that is eroding from side to side, whereas narrow canyons are associated with rivers that are vigorously downcutting. The river in this image is confined to a narrow canyon but is also meandering. Explain.

Michael Collier

5.7 DEPOSITIONAL LANDFORMS

Discuss the formation of deltas, natural levees, and alluvial fans.

KEY TERMS: bar, delta, distributary, natural levee, back swamp, yazoo tributary, alluvial fan

- A delta may form where a river deposits sediment in another water body at its mouth. The partitioning of streamflow into multiple distributaries spreads sediment in different directions.
- Natural levees result from sediment deposited along the margins of a stream channel by many flooding events. Because the levees slope gently away from the channel, the adjacent floodplain is poorly drained, resulting in back swamps and yazoo tributaries flowing parallel to the main river.
- Alluvial fans are fan-shaped deposits of alluvium that form where steep mountain fronts drop down into adjacent valleys.

Q At first glance, deltas and alluvial fans may look quite similar. How are they similar, and what sets them apart?

5.8 FLOODS AND FLOOD CONTROL

Discuss the causes of floods and some common flood control measures.

KEY TERM: flood

- Floods are triggered by heavy rains and/or snowmelt. Sometimes human interference can worsen or even cause floods. Flood control measures include the building of artificial levees and dams. Channelization may involve creating artificial cutoffs. Many scientists and engineers advocate a nonstructural approach to flood control that involves more appropriate land use.

Q Artificial levees are constructed to protect property from floods. Sometimes artificial levees in rural areas are intentionally opened up to protect a city from experiencing flooding. How does this work?

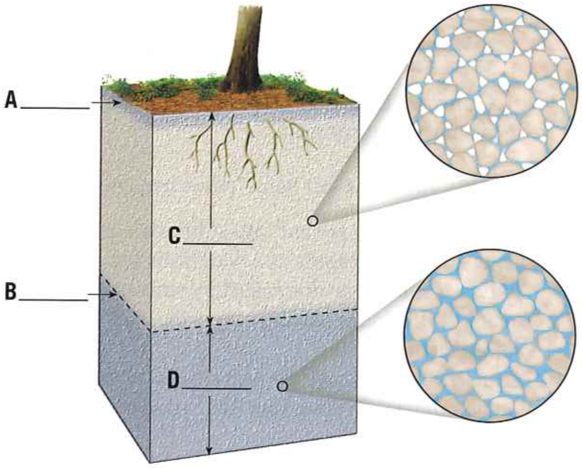
5.9 GROUNDWATER: WATER BENEATH THE SURFACE

Discuss the importance of groundwater and describe its distribution and movement.

KEY TERMS: zone of saturation, groundwater, water table, unsaturated zone, porosity, permeability, aquitard, aquifer

- Groundwater represents the largest reservoir of freshwater that is readily available to humans. Geologically, groundwater is an equalizer of streamflow, and the dissolving action of groundwater produces caverns and sinkholes.
- Groundwater is water that occupies the pore spaces in sediment and rock in a zone beneath the surface called the zone of saturation. The upper limit of this zone is called the water table. The zone above the water table where the material is not saturated is called the unsaturated zone.
- The quantity of water that can be stored in the open spaces in rock or sediment is termed porosity. Permeability, the ability of a material to transmit a fluid through interconnected pore spaces, is a key factor affecting the movement of groundwater. Aquifers are permeable materials that transmit groundwater freely, whereas aquitards are impermeable materials.

Q Examine this profile view showing the distribution of water in relatively uniform unconsolidated sediments and label the various portions of the groundwater complex.



5.10 SPRINGS, WELLS, AND ARTESIAN SYSTEMS

Compare and contrast springs, wells, and artesian systems.

KEY TERMS: spring, perched water table, hot spring, geyser, well, drawdown, cone of depression, artesian system, confined aquifer

- Springs occur where the water table intersects the land surface and a natural flow of groundwater results. When groundwater circulates deep below the surface, it may become heated and emerge at the surface as a hot spring. Geysers occur when groundwater is heated in underground chambers and expands, with some water quickly changing to steam and causing the geyser to erupt. The source of heat for most hot springs and geysers is hot igneous rock.
- Wells, which are openings bored into the zone of saturation, withdraw groundwater and may create roughly conical depressions in the water table known as cones of depression.
- Artesian wells tap into inclined aquifers bounded above and below by aquitards. For a system to qualify as artesian, the water in the well must be under sufficient pressure for the water to rise above the top of confined aquifer. Artesian wells may be flowing or nonflowing, depending on whether the pressure surface is above or below the ground surface.

5.11 ENVIRONMENTAL PROBLEMS OF GROUNDWATER

List and discuss three important environmental problems associated with groundwater.

- Groundwater can be "mined" by being extracted at a rate that is greater than the rate of replenishment. When groundwater is treated as a nonrenewable resource, as it is in parts of the High Plains aquifer, the water table drops, in some cases by more than 45 meters (150 feet).
- The extraction of groundwater can cause pore space to decrease in volume and the grains of loose Earth materials to pack more closely together. This overall compaction of sediment volume results in the subsidence of the land surface.
- Contamination of groundwater with sewage, highway salt, fertilizer, or industrial chemicals is another issue of critical concern. Once groundwater is contaminated, the problem is very difficult to solve, requiring expensive remediation or simply abandonment of the aquifer.

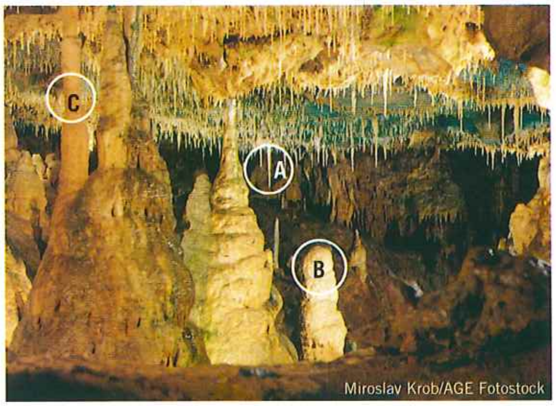
5.12 THE GEOLOGIC WORK OF GROUNDWATER

Explain the formation of caverns and the development of karst topography.

KEY TERMS: cavern, stalactite, stalagmite, karst topography, sinkhole (sink)

- Groundwater dissolves rock, in particular limestone, leaving behind void spaces in the rock. Caverns form at the zone of saturation, but later dropping of the water table may leave them open and dry—and available for people to explore.
- Dripstone is rock deposited by dripping of water containing dissolved calcium carbonate inside caverns. Features made of dripstone include stalactites, stalagmites, and columns.
- Karst topography develops in limestone regions and exhibits irregular terrain punctuated with many depressions called sinkholes. Some sinkholes form when the cavern roofs collapse.

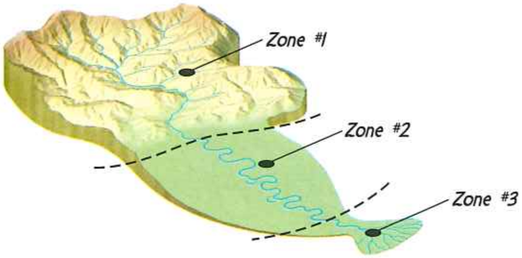
Q Identify the three cavern deposits labeled in this photograph.



Miroslav Krob/AGE Fotostock

GIVE IT SOME **THOUGHT**

1. A river system consists of three zones, based on the dominant process operating in each part of the river system. On the accompanying illustration, match each process with one of the three zones:
   - **a.** Sediment production (erosion)
   - **b.** Sediment deposition
   - **c.** Sediment transport



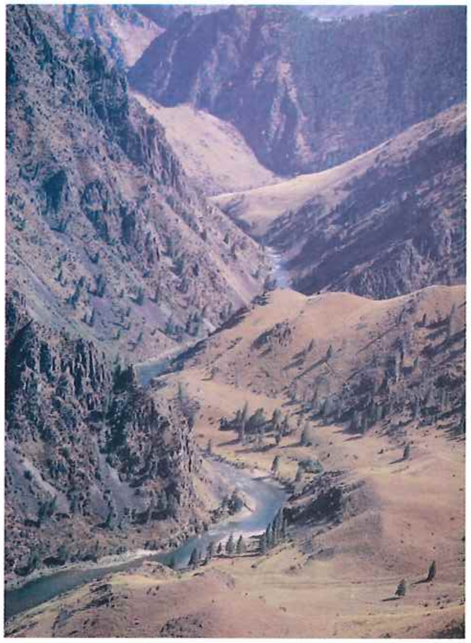
2. What factors influence how much of this rain will soak into the ground compared to how much will run off?

elwynn/Shutterstock

3. If you collect a jar of water from a stream, what part of its load will settle to the bottom of the jar? What portion will remain in the water indefinitely? What part of the stream's load would probably not be represented in your sample?
4. This satellite image shows portions of the Ohio and Wabash Rivers in May 2011. What is the base level for the Wabash River? What is base level for the Ohio River? (*Hint:* Referring to Figure 5.4 will help.) Are either of the base levels you just noted considered *ultimate base level*? Explain.

NASA

5. The Middle Fork of the Salmon River flows for about 175 kilometers (110 miles) through a rugged wilderness area in central Idaho.
   a. Is the river flowing in an alluvial channel or a bedrock channel? Explain.
   b. What process is dominant here: valley deepening or valley widening?
   c. Is the area shown in this image more likely near the mouth or the head of the river?



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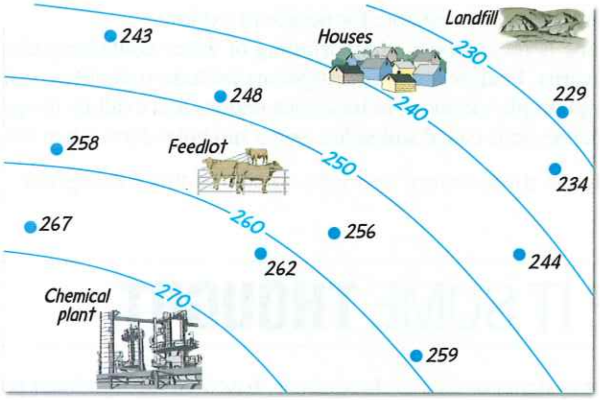
6. Which one of the three basic rock types (igneous, sedimentary, or metamorphic) is most likely to be a good aquifer? Why?
7. What is the likely difference between an intermittent stream (one that flows off and on) and a stream that flows all the time, even during extended dry periods?

Caitlin Mirra/Shutterstock

8. The cemetery in this photo is located in New Orleans, Louisiana. As in other cemeteries in the area, all of the burial plots are above ground. Based on what you have learned in this chapter, suggest a reason for this rather unusual practice.
9. During a trip to the grocery store, your friend wants to buy some bottled water. Some brands promote the fact that their product is artesian. Other brands boast that their water comes from a spring. Your friend asks, "Is artesian water or spring water necessarily better than water from other sources?" How would you answer?
10. Imagine that you are an environmental scientist who has been hired to solve a groundwater contamination problem. Several homeowners have noticed that their well water has a funny smell and taste. Some think the contamination is coming from a landfill, but others think it might be a nearby cattle feedlot or chemical plant. Your first step is to gather data from wells in the area and prepare the map of the water table shown here.
    a. Based on your map, can any of the three potential sources of contamination be eliminated? If so, explain.
    b. What other steps would you take to determine the source of the contamination?

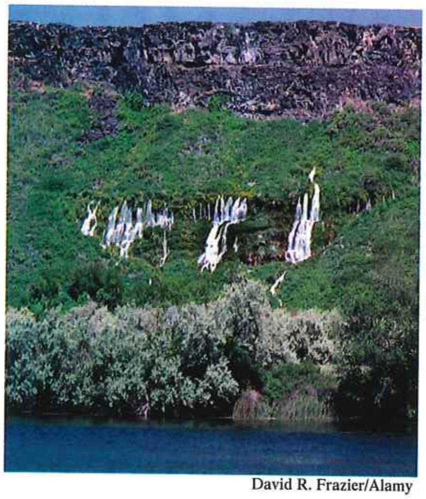


11. This black-and-white photo from the 1930s shows Franklin Roosevelt enjoying the hot springs at the presidential retreat at Warm Springs, Georgia. The temperature of these hot springs is always near 32°C (90°F). This area has no history of recent volcanic activity. What is the likely reason these springs are so warm?

New York Daily News/Getty Images

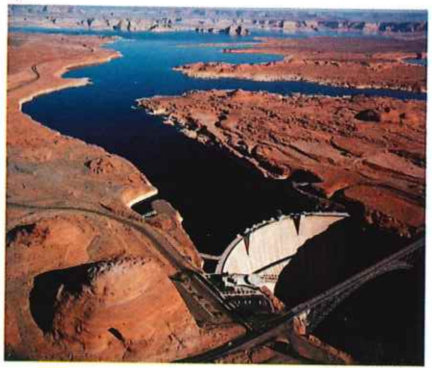
EXAMINING THE **EARTH SYSTEM**

1. This photo shows the famous Thousand Springs along the Snake River in southern Idaho. The springs are natural outlets for groundwater. Is there water in this image that can't be seen? If so, where might it be? Prepare a story that speculates on the answers to the following questions. Suggest several possibilities for both questions:
   - **a.** What journeys did the water in this image take to get to this place?
   - **b.** What paths might the water follow when it makes its way back to the ocean?



David R. Frazier/Alamy

2. Building a dam is one method of regulating the flow of a river to control flooding. Dams and their reservoirs may also provide recreational opportunities and water for irrigation and hydroelectric power generation. This image, from near Page, Arizona, shows Glen Canyon Dam on the Colorado River upstream from the Grand Canyon and a portion of Lake Powell, the reservoir it created.
   - **a.** How did the behavior of the stream likely change upstream from Lake Powell?
   - **b.** How might the behavior of the Colorado River downstream from the dam have been affected?
   - **c.** Given enough time, how might the reservoir change?
   - **d.** Speculate on the possible environmental impacts of building a dam such as this one.



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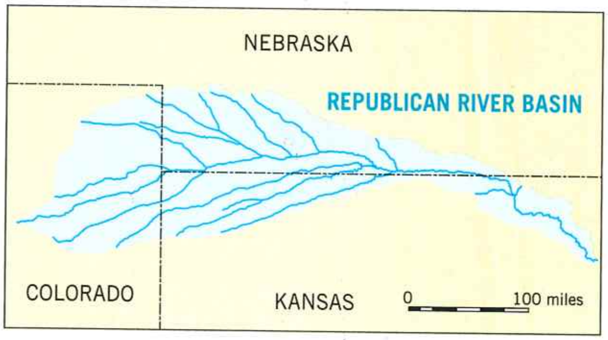
3. Imagine a water molecule that is part of a groundwater system in an area of gently rolling hills in the eastern United States. Describe some possible paths the molecule might take through the hydrologic cycle if:
   - **a.** It were pumped from the ground to irrigate a farm field.
   - **b.** There was a long period of heavy rainfall.
   - **c.** The water table in the vicinity of the molecule developed a steep cone of depression due to heavy pumping from a nearby well.

4. Combine your understanding of the hydrologic cycle with your imagination and include possible short-term and long-term destinations and information about how the molecule gets to these places via evaporation, transpiration, condensation, precipitation, infiltration, and runoff. Remember to consider possible interactions with streams, lakes, groundwater, the ocean, and the atmosphere.

5. A glance at the map shows that the drainage basin of the Republican River occupies portions of Colorado, Nebraska, and Kansas. A significant part of the basin is considered semiarid. In 1943, the three states made a legal agreement regarding sharing the river's water. In 1998, Kansas went to court to force farmers in southern Nebraska to substantially reduce the amount of groundwater they used for irrigation. Nebraska officials claimed that the farmers were not taking water from the Republican River and thus were not violating the 1943 agreement. The court ruled in favor of Kansas.
   - **a.** Explain why the court ruled that groundwater in southern Nebraska should be considered part of the Republican River system.
   - **b.** How might heavy irrigation in a drainage basin influence the flow of a river?



6. Over the oceans, evaporation exceeds precipitation, yet sea level does not drop. Why?

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