Chapter 10

Groundwater

Lechuguilla Cave, New Mexico

What You'll Learn

- How large amounts of water are stored underground.
- How groundwater dissolves limestone and forms caves and other natural features.
- How groundwater is removed from the ground by humans and what problems endanger our groundwater supply.

Why It's Important

Groundwater provides drinking water for half of the world's population and is a major source of the water used by agriculture and industry. However, groundwater supplies are threatened by overuse and pollution.

Earth Science Online

To find out more about groundwater, visit the Earth Science Web Site at earthgeu.com

Discovery Lab

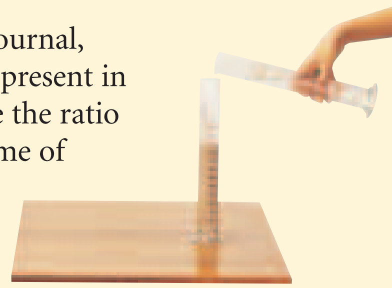
Model Underground Water Storage

Beneath your feet, there are vast amounts of water. This water fills in the pore spaces of sediments and rocks deep in the ground. In this activity, you will discover how much water can be stored in sand.

1. Fill a 250-mL graduated cylinder with dry sand.
2. Fill another 250-mL graduated cylinder with water.
3. Pour water from the second cylinder into the sand-filled cylinder until the water level is flush with the surface of the sand. Measure and record the volume of saturated sand in the cylinder.
4. Measure and record how much water is left in the second cylinder.

CAUTION: Always wear safety goggles and an apron in the lab.

Observe In your science journal, describe how much water is present in the saturated sand. Calculate the ratio of water volume to the volume of sand. Infer how many liters of water could be stored in a cubic meter of sand.



SECTION 10.1 *Movement and Storage of Groundwater*

OBJECTIVES

- **Describe** *how groundwater is stored and moves underground.*
- **Explain** *what an aquifer is.*

VOCABULARY

infiltration
porosity
zone of saturation
water table
permeability
aquifer

If you drill a deep enough hole anywhere on Earth, it will partially fill with groundwater, even in the desert! Groundwater is present everywhere beneath the surface of the land, but nevertheless is a small fraction of all the water on Earth.

THE HYDROSPHERE

The water on and in Earth's crust makes up the hydrosphere, named after *hydros,* the Greek word for "water." About 97 percent of the hydrosphere is contained in the oceans. The water contained by landmasses—nearly all of it freshwater—makes up only about 3 percent of the hydrosphere.

Freshwater is one of Earth's most abundant and important renewable resources. However, of all the freshwater, more than 90 percent is in the form of polar ice caps and glaciers. You may be surprised to

Location	Surface Area (km^2)	Water Volume (km^3)	Percentage of Total Water	Estimated Average Residence Time of Water
Oceans	361 000 000	1 230 000 000	97.2	Thousands of years
Atmosphere	510 000 000	12 700	0.001	Nine days
Rivers and streams	—	1200	0.0001	Two weeks
Groundwater: shallow, to a depth of 0.8 km	130 000 000	4 000 000	0.31	Hundreds to many thousands of years
Lakes (freshwater)	855 000	123 000	0.009	Tens of years
Ice caps and glaciers	28 200 000	28 600 000	2.15	Tens of thousands of years and longer

Table 10-1 World's Water Supply

learn that most of the remaining freshwater is groundwater. All the rivers, streams, and lakes on Earth represent only a small fraction of Earth's liquid freshwater, as shown in ***Table 10-1.***

Precipitation and Groundwater

The ultimate source of all water on land is the oceans. Evaporation of seawater introduces water into the atmosphere in the form of invisible water vapor and visible clouds. Winds and weather systems move this atmospheric moisture all over Earth, much of it over the continents. Precipitation brings atmospheric moisture back to Earth's surface, mostly in the form of rain and snow. Some of this precipitation falls directly into the oceans, and some falls on land.

Much of the precipitation that falls on land enters the ground through the process of **infiltration** and becomes groundwater. Only a small portion of precipitation becomes runoff and is returned directly to the oceans through streams and rivers. Solid precipitation, such as snow, may cover the ground for long periods of time before it melts and becomes runoff or infiltrates to become groundwater. Groundwater slowly moves through the ground, eventually returns to the surface through springs, and then flows back to the oceans.

Groundwater Storage

Puddles of water that are left after a rain quickly disappear, partly by evaporating and partly by percolating into the ground. On sandy soils, rain soaks into the ground almost immediately. Where does that water go? Subsurface Earth materials are not totally solid, but instead contain countless small openings, or pores, which make up a large portion of some of these materials, as you see in ***Figure 10-1.***

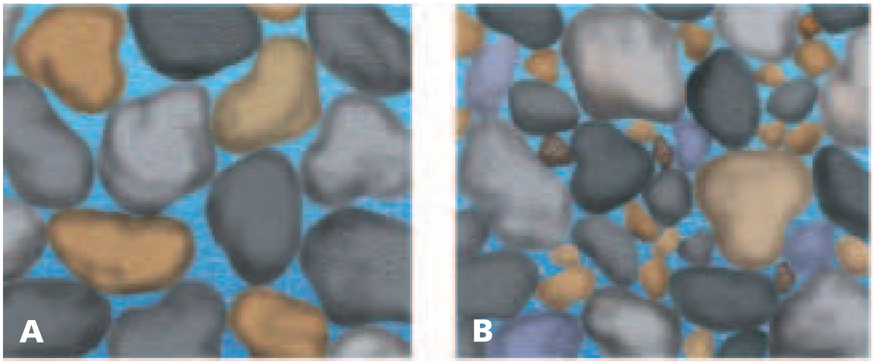


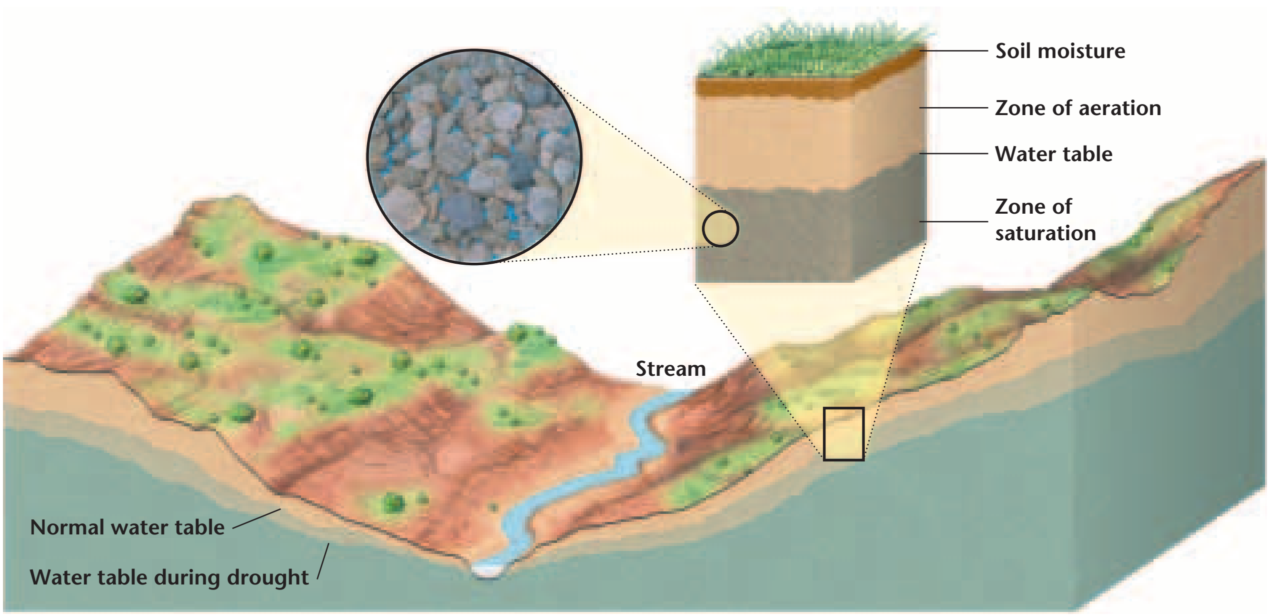
Figure 10-1 Pore spaces in sediments: the highest percentage of porosity is found in well-sorted sediments **(A)** while poorly sorted sediments **(B)** have a lower percentage.

The percentage of pore space in a material is called its **porosity.** Subsurface materials have porosities ranging from 2 or 3 percent to more than 50 percent. For example, the porosity of well-sorted sand is typically around 30 percent. In poorly sorted sediments, however, smaller particles of sediment occupy some of the pore spaces and reduce the overall porosity of these sediments. Similarly, the cement that binds the grains of sedimentary rocks together reduces the rocks' porosity. Nevertheless, enormous quantities of groundwater are stored in the pore spaces of rocks and sediments.

THE ZONE OF SATURATION

The depth below Earth's surface at which groundwater completely fills all the pores of a material is called the **zone of saturation.** The upper boundary of the zone of saturation is the **water table,** as shown in ***Figure 10-2.*** Strictly speaking, only the water in the zone of saturation is called groundwater. In the zone of aeration, which

Figure 10-2 Groundwater flows toward valleys where the water table is close to the surface. During dry periods the level of the water table falls.



is above the water table, materials are moist, but the pores contain mostly air. Water in the zone of saturation can be classified as either gravitational water or capillary water. Gravitational water is water that trickles downward as a result of gravity. Capillary water is water that is drawn upward from the water table and is held in the pore spaces of rocks and sediments as a result of surface tension. Materials that are directly above the water table, especially fine-grained materials, are nearly saturated with capillary water. Capillary action is similar to the action of water that is drawn upward through the pore spaces of a paper towel when the end of it is dipped into water.

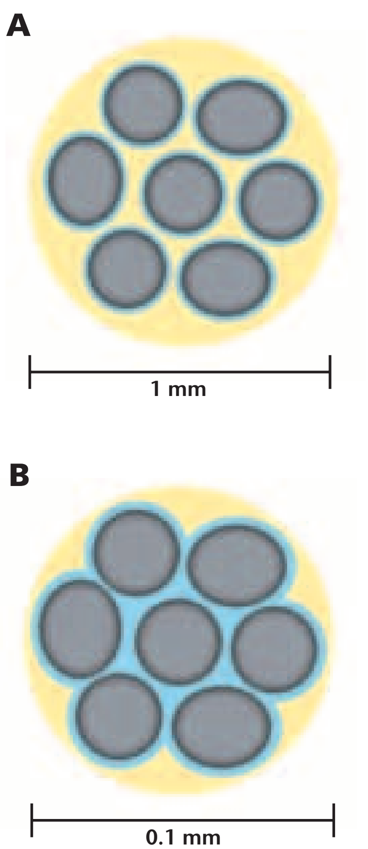


Figure 10-3 In a saturated material, all grains are coated with a thin film of motionless water. In coarse-grained material like sand **(A)** this film occupies a relatively small fraction of the pore space, and moving water can pass freely through the pores. In fine-grained material like silt **(B)** this film occupies most of the pore space and blocks the movement of water. As a result, sand has a much higher permeability than silt.

The Water Table The depth of the water table varies depending on local conditions. For example, in stream valleys, groundwater is close to Earth's surface, and thus the water table is a few meters deep at most. In swampy areas, the water table is almost at Earth's surface, whereas on hilltops or in arid regions, the water table can be tens to hundreds of meters or more beneath the surface. As shown in ***Figure 10-2,*** the topography of the water table follows the topography of the land above it. For example, the water table slopes toward valleys and forms hills under topographic hills. Water table topography forms in this way because water underground moves slowly and conforms to surface contours.

Because of its dependence on precipitation, the water table fluctuates with seasonal and other weather conditions. It rises during wet seasons, usually in spring, and drops during dry seasons, often in late summer.

GROUNDWATER MOVEMENT

Groundwater flows downhill in the direction of the slope of the water table. In most cases, this downhill movement is slow because the water has to squeeze through numerous tiny pores in the subsurface material. In fact, if the pores are small, not even individual water molecules can squeeze through. The ability of a material to let water pass through it is called **permeability.** Materials with large, connected pores, such as sand and gravel, as shown in ***Figure 10-3A,*** have high permeabilities and permit relatively high flow velocities, up to 1 m/h or more. Other permeable subsurface materials include sandstone, limestone, and all highly fractured bedrock.

Fine-grained materials typically have low permeabilities because their pores are so tiny, as shown in ***Figure 10-3B.*** These materials are said to be impermeable. Flow velocities in impermeable materials are so low that they are often measured in meters per year. Some examples of impermeable materials are silt, clay, and shale. Clay is so

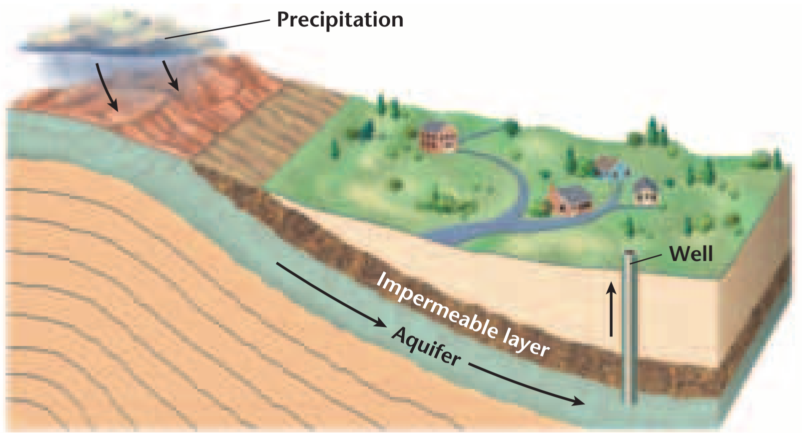


Figure 10-4 The aquifer is located in a permeable sandstone layer that is sealed beneath a capping layer of impermeable rock.

impermeable that a clay-lined depression will hold water. For this reason, clay is often used to line artificial ponds and landfills.

The flow velocity of groundwater primarily depends on the slope of the water table, because the force of gravity pulling the water downward is greater when the slope of the water table surface is steeper. You have experienced a similar effect if you have ever ridden a bicycle down a steep street and a gently sloping street. Although the flow velocity of groundwater is proportional to both the slope of the water table and the permeability of the material through which the water flows, permeability is the major factor. Thus, flow velocities through permeable materials are always higher than those through impermeable materials, regardless of the slope of the water table. Most groundwater flow takes place through permeable layers, called **aquifers,** such as the one shown in ***Figure 10-4.*** Impermeable layers, called aquicludes, are barriers to groundwater flow. In the next section, you'll discover what happens when groundwater moves slowly through materials.

Section Assessment

1. What is the greatest source of freshwater on Earth?
2. Where is the water table closest to Earth's surface: in the floodplain of a river, in a swamp, or on a hilltop?
3. What two factors determine the flow velocity of groundwater?
4. What is an aquifer?
5. **Thinking Critically** What is the difference between porosity and permeability in subsurface materials?

Skill Review

6. **Making and Using Tables** Design a data table that compares and contrasts the porosity and permeability of sand and a mixture of sand and gravel. Which material has the greater porosity? The greater permeability? For more help, refer to the *Skill Handbook*.

Español

SECTION 10.2 Groundwater Erosion and Deposition

OBJECTIVES

- **Explain** *how groundwater dissolves and deposits rocks and minerals.*
- **Describe** *how caves form and how karst topography develops on Earth's surface.*

VOCABULARY

cave
sinkhole
karst topography
stalactite
stalagmite
travertine

In Chapter 3, you learned about the corrosive properties of acids. Acids are solutions that contain hydrogen ions. Most groundwater contains some acid, in most cases carbonic acid. Carbonic acid forms when carbon dioxide dissolves in water and combines with water molecules. This happens when rain falls through the atmosphere and interacts with carbon-dioxide gas or when groundwater percolates through carbon-rich, decaying organic material in soil. As a result of these processes, groundwater is usually slightly acidic and attacks carbonate rocks, especially limestone. Limestone consists mostly of calcium carbonate ($CaCO_3$), which dissolves readily in any kind of acid, the results of which are shown in ***Figure 10-5.***

DISSOLUTION BY GROUNDWATER

The process by which carbonic acid forms and dissolves calcium carbonate can be described by three simple chemical equations.

In the first process, carbon dioxide and water combine to form carbonic acid, as represented by the following equation.

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

In the second process, the carbonic acid (H_2CO_3) molecules in the water split into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). This process is represented by the following equation.

$$H_2CO_3 \longrightarrow H^+ + HCO_3^-$$

In the third process, the hydrogen ions react with calcium carbonate and dissolve it, as represented by the following equation.

$$CaCO_3 + H^+ \longrightarrow Ca^{2+} + HCO_3^-$$

Figure 10-5 A viewing pagoda is standing among the massive limestone pillars of the stone forest in China. Carbonic acid is slowly dissolving the calcium carbonate in the limestone pillars.

For every carbon dioxide molecule dissolved in groundwater, one hydrogen ion is produced and one calcium carbonate molecule is dissolved. The resulting calcium (Ca^{2+}) and bicarbonate (HCO_3^-) ions are then flushed away by the groundwater. Eventually, they precipitate out somewhere else. Precipitation of calcium carbonate occurs when the groundwater evaporates or when the gas carbon dioxide diffuses out of the water. Both the dissolution and formation of calcium carbonate play a major role in the formation of limestone caves.

Figure 10-6 In Mammoth Cave, Kentucky, there are a series of underground passages that extend to a length of more than 500 km.

Caves A natural underground opening with a connection to Earth's surface is called a **cave.** Some caves form three-dimensional mazes of passages, shafts, and great chambers that stretch for many kilometers. Many caves have structures that hang from the caves' ceilings. Some caves are dry, while others contain underground streams or lakes. Still others are totally flooded and can be explored only by cave divers. One of the most spectacular caves is the recently discovered Lechuguilla Cave of New Mexico, shown in the photograph at the beginning of this chapter. Another cave system in New Mexico, Carlsbad Caverns, includes a huge subterranean chamber over 1 km long and 100 m high. Mammoth Cave, in Kentucky, as shown in ***Figure 10-6,*** is composed of a series of connected underground passages.

Practically all caves of significant size are formed when groundwater dissolves limestone. Most caves develop in the zone of saturation just below the water table. As groundwater percolates through the cracks and joints of limestone formations, it gradually dissolves the adjacent rock and enlarges these passages to form an interconnected network of openings. Thus, the limestone formation becomes more permeable. The resulting increased downhill flow of groundwater gradually lowers the water table until much of the cave system is filled with air. New caves then form beneath the lowered water table. If the water table continues to drop, the thick limestone formations eventually become honeycombed with caves and caverns. This is a common occurrence in limestone regions that have been uplifted by tectonic forces.

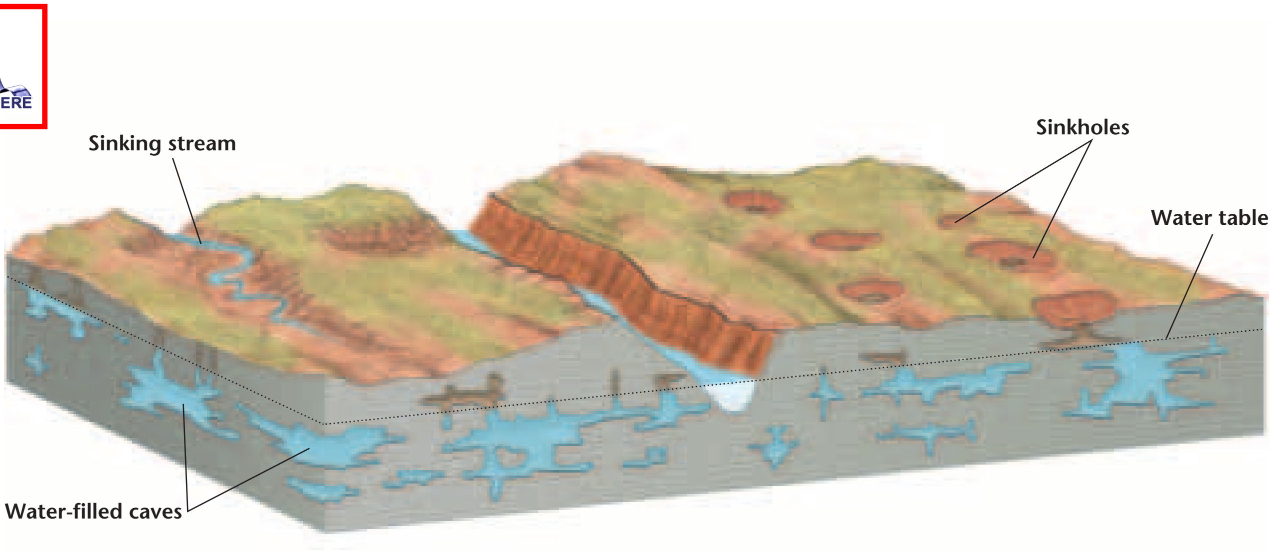


Figure 10-7 In the development of karst topography, caves form near or below the water table. Streams deepen their valleys. The water table drops and new caves form below the water table. Collapsing caves or dissolution of bedrock at the surface produce sinkholes.

Karst Topography *Figure 10-7* shows some of the characteristic surface features produced by the dissolution of limestone. The main feature is a **sinkhole,** as shown in ***Figure 10-8.*** A sinkhole is a depression in the ground caused by the collapse of a cave or by the direct dissolution of bedrock by acidic rain or moist soil. Another type of feature forms when a surface stream drains into a cave system, continues underground, and leaves a dry valley above. Such a stream, called a sinking stream, sometimes reemerges abruptly on Earth's surface as a karst spring.

Limestone regions that have sinkholes, sinks, and sinking streams are said to have **karst topography.** The word *karst* comes from the name of a limestone region in Croatia where these features are

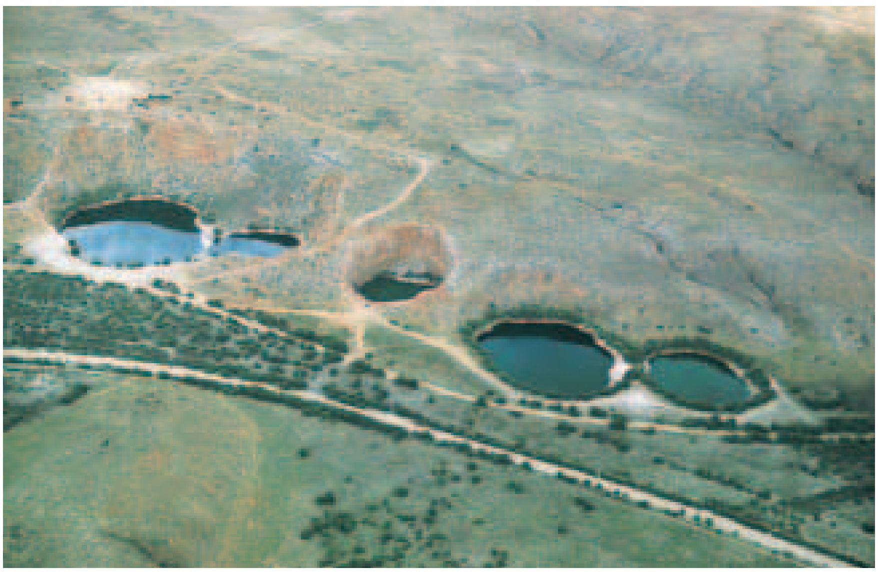


Figure 10-8 Sinkholes developed near Roswell, New Mexico.

Figure 10-9 Dissolved minerals can build up thick deposits in plumbing pipes.

especially well developed. Prominent karst regions in the United States are located in Kentucky. The Mammoth Cave region in Kentucky has karst topography that contains tens of thousands of sinkholes. Most of the lakes in Central Florida are sinkholes.

Groundwater Deposits

You are probably aware that your tap water contains various dissolved materials. Some water contains sulfur compounds, and some contains dissolved iron compounds. Water that contains iron compounds typically leaves brownish or red stains on kitchen and bathroom fixtures.

Hard Water Water that contains high concentrations of calcium, magnesium, or iron is called hard water. Hard water is common in limestone areas where the groundwater is nearly saturated with calcium carbonate. Household use of hard water usually can cause a problem: deposits of calcium bicarbonate eventually clog water pipes, as shown in ***Figure 10-9.*** These problems can be controlled with a water softener, which removes dissolved ions from hard water. Water that contains few dissolved ions is called soft water.

Natural Deposits The most remarkable deposits produced by groundwater are the dripstone formations that decorate many caves above the water table. As their name indicates, these formations are built slowly as water drips through caves. Each drop of water hanging on the ceiling of a cave loses some of its carbon dioxide and deposits a tiny amount of calcium carbonate. Over many years, these deposits gradually form cone-shaped or cylindrical structures called

Using Math

Using Numbers
Each drop of water deposits a 1-nm-thick layer of calcium carbonate at the tip of a stalactite growing in a cave. Given that 1 nm = 10^{-9} m, if a drop falls every 30 seconds, what length, in centimeters, will the stalactite be in 100 years? How many years will it take for the stalactite to reach a length of 5 m?

Figure 10-10 Stalactites, stalagmites, and dripstone columns are found in the Carlsbad Caverns of New Mexico.

stalactites that hang from the cave's ceiling like icicles. As the water drops splash to the floor of the cave, they gradually build mound-shaped dripstone deposits, called **stalagmites,** underneath the stalactites. In time, stalactites and stalagmites may grow together to form dripstone columns, such as the ones shown in ***Figure 10-10.*** These and other types of dripstone formations are composed of a type of limestone called **travertine.**

SECTION ASSESSMENT

1. What acid is most commonly present in groundwater?
2. How do caves form?
3. Compare the formation of stalactites and stalagmites.
4. What is karst topography?
5. **Thinking Critically** If you visited a region that consisted mostly of igneous rocks, would you expect to find karst topography? Explain.

SKILL REVIEW

6. **Concept Mapping** Use the following terms to construct a concept map to organize the major ideas in this section. For more help, refer to the *Skill Handbook.*

clogged water pipes | stalagmites | sinkholes | karst topography | calcium carbonate | hard water | Croatia | stalactites | caves

SECTION 10.3 Groundwater Systems

The average length of time that groundwater remains underground is several hundred years. Groundwater moves slowly but continuously through aquifers and eventually returns to Earth's surface. You may wonder how this can happen. Can groundwater flow upward against gravity? In some cases, it can, as you will learn in this section. In most cases, however, groundwater emerges wherever the water table intersects Earth's surface. Such intersections commonly occur in areas that have sloping surface topography. The exact places where groundwater emerges depend on the arrangement of aquifers and aquicludes in an area.

OBJECTIVES

- **Relate** *the different types of springs to common systems of aquifers.*
- **Explain** *how groundwater is withdrawn from aquifer systems by wells.*
- **Describe** *the major problems that threaten groundwater supplies.*

VOCABULARY

spring
hot spring
geyser
well
drawdown
recharge
artesian well

SPRINGS

You have learned that aquifers are permeable underground layers through which groundwater moves with relative ease, while aquicludes are impermeable layers. Aquifers are commonly composed of layers of sand and gravel, sandstone, and limestone. Because of its many solution cavities, limestone is usually highly permeable and permits high flow velocities. Underground streams in cavernous limestone formations may transport groundwater at a rate of several kilometers per day. In contrast, aquicludes, such as layers of clay or shale, block groundwater movement. As a result, groundwater tends to discharge at Earth's surface where an aquifer and an aquiclude come in contact, as shown in ***Figure 10-11.*** These natural discharges of groundwater are called **springs.**

Figure 10-11 A spring occurs where an aquifer and an aquiclude come in contact at Earth's surface. At this point, the water flows out of the rock.

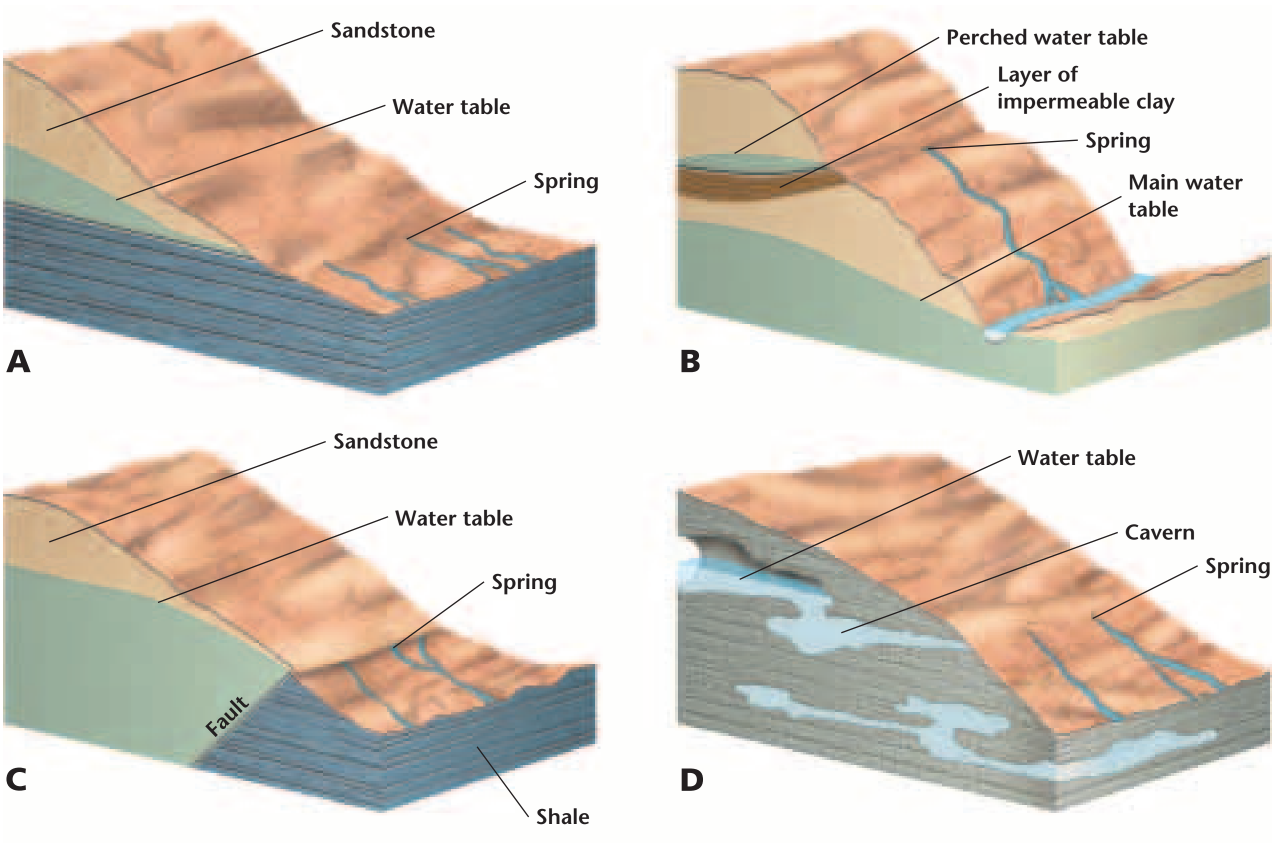


Figure 10-12 Springs occur in various places, such as at the sides of valleys and at the edges of perched water tables. The volume of water varies from the flow of a small spring to the rush of a large river.

Emergence of Springs The volume of water that is discharged by a spring may be a mere trickle, or, in karst regions, an entire river may emerge from the ground. Such a superspring is called a karst spring. Many of Florida's lakes are flooded sinkholes that are fed by karst springs whose discharge causes full-sized rivers to flow out of these lakes. In regions of near-horizontal sedimentary rocks, springs often emerge on the sides of valleys at about the same elevation, at the bases of aquifers, as shown in ***Figure 10-12A.*** Springs may also emerge at the edges of perched water tables. A perched water table, as shown in ***Figure 10-12B,*** is a zone of saturation that overlies an aquiclude that separates it from the main water table below. Other areas where springs tend to emerge are along faults, which are huge fractures that offset rock formations and sometimes block aquifers, as shown in ***Figure 10-12C.*** In limestone regions, springs discharge water from underground pathways, as shown in ***Figure 10-12D.***

Temperature of Springs Spring water is usually thought of as being cool and refreshing. Actually, the temperature of groundwater that is discharged through a spring is generally the average annual temperature of the region in which it is located. Thus, springs in New

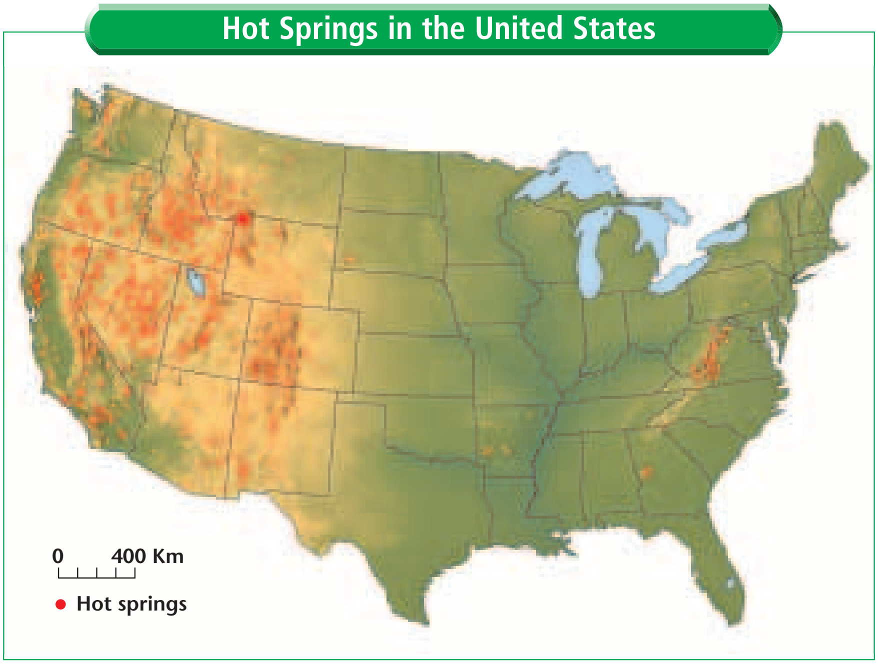


Figure 10-13 Hot springs occur in many areas of the United States.

England have year-round temperatures of about 10°C, while those in the Gulf states have temperatures of about 20°C.

Compared to air temperatures, groundwater is colder in the summer and warmer in the winter. However, in some regions of the United States, certain springs discharge water that is much warmer than the average annual temperature. These springs are called warm springs or hot springs, depending on their temperatures. **Hot springs** have temperatures higher than that of the human body. There are thousands of hot springs in the United States alone, as shown in ***Figure 10-13.*** Most of these are located in the western United States in areas where the subsurface is still quite hot from relatively recent igneous activity. A number of hot springs also occur in some eastern states. These eastern hot springs emerge from aquifers that descend to great depths in Earth's crust and allow deep, hot water to rise. The underground water is hot because temperatures in Earth's crust increase with depth by about 25°C for every kilometer. Among the most spectacular features produced by Earth's underground heat in volcanic regions are geysers, as shown in ***Figure 10-14.*** **Geysers** are explosive hot springs that erupt at regular intervals. One of the world's most famous geysers, Old Faithful, is located in Yellowstone National Park, Wyoming. Old Faithful erupts approximately every hour with a 40-m high column of boiling water and steam.

Figure 10-14 The Black Rock Desert geyser is a hot spring that erupts at regular intervals in Nevada.

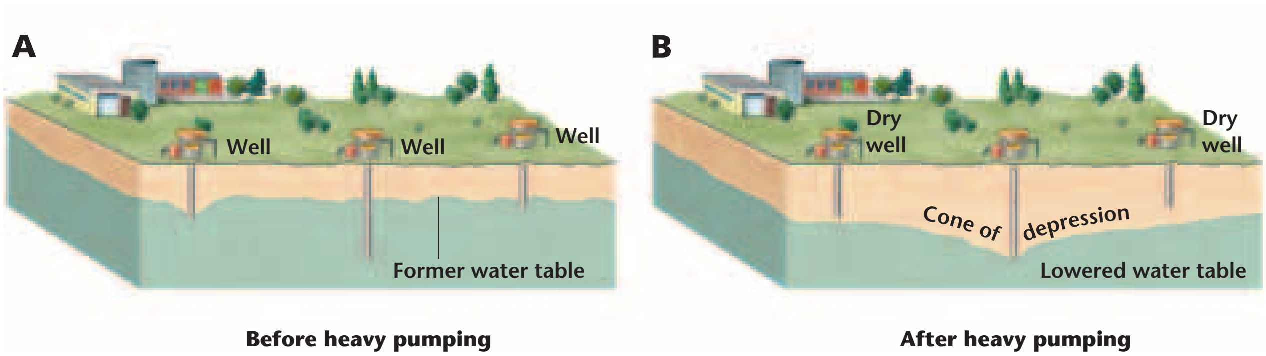


Figure 10-15 Wells must be drilled far enough below the water table so that they are not affected by seasonal water table fluctuations **(A).** Overpumping of wells causes a lowering of the entire water table **(B).**

WELLS

Wells are holes dug or drilled deep into the ground to reach a reservoir of groundwater. To produce water, a well must tap into an aquifer. The simplest wells are those that are dug or drilled below the water table, into the zone of saturation, and into what is called a water-table aquifer, as shown in ***Figure 10-15A.*** Initially, the water level in such a well is the same as the level of the water table. However, overpumping of the well lowers the water level in it and produces a cone of depression in the water table around the well, as shown in ***Figure 10-15B.*** The difference between the original water-table level and the water level in the pumped well is called the **drawdown.** If many wells withdraw water from a water-table aquifer, their cones of depression may overlap and cause an overall lowering of the water table, which can cause shallow wells to go dry. Water from precipitation and runoff is added back to the zone of saturation in the process of **recharge.** Groundwater recharge from precipitation and runoff sometimes replenishes the water withdrawn from wells. However, if recharge does not keep pace with groundwater withdrawal, the water table continues to drop until all wells in the area go dry.

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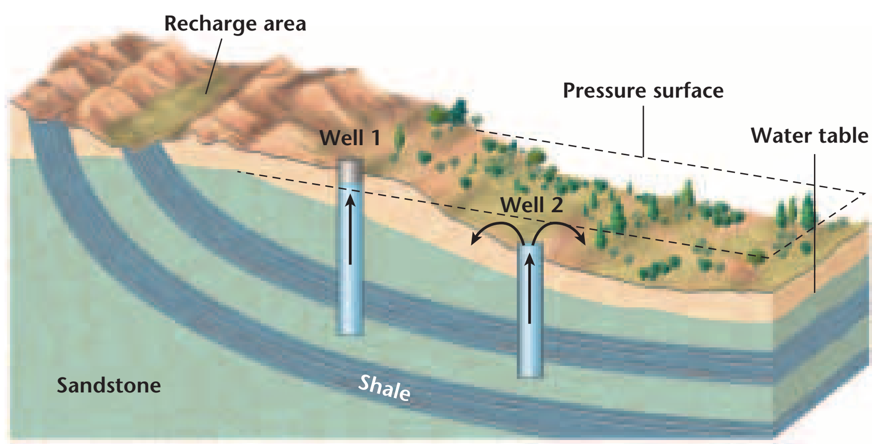


Figure 10-16 The level to which the water in an artesian well can rise is called the pressure surface.

CONFINED AQUIFERS

Water-table aquifers are unconfined and unprotected, and thus, they are easily polluted. Surface spills of pollutants often reach the water table and spread throughout aquifers. More reliable and less easily polluted water supplies can be found in deeper aquifers, called confined aquifers, which are generally sandwiched between aquicludes. The aquicludes form barriers that prevent pollutants from reaching such aquifers.

Artesian Wells Because the area of recharge is usually at a higher elevation than the rest of an aquifer, a confined aquifer contains water under pressure, as you can see by doing the *Problem-Solving Lab* on this page. The aquifer is called an artesian aquifer. When the rate of recharge is high enough, the pressurized water in a well drilled into a confined aquifer may spurt above the land surface in the form of a fountain called an **artesian well,** as shown in ***Figure 10-16.*** Similarly, a spring that discharges pressurized water is called an artesian spring.

Problem-Solving Lab

Using Tables and Making Graphs

Make inferences about the water levels of an artesian aquifer Artesian aquifers contain water under pressure. The table provides the following data about an artesian aquifer for three sites, spaced 100 m apart, along a survey line: elevations of the land surface, the water table, and the upper surface of the aquiclude on top of the artesian aquifer; and the artesian pressure surface, which is the level to which the artesian water can rise.

Site	Surface Elevation	Water Table Elevation	Aquiclude Elevation	Pressure Surface
1	396 m	392 m	388 m	394 m
2	394	390	386	393
3	390	388	381	392

Analysis

1. Plot the elevation data on a graph with the sites on the *x*-axis and the elevations on the *y*-axis. Make a cross section of the survey line from site 1 to site 3. Use a heavy line to indicate the land surface.
2. A well has been drilled at each site. The wells at sites 1 and 3 are 7 m deep. The well at site 2 was drilled into the artesian aquifer at a depth of 14 m. Sketch the wells at their proper depths on your cross section.

Thinking Critically

3. At what depth below the ground surface are the water levels in the three wells before they are pumped?
4. What would happen if a well was drilled into the confined aquifer at site 3?
5. At what sites could there be an artesian spring?

MiniLab

How does an artesian well work?

Model the changes that an artesian aquifer undergoes when a well is dug into it. What causes the water to rise above the ground surface?

Procedure ***CAUTION: Always wear safety goggles and an apron in the lab.***

1. Half-fill a plastic shoe box or other container with sand. Add enough water to saturate the sand. Cover the sand completely with a 1-or 2-cm layer of clay or a similar impermeable material.
2. Tilt the box at an angle of about 10°. Use a book for a prop.
3. Punch three holes through the clay, one each near the low end, the middle, and the high end of the box. Insert a clear straw through each hole into the sand below. Seal the holes around the straws.

Analyze and Conclude

1. Observe the water levels in the straws. Where is the water level the highest? The lowest?
2. Where is the water table in the box?
3. Where is the water under greatest pressure? Explain.
4. Predict what will happen to the water table and the surface if the water flows from one of the straws.

The name *artesian* is derived from the French province of Artois, where such wells were first drilled almost 900 years ago. To discover how an artesian well works, refer to the *MiniLab* on this page.

An important artesian aquifer in the United States is the Ogallala Aquifer, which is located in the Great Plains. This aquifer delivers water to a huge area stretching from South Dakota to Texas. The recharge areas of the Ogallala Aquifer are located in the Black Hills and the Rocky Mountains.

Threats to Our Water Supply

Freshwater is Earth's most precious natural resource. Think about it! You can survive without gasoline, without electricity, and without most of the other materials that may seem to be essential, but you can't live without water. Human demands for freshwater are enormous. Not only is water used in households, but it is also used extensively in agriculture and industry, as shown in ***Figure 10-17.*** Groundwater supplies much of this water.

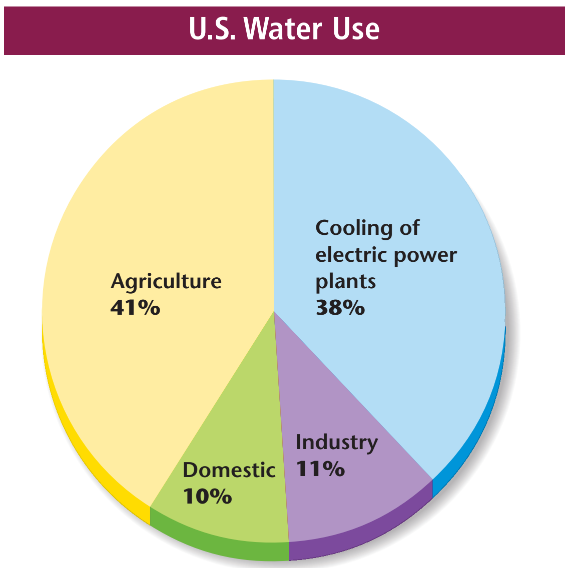


Figure 10-17 In the United States, the greatest amount of water usage is for agricultural activities, mostly for irrigation.

Overuse Groundwater supplies can be depleted. If groundwater is pumped out at a rate greater than the recharge rate, the groundwater supply will inevitably decrease, and the water table will drop. This is what is happening to the Ogallala Aquifer. Its water, used mostly for irrigation, is being withdrawn at a rate much higher than the recharge rate. You will learn more about the Ogallala Aquifer in the *Science & Environment* feature at the end of the chapter.

Subsidence Another problem caused by the excessive withdrawal of groundwater is ground subsidence, the sinking of land. The weight of the material overlying an aquifer is partly borne by water pressure. If that pressure is reduced, the weight of the overlying material is increasingly transferred to the aquifer's mineral grains, which then squeeze together more tightly. As a result, the land surface above the aquifer sinks.

Pollution in Groundwater In general, the most easily polluted groundwater reservoirs are water-table unconfined aquifers. Confined aquifers are affected less frequently by local pollution because they are protected by impermeable barriers. When the recharge areas of confined aquifers are polluted, however, those aquifers become contaminated as well.

The most common sources of groundwater pollution are sewage, industrial waste, landfills, and agricultural chemicals. These pollutants enter the ground above the water table, but they are eventually flushed downward by infiltrating precipitation and become mixed with the groundwater. Most sewage enters groundwater from sources such as faulty septic tanks. In highly permeable aquifers, all pollutants, including raw sewage, can spread quickly, as shown in ***Figure 10-18.***

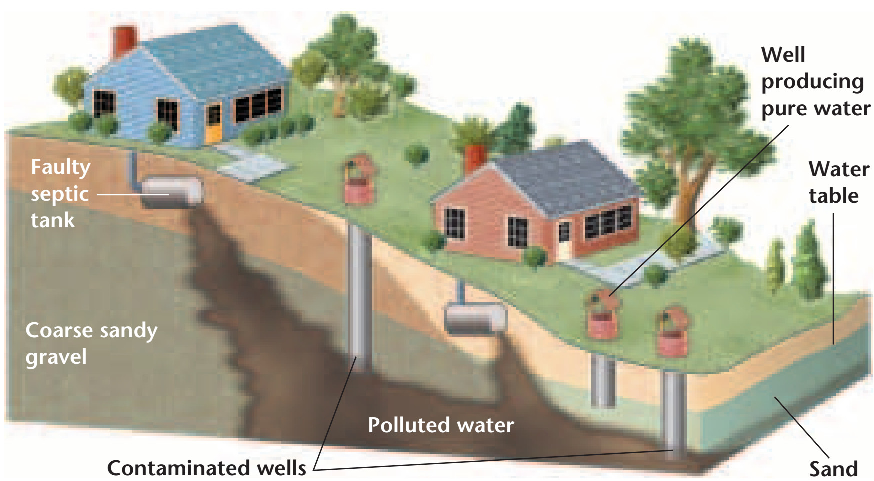


Figure 10-18 Pollutants from sewage are traveling through a coarse-grained aquifer that will contaminate downslope wells.

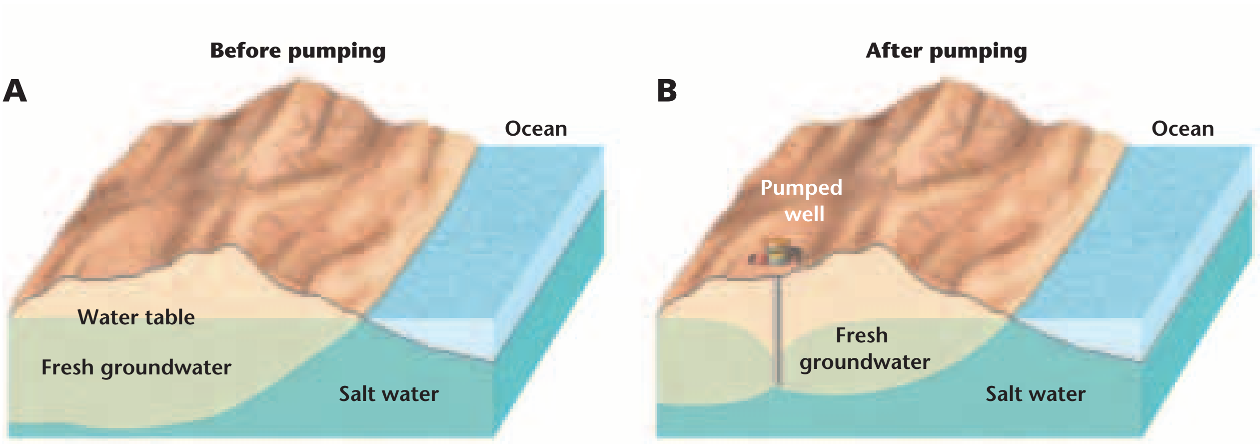


Figure 10-19 Saltwater incursion into groundwater can occur in coastal areas **(A).** Freshwater floats on top of denser seawater within the aquifer **(B).** Overpumping of wells draws the underlying saltwater into the wells and the freshwater zone.

Chemicals Chemicals dissolved or transported with groundwater are in the form of ions and molecules, so they cannot be filtered out in fine-grained sediments. For this reason, chemicals such as arsenic can contaminate any type of aquifer. They generally move downslope from a source in the form of a pollution plume, a mass of contaminants that spreads through the environment. Once chemical contaminants have entered groundwater, they cannot be easily removed.

Salt Not all pollutants are toxic or unhealthful in and of themselves. For example, ordinary table salt is widely used to season food. However, water is undrinkable when its salt content is too high. In fact, salt pollution is one of the major threats to groundwater supplies. In many coastal areas, the contamination of freshwater by salt water is the major problem. In such areas, the fresh groundwater near Earth's surface is underlain by denser, salty seawater as shown in ***Figure 10-19A.*** The overpumping of wells can cause the underlying salt water to rise into the wells and contaminate the freshwater aquifer, as shown in ***Figure 10-19B.***

Radon Another source of natural pollution is radioactive radon gas, which is one of the leading causes of cancer in the United States. This form of radon is generated by the radioactive decay of uranium in rocks and sediments, and it usually occurs in very low concentrations in all groundwater. However, some rocks, especially granite and shale, contain more uranium than others. The groundwater in areas where these rocks are present therefore contains more radioactive radon than normal. Some of this radon may seep into houses, and, because it is heavier than air, it can accumulate in poorly ventilated basements. The U. S. Environmental Protection Agency (EPA) advises homeowners in radon-prone regions to regularly have their homes tested for radon gas.

Earth Science Online

Topic: Groundwater
To find out more about the ways to protect groundwater, visit the Earth Science Web Site at earthgeu.com

Activity: Write a TV ad describing measures being taken in your community to protect the groundwater.

Table 10-2 Groundwater Pollution Sources

Accidental spills from vehicles
Leaks from storage tanks
Seepage from acid mine drainage
Seepage from faulty septic systems
Saltwater intrusion into aquifers near shorelines
Leaks from waste disposal sites

Protecting Our Water Supply

There are a number of ways in which groundwater resources can be protected and restored. First, all major pollution sources, which are listed in ***Table 10-2,*** need to be identified and eliminated. Pollution plumes that are already in the ground can be monitored with observation wells and other techniques. You will learn more about pollution plumes in the *Mapping GeoLab* at the end of this chapter. Most pollution plumes spread slowly. Thus, there is often time for alternate water supplies to be found. In some cases, pollution plumes can be stopped by the building of impermeable underground barriers. Polluted groundwater can be pumped out for chemical treatment on the surface.

While these measures can have limited success, they alone cannot save Earth's water supply. An important part of the solution is for humans to become more aware of how their activities impact the groundwater system.

Section Assessment

1. How are springs related to the water table?
2. What is the basic characteristic of an artesian well?
3. List four common sources of groundwater pollution.
4. Why are chemical contaminants a serious pollution problem in groundwater?
5. Artesian aquifers contain water under pressure. Explain why.
6. **Thinking Critically** What can you do to conserve and protect groundwater so that there will be safe and abundant water supplies in the future?

Skill Review

7. **Comparing and Contrasting** Compare and contrast different uses of water in the United States. For more help, refer to the *Skill Handbook.*

earthgeu.com/self_check_quiz

Mapping GeoLab

Mapping Pollution

You can use a map to estimate the direction of groundwater flow and the movement of a pollution plume from its source, such as a leaking underground gasoline storage tank.

Preparation

Problem

A major gasoline spill occurred at Jim's Gas Station near Riverside Acres, Florida. How can you determine the movement of the resulting pollution plume?

Materials

USGS topographic map of Forest City, Florida
transparent paper
ruler
graph paper
calculator

Procedure

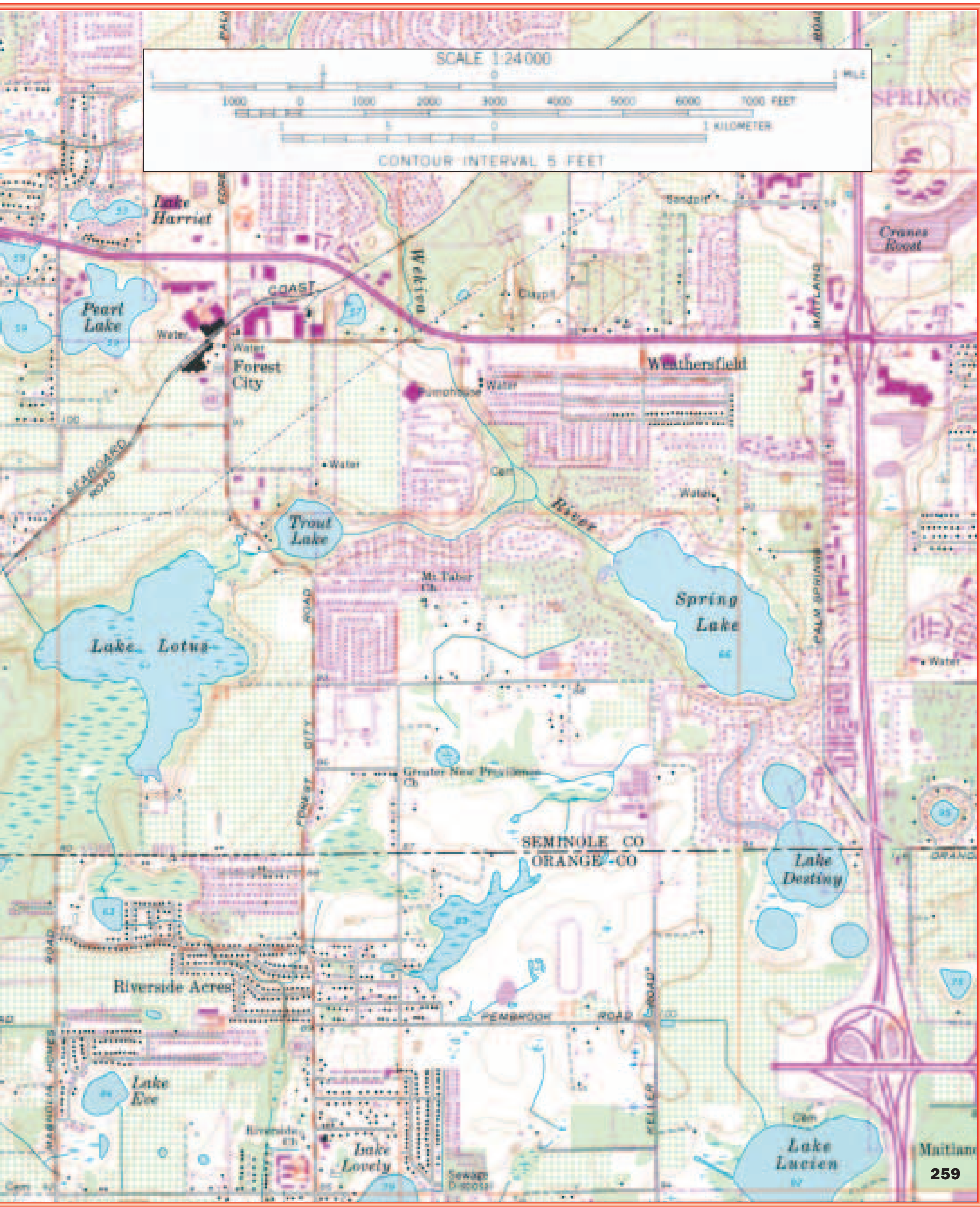
1. Identify the lakes and swamps in the southeast corner of this map, and list their names or numbers and elevations in a data table. Note: The elevations are given or can be estimated from the contour lines.
2. Place the transparent paper over the southeast part of the map and trace the approximate outlines of these lakes or swamps, as well as the major roads. Enter lake or swamp elevations on your overlay, and indicate the location of Jim's gas station on Forest City Rd., about 1400 feet north of the Seminole County line (at the 96 foot elevation mark).
3. Add contour lines to your overlay using a contour interval of 10 feet.
4. Construct a cross section of the surface topography and the water table from Lake Lotus to Lake Lucien (through Jim's Gas Station).

Analyze

1. What is the slope of the water table at Jim's Gas Station?
2. What is the approximate direction of the water table slope at Jim's Gas Station?
3. In which direction will the pollution plume move?
4. Which settlements or houses are threatened by this pollution plume?

Conclude & Apply

1. How far below the surface is the water table in the highest area?
2. What is the relationship of the water table to the surface topography?


SCALE 1:24 000
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 KILOMETER
CONTOUR INTERVAL 5 FEET
Lake Harriet
Pearl Lake
COAST
Forest City
SEABOARD ROAD
Wekiva
Trout Lake
Lake Lotus
Mt. Tabor Ch.
River
Spring Lake
Weathersfield
Pumphouse
Water
Cem
Sandpit
Cranes Roost
SPRINGS
MAITLAND
PALM SPRINGS
FOREST CITY ROAD
Greater New Providence Ch
SEMINOLE CO
ORANGE CO
Lake Destiny
Riverside Acres
PEMBROOK ROAD
KELLER ROAD
MAGNOLIA HOMES
Lake Eve
Riverside Ch
Lake Lovely
Sewage Disposal
Lake Lucien
Maitland

The High Plains Aquifer

The High Plains Aquifer, also known as the Ogallala Aquifer, is located beneath parts of Colorado, Kansas, Nebraska, New Mexico, South Dakota, Texas, Oklahoma, and Wyoming. Environmentalists are concerned about the future of this source of fresh groundwater.

Long Term Effects of Water Use

Buried beneath 106 250 km^2 of sand and rock lies the largest groundwater system in the United States, the High Plains Aquifer, also known as the Ogallala Aquifer. The High Plains Aquifer, which contains the Ogallala Formation, is made of clay, gravel, sand, and silt. The result of deposition from an ancient snow melt in the Rocky Mountains region, the formation is divided into two sections. The upper section is known as the unsaturated zone. The lower section contains the Ogallala Aquifer, the water-bearing area. The Ogallala makes up approximately 80 percent of the High Plains Aquifer.

The aquifer's freshwater supply has been used for many years. Shortly after World War I, farmers began tapping into the groundwater reserves in Texas. By 1940, the aquifer had become a widely used source of irrigation in the Great Plains region as more and more farmers began to pump water from the aquifer.

By 1980, it was estimated that parts of the aquifer's water level were down as much as 30 meters. Because of concern about the decline in water levels, the U.S. Geological Survey began a monitoring program in 1988. The program revealed that from 1980 to 1994, water levels continued to decline in certain areas of the Texas High Plains, the Oklahoma Panhandle, and southwestern Kansas. In the eastern High Plains of Nebraska, higher than normal amounts of rainfall since 1980 have caused either a rise in the water level or a slower decline.

Demand placed upon the water supply over the years increased rapidly as more wells were drilled. In 1950, an estimated 8.6 trillion L of water were pumped from the aquifer. By 1980, the estimated amount had increased to 24 trillion L. The amount of water currently being pumped from the aquifer far exceeds the amount of water naturally replenished. Presently, 89 percent of the aquifer's water supply is still available despite the 170 000 wells drawing water. However, it has been predicted that by the year 2020, 25 percent of the water supply could be exhausted.

What Needs to be Done

While scientists cannot be sure that the aquifer will ever be completely depleted, there is reason to be concerned about the continuous lowering of water levels in the region. Wells in some areas overlying the aquifer have gone dry. Concerns about the depletion of the water supply have prompted several states to develop regulatory policies to protect this natural resource, which has often been taken for granted.

Activity

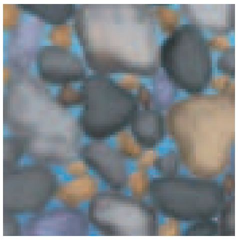
Research and construct a 3-dimensional model of the Ogallala Aquifer. Include the states that are part of the groundwater system. Label the aquifer's zone of saturation and water table.

CHAPTER 10 Study Guide

Summary

SECTION 10.1

Movement and Storage of Groundwater



Main Ideas

- Some precipitation infiltrates the ground to become groundwater.
- Groundwater is stored below the water table in the pore spaces of rocks and moves through permeable layers called aquifers. Impermeable layers are called aquicludes.

Vocabulary

aquifer (p. 243)
infiltration (p. 240)
permeability (p. 242)
porosity (p. 241)
water table (p. 241)
zone of saturation (p. 241)

SECTION 10.2

Groundwater Erosion and Deposition

Main Ideas

- Groundwater dissolves limestone and forms underground caverns. Sinkholes form at Earth's surface when bedrock is dissolved or when caves collapse. Irregular topography caused by groundwater dissolution is called karst topography.
- The precipitation of dissolved calcium carbonate forms stalactites, stalagmites, and travertine deposits, including dripstone columns, in caves.

Vocabulary

cave (p. 245)
karst topography (p. 246)
sinkhole (p. 246)
stalactite (p.248)
stalagmite (p. 248)
travertine (p. 248)

SECTION 10.3

Groundwater Systems

Main Ideas

- The natural discharge of groundwater takes place through springs. Springs emerge where the water table intersects Earth's surface.
- Wells are drilled into the zone of saturation to provide water for human needs. The pumping of shallow wells produces cones of depression in the water table. Artesian wells tap deep, confined aquifers that contain water under pressure.
- In many regions, groundwater withdrawal exceeds groundwater recharge and causes considerable lowering of the water table as well as ground subsidence.
- The most common sources of groundwater pollution are sewage, industrial waste, landfills, and agricultural chemicals.

Vocabulary

artesian well (p. 253)
drawdown (p. 252)
geyser (p. 251)
hot spring (p. 251)
recharge (p. 252)
spring (p. 249)
well (p. 252)

earthgeu.com/vocabulary_puzzlemaker

CHAPTER 10 Assessment

Understanding Main Ideas

1. Where is most freshwater found on Earth?
   a. the oceans
   b. the atmosphere
   c. polar ice caps and glaciers
   d. lakes and rivers

2. What is a major source of freshwater in the United States?
   a. the Rocky Mountain snowpack
   b. the Mississippi River
   c. groundwater
   d. the Great Lakes

3. What happens to most of the precipitation that falls on land?
   a. It evaporates. **c.** It seeps into the ground.
   b. It becomes runoff. **d.** It becomes glacial ice.

4. What source usually replenishes groundwater?
   a. precipitation **c.** underground streams
   b. surface water **d.** municipal wastewater

5. Of the following materials, which is the most porous?
   a. a well-sorted sand **c.** sandstone
   b. a poorly sorted sand **d.** granite

6. Of the following materials, which is the most permeable?
   a. sandstone **c.** silt
   b. shale **d.** clay

7. What is the main characteristic of an aquifer?
   a. surface topography **c.** subsidence
   b. permeability **d.** dissolution

8. Which rock type is most easily dissolved by groundwater?
   a. sandstone **c.** limestone
   b. granite **d.** shale

9. What are the cone-shaped dripstone deposits that are found on the floor of caves?
   a. icicles **c.** stalactites
   b. rocksicles **d.** stalagmites

10. Which of the following are typical features of karst topography?
    a. moraines **c.** sinkholes
    b. dunes **d.** landslides

11. Where is groundwater closest to Earth's surface?
    a. in stream valleys
    b. on hilltops
    c. on mountaintops
    d. in arid regions

12. What does hard water usually contain?
    a. fluorine **c.** carbonic acid
    b. chloride **d.** calcium

13. What do artesian aquifers always contain?
    a. hot water **c.** salt water
    b. water under pressure **d.** steam

14. Which of the following is a common groundwater problem in coastal areas?
    a. saltwater contamination
    b. contamination by crude oil
    c. high sulfur content
    d. excessive recharge

Test-Taking Tip

BREATHE Oxygen helps to calm the anxiety associated with test-taking. When you start to feel your stomach lurch, take a deep breath and exhale slowly.

Assessment

Applying Main Ideas

15. What is the difference between soft water and hard water?

16. What type of bedrock most likely exists in an area that has numerous sinkholes?

17. Subsurface temperatures increase with depth by about 25°C/km. What is the subsurface temperature 2 km below the surface in a region where the average annual surface temperature is 10°C?

18. A dripping water faucet in your home has produced brownish-red stains in the sink. What could have caused these stains?

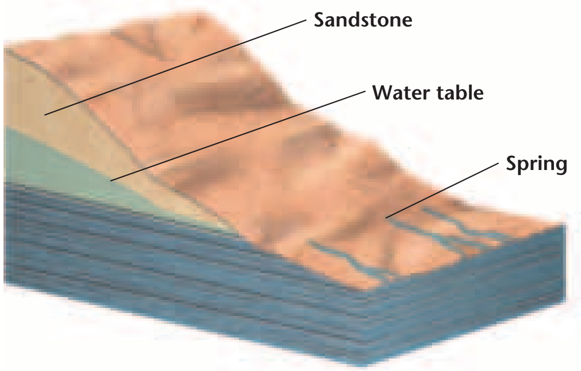
19. Describe the processes involved in the formation of caves.

20. If the withdrawal of groundwater from an artesian aquifer exceeds the groundwater recharge, what consequence can be expected?

Thinking Critically

21. A well drilled into a water-table aquifer produces water only during springtime. Why?

Use the diagram below to answer question 22.



22. Make an inference on what can happen to the spring if the water table drops.

Standardized Test Practice

1. Which of the following materials would be best suited for lining a pond?
a. gravel
b. limestone
c. clay
d. sand

2. What are natural structures hanging from a cave's ceiling?
a. geyserites
b. travertines
c. stalagmites
d. stalactites

3. Which of the following usually describes the temperature of groundwater flowing through a natural spring?
a. hotter than the region's average temperature
b. cooler than the region's average temperature
c. the same temperature no matter where the spring is located
d. the same temperature as the region's average temperature

4. Which of the following water sources are the most easily polluted?
a. water-table aquifers
b. confined aquifers
c. artesian wells
d. hot springs

5. What is the composition of dripstone formations?
a. carbonic acid
b. carbon dioxide
c. iron oxide
d. calcium carbonate

earthgeu.com/standardized_test

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UNIT 3

GeoDigest

For a **preview** of Earth's surface processes, study this GeoDigest before you read the chapters. After you have studied the chapters, you can use the GeoDigest to **review** the unit.

Surface Processes on Earth

Weathering, Erosion, and Soil

Chemical and mechanical weathering break down Earth materials. Chemical weathering causes a change in the composition of a rock. Agents of chemical weathering include hydrolysis, oxidation, acids from decaying organic matter, and acid precipitation. Each of these processes or substances combines with Earth materials, resulting in new combinations of minerals or in other substances. Mechanical weathering causes a change only in a rock's size and shape. Temperature and pressure are the major factors in mechanical weathering. Temperature changes can cause rocks to split. Pressure changes can cause rocks to crack or break apart.

Yosemite National Park, California

Erosion and Deposition Gravity is the driving force behind all agents of erosion, the process by which weathered pieces of rock are moved to new locations. Other agents of erosion include moving water, wind, and glaciers. Deposition occurs when the movement of transported materials slows down and they are dropped in a new location.

Formation of Soil Soils vary with climate and are classified as polar, temperate, desert, or tropical. A single centimeter of soil takes hundred of years to develop, but can erode away in just seconds. Soil is made of weathered rock and decayed organic matter called humus. Residual soil remains on top of its parent bedrock. Transported soil is moved away from its parent bedrock by weathering agents. A cross section of layers of soil is called a soil profile. The top layer, called horizon A, is topsoil. Horizons B and C are subsoil. Below horizon C is solid bedrock. Parent rock and environmental conditions determine a soil's composition. Soil texture is determined by the relative amounts of clay, sand, and silt the soil contains. Soil fertility is a soil's ability to grow crops. Farmers conserve soil through methods that include wind barriers.

Mass Movements, Wind, and Glaciers

The landscape is changed by mass movements, wind, and glaciation. Mass movement refers to the movement of Earth materials downslope as a result of gravity. Almost all of Earth's surface undergoes mass movements, which may be slow, as in creep, or rapid, as in landslides, mudflows, rock slides, rock falls, and avalanches. Mass movements are affected by the weight of the material involved, its level of

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GeoDigest

saturation, its resistance to sliding, and sometimes, a trigger such as an earthquake. Mass movements can cause great damage and loss of life.

Wind Limited precipitation and scarce vegetation, conditions common to arid, semi-arid, and seashore environments, contribute to wind erosion. Wind-carried sediment causes abrasive action which wears down or polishes the sides of rocks that face the wind. Wind-formed Earth features include deflation blowouts, desert pavement, and sand dunes. Dunes are classified by shape as barchan, transverse, longitudinal, or parabolic. Wind-deposited soils called loess contain minerals and nutrients and are highly fertile.

Glaciers Large, moving masses of ice called glaciers form near Earth's poles and high in mountains, where cold temperatures keep fallen snow from completely melting. Over time, the weight of the snow exerts enough downward pressure to cause the accumulated snow to recrystallize into ice. Glacial features include U-shaped valleys, hanging valleys, and waterfalls in the mountains; moraines, drumlins, and kettles in outwash plains; and a variety of glacially formed lakes. Valley glaciers form in mountains and move downslope. Valley glaciers are much smaller than continental glaciers, which form over broad regions and spread out from their centers.

Tahquamenon River, Michigan

Sand overwhelms building, Namibia

Surface Water

Many landscape features on Earth are produced and changed by surface water. The amount of water in the ground depends on the number and sizes of pores in a particular Earth material and the amount of vegetation. A watershed or drainage basin is the land area drained by a stream system. Divides, which are raised areas of land, separate watersheds. All of the material carried by the stream, including material in solution, in suspension, and as bed load, is called the stream's load. Throughout history, humans built communities near water sources for survival and economic reasons. However, this practice has left humans vulnerable to dangerous floods. Weather and stream monitoring provides warnings of flooding.

Stream Development At a stream's source, or headwaters, water from precipitation begins its flow in channels confined by the stream's banks. Mountain streams have rapidly flowing water and often form waterfalls. When stream velocity

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GeoDigest

decreases, the stream's load is deposited in triangle-shaped alluvial fans or deltas. Alluvial fans form when streams flow out onto plains. Deltas form when streams enter large bodies of water. Uplifting of the land or lowering of the base level causes a stream to undergo rejuvenation and again begin to cut a V-shaped valley.

Lakes and Freshwater Wetlands Lakes form when depressions on land fill with water. Some lakes are human-made. When nutrients from fertilizers, detergents, or sewage enter a lake, eutrophication may be accelerated. The nutrients lead to an overabundance of some organisms and then a depletion of oxygen. Wetlands such as bogs, marshes, and swamps are low areas that regularly fill with water and support specific plants. Wetlands filter and clean water and are protected by law.

Groundwater

Groundwater is the largest source of freshwater available for human use. Groundwater is the portion of precipitation that infiltrates into the ground and is stored below the water table in the pore spaces of rocks. Groundwater moves through permeable layers called aquifers. Most groundwater contains carbonic acid which attacks carbonate rocks such as limestone which consists of calcium carbonate. The dissolution and precipitation of calcium carbonate plays a role in the formation of limestone caves. Caverns, sinkholes, karst topography, and travertine deposits are formed from groundwater action.

Groundwater Systems Springs, which are natural discharges of groundwater, emerge where the water table intersects Earth's surface. Wells drilled into the zone of saturation provide water for humans, but pumping of these wells may cause cones of depression in the water table. Artesian wells contain water under pressure from confined aquifers. When groundwater withdrawal exceeds groundwater recharge, it causes considerable lowering of the water table and ground subsidence. Pollution of aquifers may come from sewage, industrial waste, agricultural chemicals, and landfills.

Vital Statistics

Earth's Eight Longest Rivers

Nile (Africa)	6650 km
Amazon (South America)	6400 km
Yangtze (Asia)	6300 km
Mississippi-Missouri (North America)	5971 km
Yenisey (Asia)	5540 km
Ob-Irtysh (Asia)	5410 km
Paraná (South America)	4880 km
Congo (Africa)	4700 km

FOCUS ON CAREERS

Landscaper

A landscaper makes a plan for outdoor scenery in an area and then follows the plan by planting the gardens and grounds. In addition to knowing about plants, a landscaper needs to know the soil characteristics and water drainage patterns in the area. Landscape architects have college degrees, but many others in the field start out with a high school degree and then gather the training they need on the job.

GeoDigest

ASSESSMENT

Understanding Main Ideas

1. What is the most powerful agent of erosion?
   a. water
   b. wind
   c. glaciers
   d. living things

2. What material makes up horizon B in a soil profile?
   a. topsoil
   b. loess
   c. subsoil
   d. bedrock

3. What is the underlying force of all agents of erosion?
   a. suspension
   b. friction
   c. magnetism
   d. gravity

4. Which of the following types of mass movement is not rapid?
   a. a landslide
   b. a mudflow
   c. an avalanche
   d. creep

5. What erosional agent causes deflation blowouts, desert pavement, and dunes?
   a. wind
   b. water
   c. earthquakes
   d. groundwater

6. Which of the following is a characteristic of valley glaciers?
   a. They form over broad regions.
   b. They move downslope.
   c. They are larger than continental glaciers.
   d. They completely melt each summer.

7. Which of the following occurs when a stream's velocity decreases?
   a. The stream load increases.
   b. The stream cuts a V-shaped valley.
   c. Deposition occurs.
   d. A drainage basin is formed.

8. Where do alluvial fans mostly occur?
   a. near lakes
   b. along the bases of mountains
   c. on the outside of meanders
   d. where streams enter the ocean

9. Of the following materials, which one is most permeable?
   a. mud
   b. clay
   c. silt
   d. gravel

10. What is the largest source of freshwater on Earth?
    a. lakes
    b. groundwater
    c. oceans
    d. glaciers

Thinking Critically

1. Describe the agents of erosion involved in chemical weathering.
2. Explain how groundwater works to form sedimentary rock.
3. How would you describe a soil's texture?
4. Discuss at least two factors that affect mass movement.
5. List at least two reasons why wetlands should be protected.

Himalayas