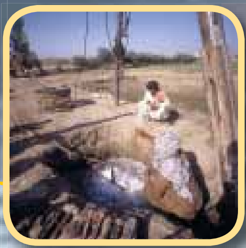
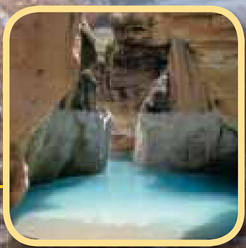
Chapter 16

Groundwater

Chapter Outline





Why It Matters

Groundwater is a major source of fresh water for humans. Where molten rock in Earth's crust heats groundwater and surrounding rock, hot springs form. These macaque monkeys bathe in hot springs in Jigokudani National Park in Japan.

Inquiry Lab Growing Stalactites

15 min

Place **two jars** on a **piece of cardboard.** Fill each jar two-thirds full of **Epsom salts.** Then, fill with **warm water** to the top of the salt and stir to make a thick solution. Soak a **40 cm piece of twine** in the solution until it is thoroughly wet. Then tie a **weight** onto each end of the twine. Place one end of the twine in each jar. The middle of the twine should hang between the two jars, lower than the water levels, but should not touch the cardboard. Place your set-up somewhere where it will not be disturbed. Observe what happens to the twine over several days.

Questions to Get You Started

1. Describe the formation that appears on the twine. How do you think this formed?
2. How is the formation on the twine similar to the natural formation called a stalactite?

READING TOOLBOX

These reading tools will help you learn the material in this chapter.

Word Origins

Words that Come from Place Names In Section 2, you will learn about *karst topography,* a landscape characterized by caverns, sinkholes, and underground drainage. The term *karst topography* comes from *Karst,* the German name for a region of Slovenia, formerly a part of Yugoslavia, known for its caves.

Your Turn In Section 1, you will learn about *artesian wells*. Use a dictionary or the Internet to learn how these wells got their name. Create a table like the one below and use the information you find to fill it in.

Term	Definition	Etymology (Word Origin)
Artesian wells		

Describing Time

Temporal Language The word *temporal* means "related to time." Temporal language is language that is used to describe time. Paying careful attention to temporal language can help you understand the temporal nature of events and processes.

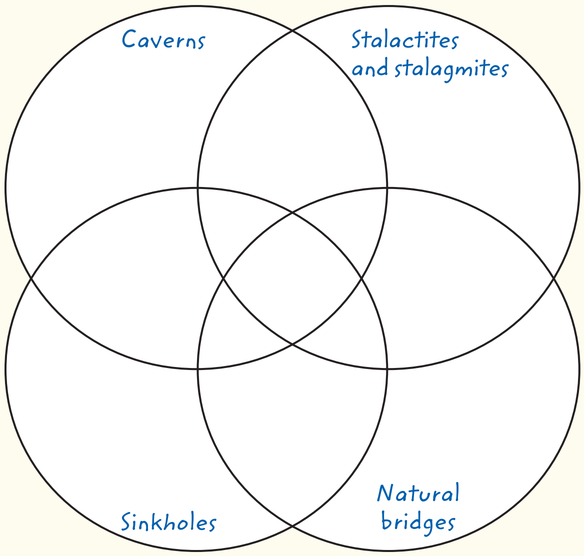
Your Turn As you read Section 2, make a two-column table. In the first column, write words or phrases in the text that refer to time. In the second column, note the context of the time reference.

Time Reference	Context of Time Reference
slowly	how carbonic acid dissolves limestone
often	when stalactites and stalagmites grow together to form columns

Graphic Organizers

Venn Diagrams A Venn diagram is a graphic representation of the relationships between similar things or ideas. See Appendix A for instructions for making a Venn diagram.

Your Turn As you read Section 2, complete a Venn diagram to represent the relationships between different features formed by chemical weathering.



For more information on how to use these and other tools, see **Appendix A.**

SECTION 1 Water Beneath the Surface

Key Ideas	Key Terms	Why It Matters
❯ Identify properties of aquifers that affect the flow of groundwater. ❯ Describe the water table and its relationship to the land surface. ❯ Compare wells, springs, and artesian formations. ❯ Describe two land features formed by hot groundwater.	**groundwater** **aquifer** **porosity** **permeability** **water table** **artesian formation**	Almost one-fourth of all fresh water used in the United States comes from groundwater sources. Understanding how water and the ground interact may affect the way you treat the environment.

Surface water that does not run off into streams and rivers may seep down through the soil into the upper layers of Earth's crust. There, the water fills spaces, or *pores,* between rock particles. Water may also fill fractures or cavities in rock that were caused by erosion. Water that fills and moves through these spaces in rock and sediment is called **groundwater.**

Properties of Aquifers

A body of rock or sediment in which large amounts of water can flow and be stored is called an **aquifer.** For water to flow freely through an aquifer, the pores or fractures in the aquifer must be connected. The ease with which water flows through an aquifer is affected by many factors, including porosity and permeability.

groundwater the water that is beneath Earth's surface

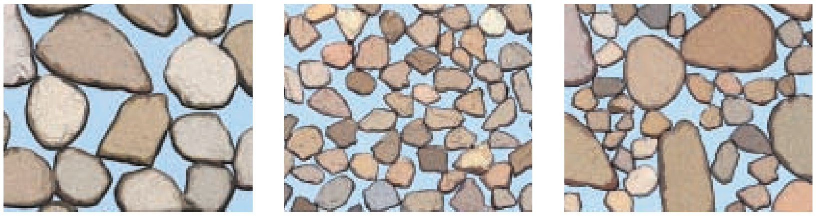
aquifer a body of rock or sediment that stores groundwater and allows the flow of groundwater

porosity the percentage of the total volume of a rock or sediment that consists of open spaces

Porosity

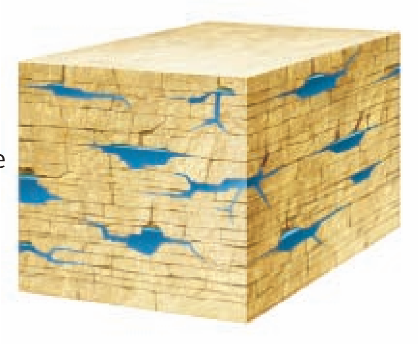
In a set volume of rock or sediment, the percentage of the rock or sediment that consists of open spaces is **porosity.** One factor that affects porosity is sorting. *Sorting* is the amount of uniformity in the size of the rock or sediment particles, as **Figure 1** shows. Most particles in a well-sorted sediment are about the same size. Poorly sorted sediment contains particles of many sizes. Small particles fill the spaces between large particles, which makes the rock less porous. Particle packing also affects porosity. Loosely packed particles leave many open spaces that can store water, so the rock has high porosity. Rock that has tightly packed particles contains few open spaces and thus has low porosity. Grain shape also affects porosity. In general, the more irregular the grain shape is, the more porous the rock or sediment is.

Figure 1 Differences in Porosity



Well Sorted   Well Sorted   Poorly Sorted

Pores and fractures are empty spaces that make a rock porous. Here, fractures in the rock are filled with water.



Rock is considered permeable if its empty spaces are connected so that water may flow from one space to the next.

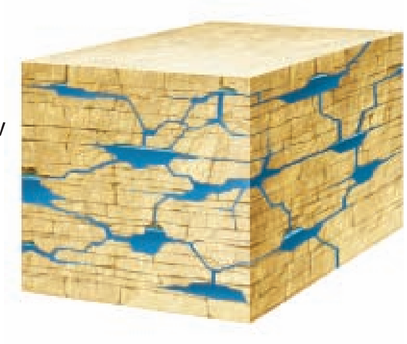


Figure 2 Porous rocks do not make good aquifers unless water can move freely through the rocks.

permeability the ability of a rock or sediment to let fluids pass through its open spaces, or pores

Permeability

The ease with which water passes through a porous material is called **permeability.** For a rock to be permeable, the open spaces must be connected, as shown in **Figure 2.** Rock that has high porosity is not permeable if the pores or fractures are not connected. Permeability is also affected by the size and sorting of the particles that make up the rock or sediment. The larger and better sorted the particles are, the more permeable the rock or sediment tends to be. The most permeable rock, such as sandstone, is composed of coarse particles. Other types of rock, such as limestone, may be permeable if they have interconnected cracks. Clay is a sediment composed of flat, very fine-grained particles. Because of this characteristic composition, clay is essentially *impermeable,* which means that water cannot flow through it.

Quick Lab — Permeability

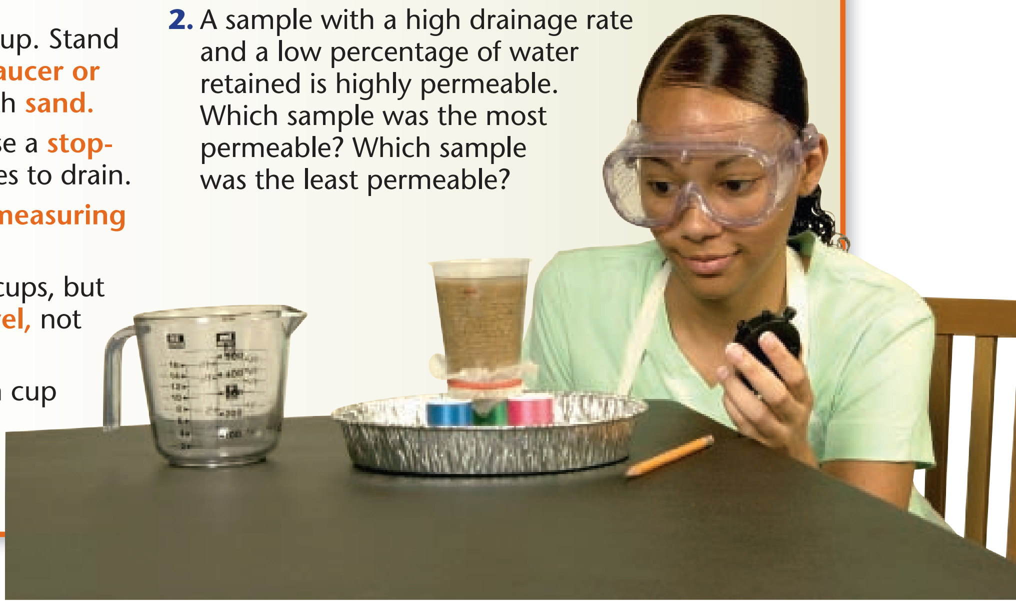
20 min

Procedure

1. With a **sharpened pencil,** make seven tiny holes in the bottom of each of **three paper or plastic cups.** Stretch **cheesecloth** tightly over the bottom of each cup. Secure the cloth with a **rubber band.**
2. Mark a line 2 cm from the top of one cup. Stand the cup on **three thread spools** in a **saucer or pie pan,** and fill the cup to the line with **sand.**
3. Pour **120 mL of water** into the cup. Use a **stopwatch** to time how long the water takes to drain.
4. Pour the water from the saucer into a **measuring cup.** Record the amount of water.
5. Repeat steps 2 to 4 with the two other cups, but fill one cup with **soil** and one with **gravel,** not sand.
6. Calculate the rates of drainage for each cup by dividing the amount of water that drained by the time the water took to drain.
7. For each cup, calculate the percentage of water retained by subtracting the amount of water drained from 120 mL. Divide this volume by 120.

Analysis

1. Which cup had the highest drainage rate?
2. A sample with a high drainage rate and a low percentage of water retained is highly permeable. Which sample was the most permeable? Which sample was the least permeable?



Zones of Aquifers

Soil particles attract water molecules and hold water in the soil. When there is more water than the soil can hold, gravity pulls water down through the rock layers until it reaches impermeable rock. As more water soaks into the ground, the water level rises underground and forms two distinct zones of groundwater, as shown in **Figure 3.**

Zone of Saturation

The layer of an aquifer in which the pore space is completely filled with water is the *zone of saturation*. The term *saturated* means "filled to capacity." The zone of saturation is the lower of the two zones of groundwater. The upper surface of the zone of saturation is called the **water table.**

water table the upper surface of underground water; the upper boundary of the zone of saturation

Zone of Aeration

The zone that lies between the water table and Earth's surface is called the *zone of aeration*. The uppermost region of the zone of aeration holds soil moisture—water that forms a film around grains of topsoil. The bottom region, just above the water table, is the capillary fringe. Water is drawn up from the zone of saturation into the capillary fringe by capillary action. *Capillary action* is caused by the attraction of water molecules to other materials, such as soil. For example, when a paper towel soaks up a spill, capillary action draws moisture into the towel. Between the soil moisture region and the capillary fringe is a region that contains both air and water in its pores.

SCILINKS.
www.scilinks.org
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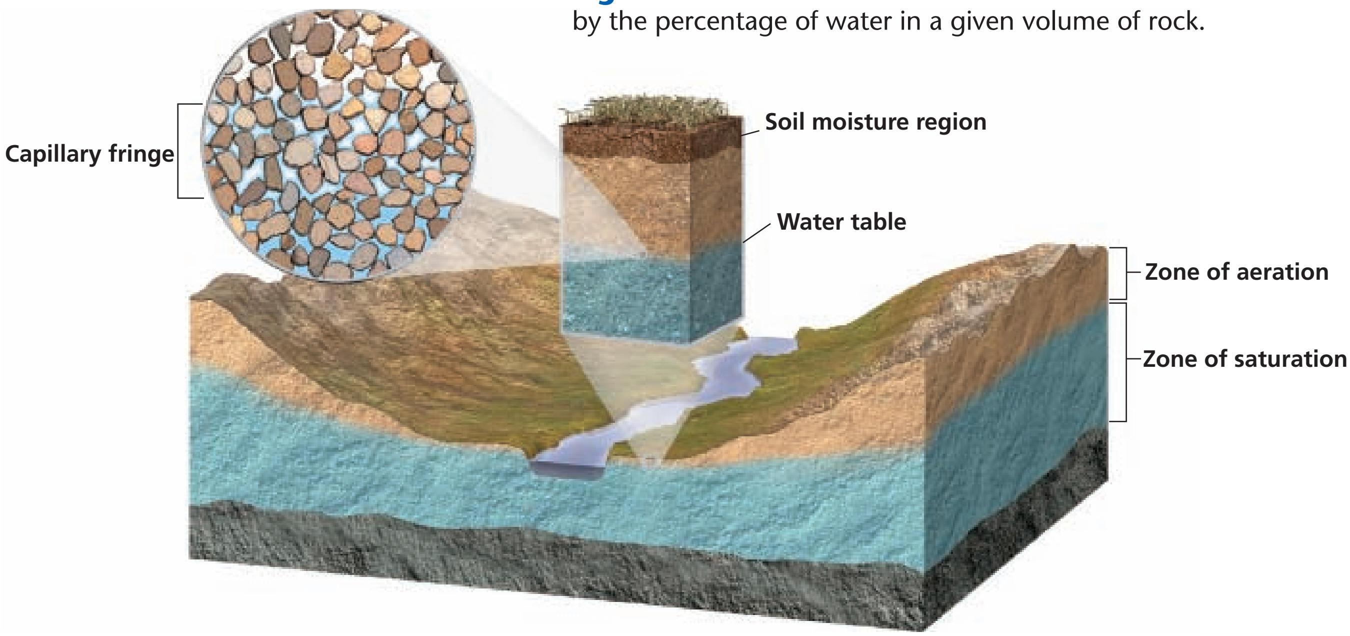
Reading Check **What are the two zones of groundwater?** (See Appendix G for answers to Reading Checks.)

Figure 3 Groundwater is divided into zones that are defined by the percentage of water in a given volume of rock.



Movement of Groundwater

Like water on Earth's surface, groundwater flows downward in response to gravity. Water passes quickly through highly permeable rock and slowly through rock that is less permeable. The rate at which groundwater flows horizontally depends on both the permeability of the aquifer and the gradient of the water table. *Gradient* is the steepness of a slope. The speed of groundwater increases as the water table's gradient increases.

Math Skills

Rate of Groundwater Depletion In some areas, more groundwater is removed than is naturally replaced. In one area, for example, 575 million cubic meters of water enters the rock every year, while 1,500 million cubic meters of water is removed each year. What is the rate of groundwater depletion in that area? The total amount of groundwater available is 6,475 million cubic meters. If groundwater use continues at the current rate, in how many years will the water be completely depleted?

Topography and the Water Table

The depth of the water table below the ground surface depends on surface topography, the permeability of the aquifer, the amount of rainfall, and the rate at which humans use the water. Generally, shallow water tables match the contours of the surface, as shown in **Figure 4.** During periods of prolonged rainfall, the water table rises. During periods of drought, the water table falls and flattens because water that leaves the aquifer is not replaced.

Only one water table exists in most areas. In some areas, however, a layer of impermeable rock lies above the main water table. This rock layer prevents water from reaching the main zone of saturation. Water collects on top of this upper layer and creates a second water table, which is called a *perched water table*.

Reading Check **What four factors affect the depth of a water table?**

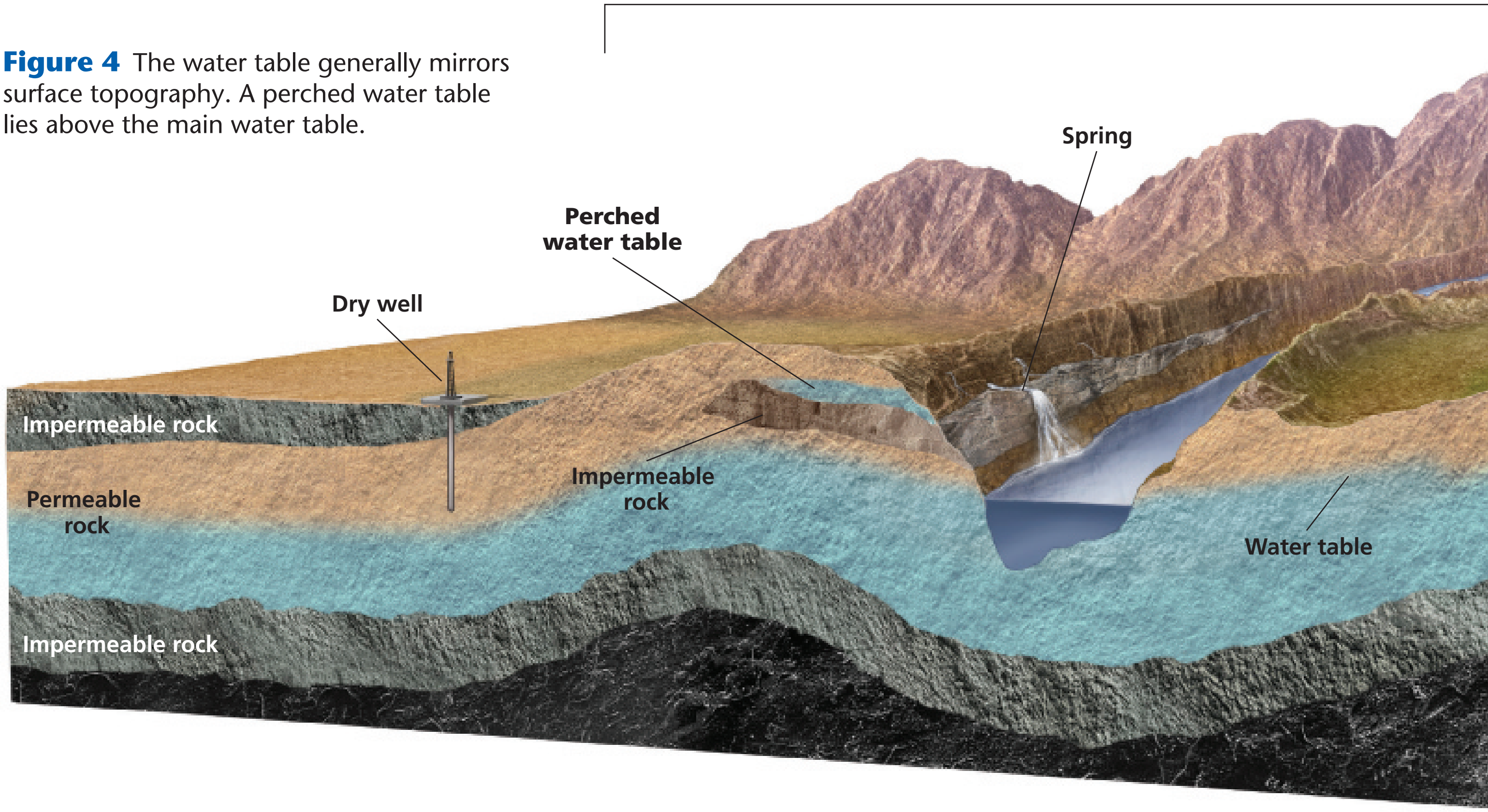


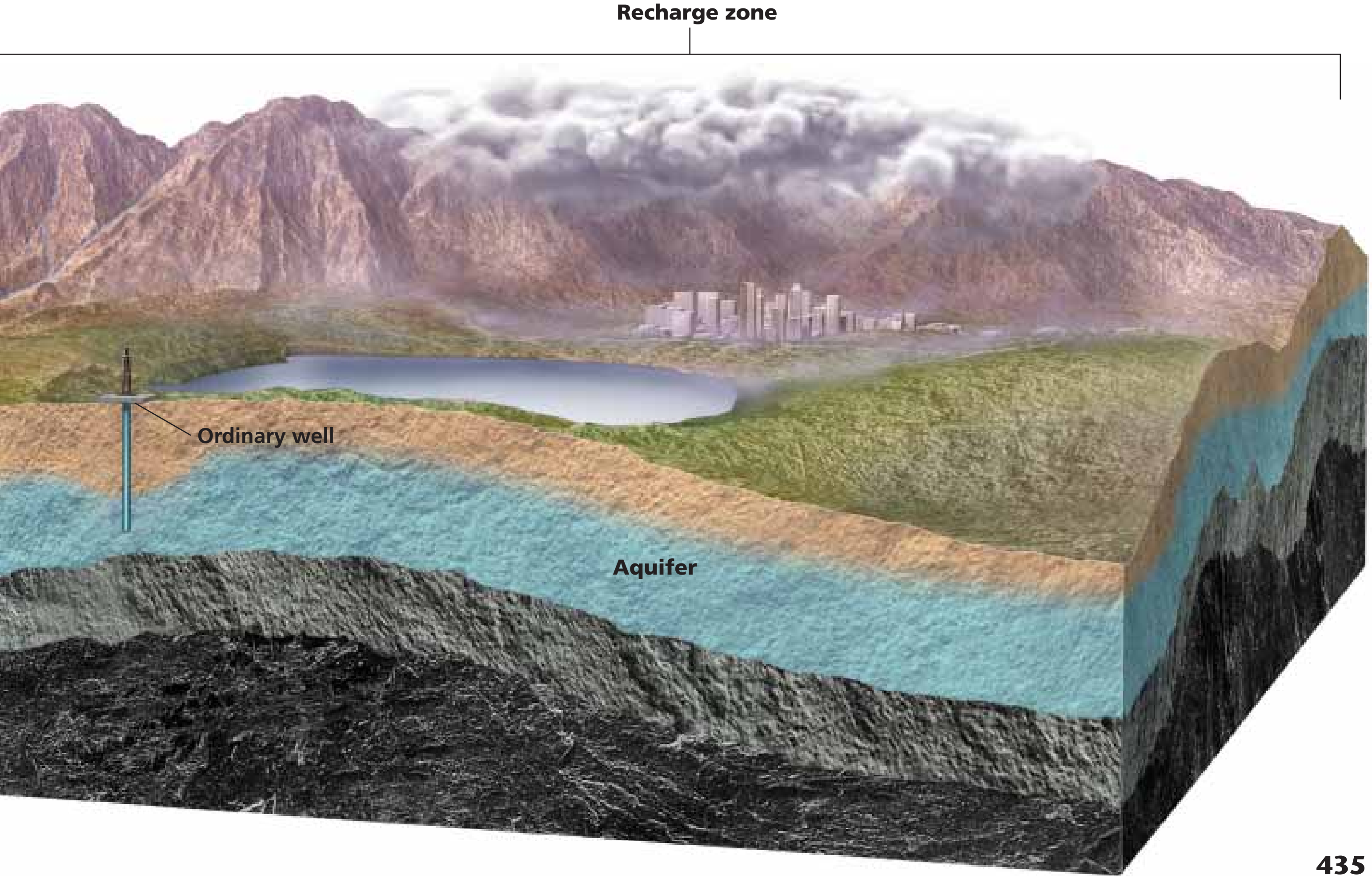
Figure 4 The water table generally mirrors surface topography. A perched water table lies above the main water table.

Conserving Groundwater

In many communities, groundwater is the only source of fresh water. Although groundwater is renewable, its long renewal time limits its supply. Groundwater collects and moves slowly, and the water taken from aquifers may not be replenished for hundreds or thousands of years. Communities often regulate the use of groundwater to help conserve this valuable resource. They can monitor the level of the local water table and discourage excess pumping. Some communities recycle used water. This water is purified and may be used to replenish the groundwater supply.

Surface water enters an aquifer through an area called a recharge zone. A *recharge zone* is anywhere that water from the surface can travel through permeable rock to reach an aquifer, as shown in **Figure 4.** Recharge zones are environmentally sensitive areas because pollution in the recharge zone can enter the aquifer. Therefore, recharge zones are often labeled by signs like the one shown in **Figure 5.** Pollution can enter an aquifer from waste dumps and underground storage tanks for toxic chemicals, from fertilizers and pesticides used in agriculture and on lawns, or from leaking sewage systems. If too much groundwater is pumped from an aquifer that is near the ocean, salt water from the ocean can then flow into the aquifer and contaminate the groundwater supply.

Figure 5 Water that enters this drain runs off into the Charles River and surrounding aquifers in Massachusetts.

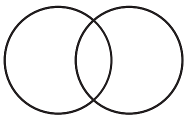


Wells and Springs

Groundwater reaches Earth's surface through wells and springs. A *well* is a hole that is dug to below the level of the water table and through which groundwater is brought to Earth's surface. A *spring* is a natural flow of groundwater to Earth's surface in places where the ground surface dips below the water table. Wells and springs are classified into two groups—ordinary and artesian.

READING TOOLBOX

Venn Diagrams
Draw a Venn diagram with two circles. Label one circle "Ordinary wells" and the other circle "Artesian wells." In the area where the circles overlap, write shared characteristics. In each of the other areas, write characteristics that are unique to each type of well.



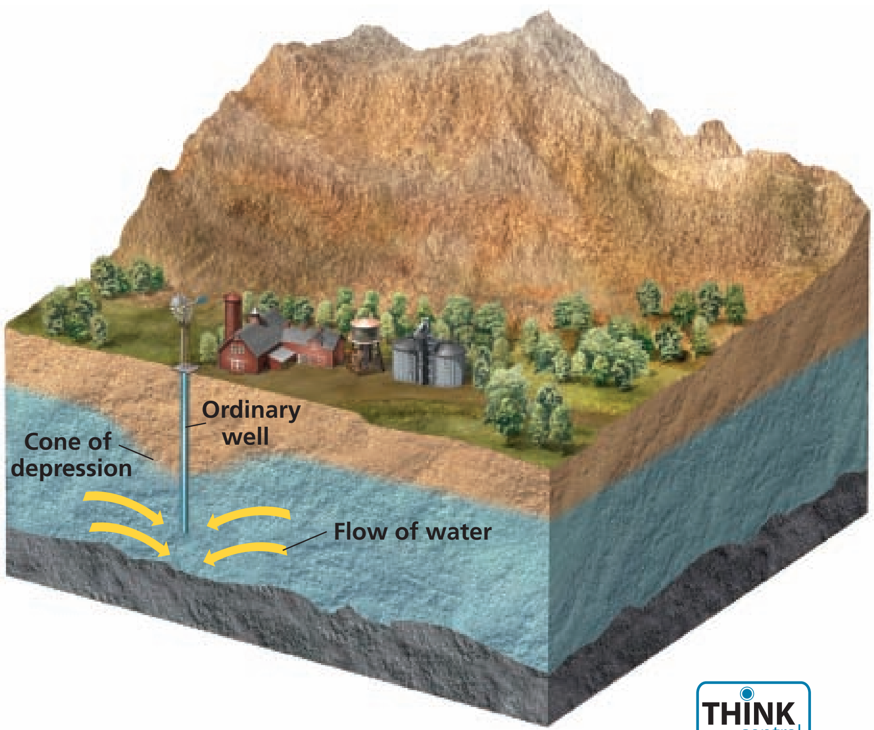
Ordinary Wells and Springs

Ordinary wells work only if they penetrate highly permeable sediment or rock below the water table. If the rock is not permeable enough, groundwater cannot flow into the well quickly enough to replace the water that is withdrawn.

Pumping water from a well lowers the water table around the well and forms a *cone of depression*, as shown in **Figure 6.** If too much water is taken from a well, the cone of depression may drop to the bottom of the well and the well will go dry. The lowered water table may extend several kilometers around the well and may cause surrounding wells to become dry.

Ordinary springs are usually found in rugged terrain where the ground surface drops below the water table. These springs may not flow continuously if the water table in the area has an irregular depth as a result of variable rainfall. Springs that form from perched water tables that intersect the ground surface are very sensitive to the amount of local precipitation. Thus, these springs may go dry during dry seasons or severe droughts.

Figure 6 A cone of depression develops in the water table around a pumping well.



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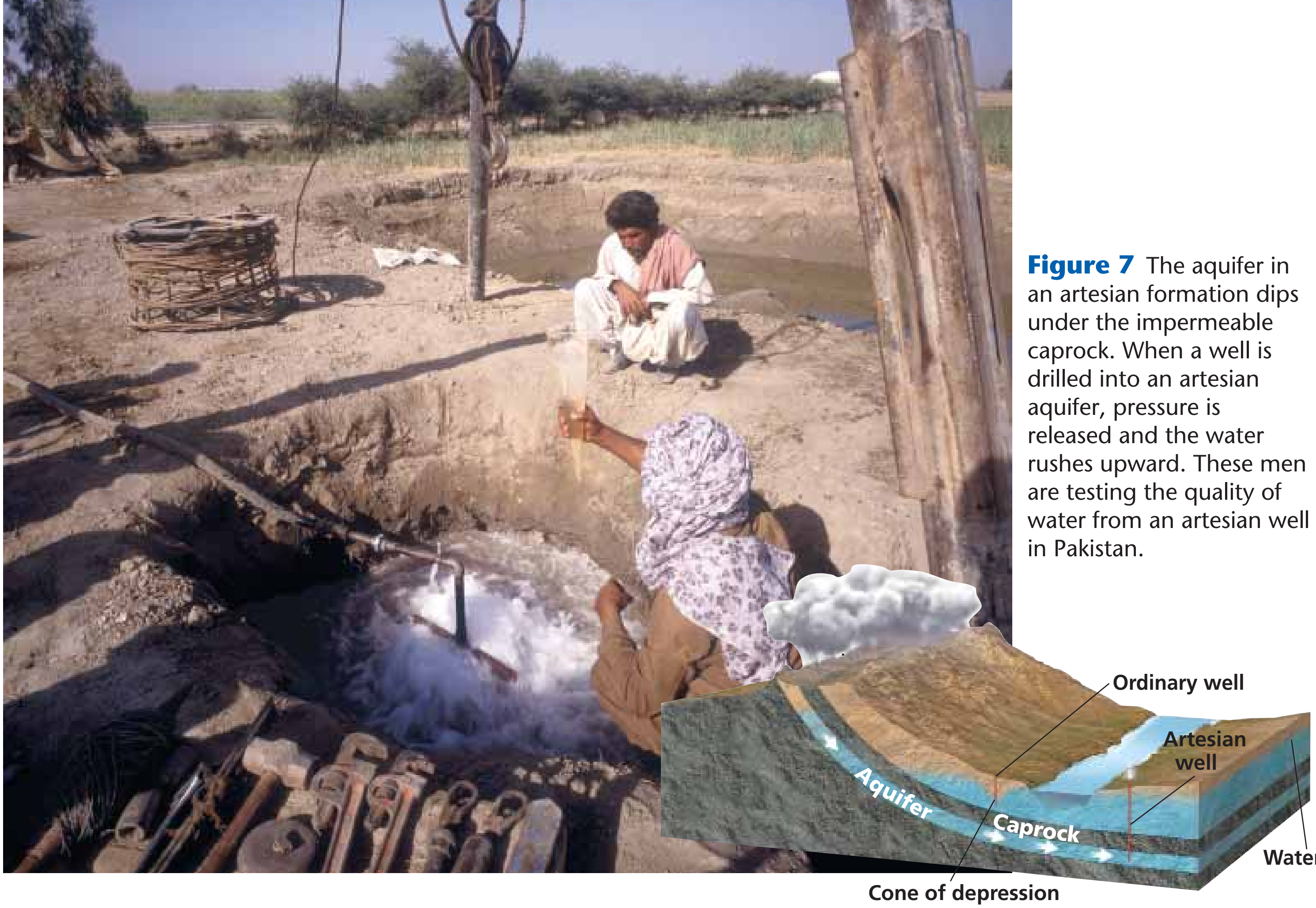


Figure 7 The aquifer in an artesian formation dips under the impermeable caprock. When a well is drilled into an artesian aquifer, pressure is released and the water rushes upward. These men are testing the quality of water from an artesian well in Pakistan.

Artesian Wells and Springs

The groundwater that supplies many wells comes from local precipitation. However, the water in some wells may come from as far away as hundreds of kilometers. Water may travel through an aquifer to a distant location. Because the aquifer is so extensive, it may become part of an artesian formation, an arrangement of permeable and impermeable rock.

An **artesian formation** is a sloping layer of permeable rock that is sandwiched between two layers of impermeable rock, as shown in **Figure 7.** The permeable rock is the aquifer, and the top layer of impermeable rock is called the *caprock*. Water enters the aquifer at a recharge zone and flows downhill through the aquifer. As the water flows downward, the weight of the overlying water causes pressure in the aquifer to increase. Because the water is under pressure, when a well is drilled through the caprock, the water quickly flows up through the well and may even spout from the surface. An *artesian well* is a well through which water flows freely without being pumped.

artesian formation a sloping layer of permeable rock sandwiched between two layers of impermeable rock and exposed at the surface

Artesian formations are also the source of water for some springs. When cracks occur naturally in the caprock, water from the aquifer flows through the cracks. This flow forms *artesian springs*.

Academic Vocabulary

source (SOHRS) the thing from which something else comes

Reading Check **What is the difference between ordinary springs and artesian springs?**

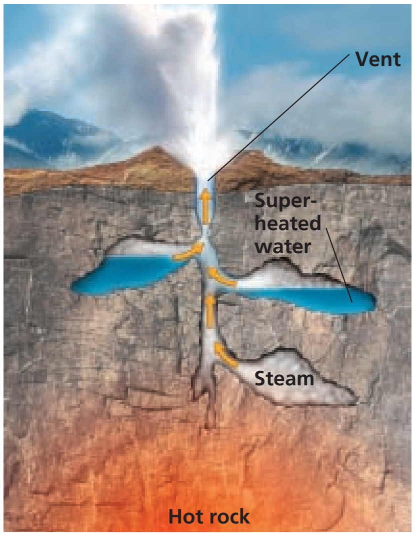


Figure 8 The vent and underground chambers of a geyser enable water to become superheated and to eventually erupt to the surface.

Hot Springs

Groundwater is heated when it passes through rock that has been heated by magma. Hot groundwater that is at least 37 °C and that rises to the surface before cooling produces a *hot spring*. When water in a hot spring cools, the water deposits minerals around the spring's edges. The deposits form steplike terraces of calcite called *travertine. Mud pots* form when chemically weathered rock mixes with hot water to form a sticky, liquid clay that bubbles at the surface. Mud pots are called *paint pots* when the clay is brightly colored by minerals or organic materials.

Geysers

Hot springs that periodically erupt from surface pools or through small vents are called *geysers*. A geyser consists of a narrow vent that connects one or more underground chambers with the surface. The hot rocks that make up the chamber walls superheat the groundwater. The water in the vent exerts pressure on the water in the chambers, which keeps the water in the chambers from boiling for a time. When the water in the vent finally begins to boil, the boiling water produces steam that pushes the water above it to the surface. Release of the water near the top of the vent relieves the pressure on the superheated water farther down. With the sudden release of pressure, the superheated water changes into steam and explodes toward the surface, as shown in **Figure 8.** The eruption continues until most of the water and steam are emptied from the vent and chambers. After the eruption, groundwater begins to collect again and the process is repeated, often at regular intervals.

Section 1 Review

Key Ideas

1. **Identify** the difference between porosity and permeability, and explain how permeability affects the flow of groundwater.
2. **Name and describe** the two zones of groundwater.
3. **Describe** how the contour of a shallow water table compares with the local topography.
4. **Explain** why ordinary springs often flow intermittently.
5. **Define** the term *cone of depression.*
6. **Compare** the rock layers in an artesian formation with those in an ordinary aquifer.
7. **Compare** artesian wells and ordinary wells.

Critical Thinking

8. **Making Inferences** Which type of well would provide a community with a more constant source of water: an ordinary well or an artesian well? Explain your answer.
9. **Identifying Relationships** Why is protecting the environment from pollution important for communities in recharge zones?
10. **Analyzing Ideas** Why don't shallow pools of hot water erupt the way that geysers erupt?

Concept Mapping

11. Use the following terms to create a concept map: *groundwater, water table, zone of saturation,* and *zone of aeration.*

SECTION 2

Groundwater and Chemical Weathering

Key Ideas	Key Terms	Why It Matters
❯ Describe how water chemically weathers rock.	**cavern**	Water underground causes problems as well as opportunities for adventure and discovery.
❯ Explain how caverns and sinkholes form.	**sinkhole**	
❯ Identify two features of karst topography.	**karst topography**	

As groundwater passes through permeable rock, minerals in the rock dissolve. The warmer the rock is and the longer it is in contact with water, the greater the amount of dissolved minerals in the water. Water that contains relatively high concentrations of dissolved minerals, especially minerals rich in calcium, magnesium, and iron, is called *hard water*. Water that contains relatively low concentrations of dissolved minerals is called *soft water*.

Many people think that using hard water is unappealing. For example, more soap is needed to produce suds in hard water than in soft water. Also, many people prefer not to drink hard water because of its metallic taste. Some household appliances or fixtures may be damaged by the buildup of mineral deposits from hard water. **Figure 1** shows some results of the long-term presence of hard water.

Results of Weathering by Groundwater

One way that minerals become dissolved in groundwater is through chemical weathering. As water moves through soil and other organic materials, the water combines with carbon dioxide to form carbonic acid. This weak acid chemically weathers the rock that the acid passes through by breaking down and dissolving the minerals in the rock.

Figure 1 Soap scum forms when soap reacts with calcium carbonate in hard water (inset). During high-water stages, hard water deposited a residue of calcium carbonate on the canyon walls that border this creek.

Quick Lab

25 min

Chemical Weathering

Procedure

1. Place **limestone, granite, pyrite,** and **chalk chips** into separate **small beakers.**
2. Cover the rocks in **1% HCl solution.**
3. After 20 min, observe the rocks.

Analysis

1. How have the rocks changed?
2. How is this process of change like the process of chemical weathering by groundwater?

Figure 2 The formations in Carlsbad Caverns in New Mexico are made of calcite. ***Which formations in this photo are stalagmites?***

Caverns

Rocks that are rich in the mineral calcite, such as limestone, are especially vulnerable to chemical weathering. Although limestone is not porous, vertical and horizontal cracks commonly cut through limestone layers. As groundwater flows through these cracks, carbonic acid slowly dissolves the limestone and enlarges the cracks. Eventually, a cavern may form. A **cavern** is a large cave that may consist of many smaller connecting chambers. Carlsbad Caverns in New Mexico is a good example of a large limestone cavern, as shown in **Figure 2.**

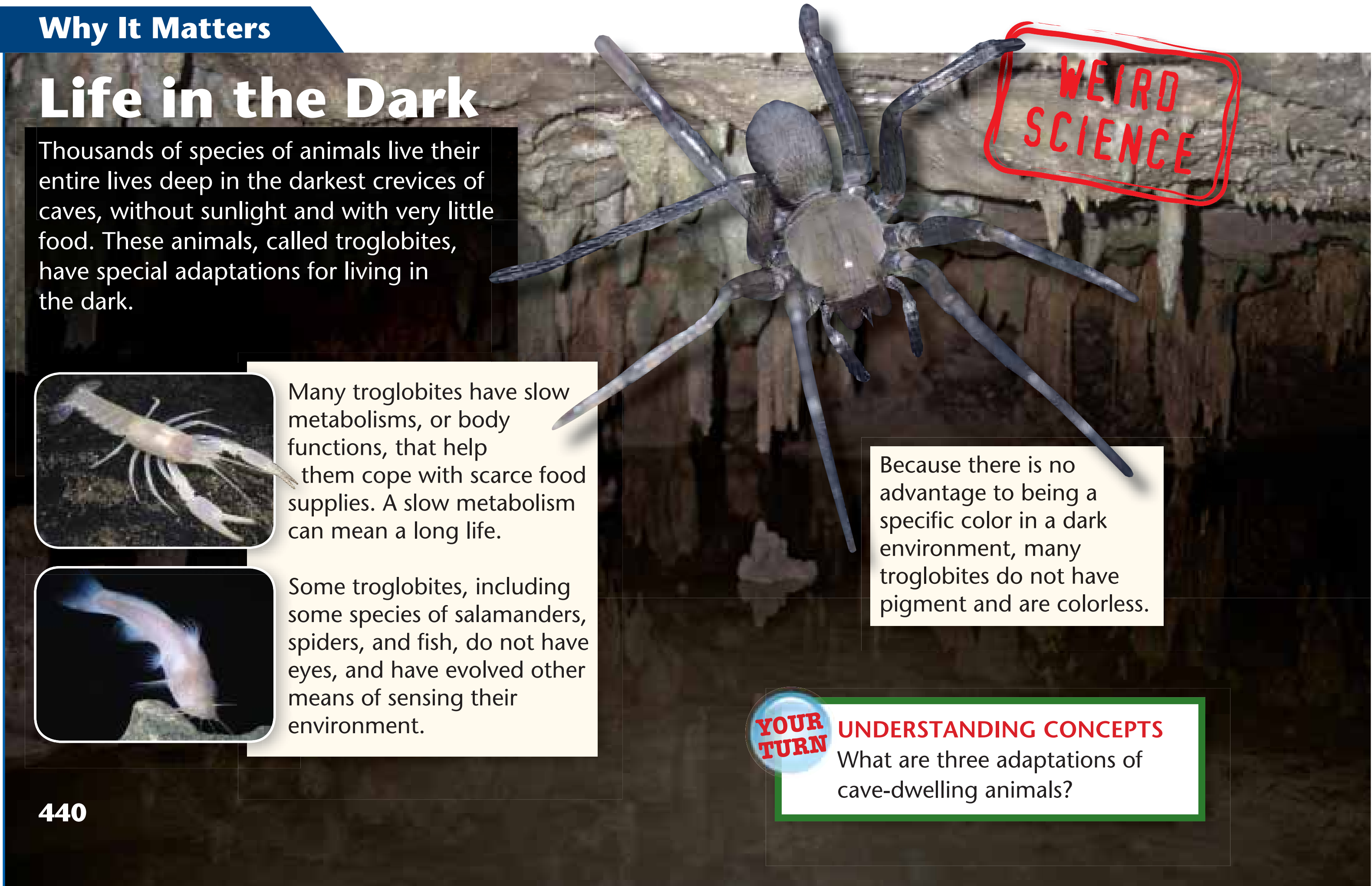
cavern a natural cavity that forms in rock as a result of the dissolution of minerals; also a large cave that commonly contains many smaller, connecting chambers

Stalactites and Stalagmites

Although a cavern that lies above the water table does not fill with water, water still passes through the rock surrounding the cavern. When water containing dissolved calcite drips from the ceiling of a limestone cavern, some of the calcite is deposited on the ceiling. As this calcite builds up, it forms a suspended, cone-shaped deposit called a *stalactite* (stuh LAK TIET). When drops of water fall on the cavern floor, calcite builds up to form an upward-pointing cone called a *stalagmite* (stuh LAG MIET). Often, a stalactite and a stalagmite will grow until they meet and form a calcite deposit called a *column*.

Why It Matters

Life in the Dark



Thousands of species of animals live their entire lives deep in the darkest crevices of caves, without sunlight and with very little food. These animals, called troglobites, have special adaptations for living in the dark.

Many troglobites have slow metabolisms, or body functions, that help them cope with scarce food supplies. A slow metabolism can mean a long life.

Some troglobites, including some species of salamanders, spiders, and fish, do not have eyes, and have evolved other means of sensing their environment.

Because there is no advantage to being a specific color in a dark environment, many troglobites do not have pigment and are colorless.

YOUR TURN UNDERSTANDING CONCEPTS
What are three adaptations of cave-dwelling animals?

Sinkholes

A circular depression that forms at the surface when rock dissolves, when sediment is removed, or when caves or mines collapse is a **sinkhole.** Most sinkholes form by dissolution, in which the limestone or other rock dissolves where weak areas in the rock, such as fractures, previously existed. The dissolved material is carried away from the surface, and a small depression forms. *Subsidence sinkholes* form by a similar process except that as rock dissolves, overlying sediments settle into cracks in the rock and a depression forms.

Collapse sinkholes may form when sediment below the surface is removed and an empty space forms within the sediment layer. Eventually, the overlying sediments collapse into the empty space below. Collapse sinkholes may also form during dry periods, when the water table is low and caverns are not completely filled with water. Because water no longer supports the roof of the cavern, the roof may collapse. Collapse sinkholes may develop abruptly and cause extensive damage. A collapse sinkhole is shown in **Figure 3.**

Figure 3 When land overlying a cavern collapses to form a sinkhole, human-made structures, such as this highway, can be damaged.

sinkhole a circular depression that forms when rock dissolves, when overlying sediment fills an existing cavity, or when the roof of an underground cavern or mine collapses

Natural Bridges

When the roof of a cavern collapses in several places, a relatively straight line of sinkholes forms. The uncollapsed rock between each pair of sinkholes forms an arch of rock called a *natural bridge*, such as the one shown in **Figure 4.** When a natural bridge first forms, it is thick, but erosion causes the bridge to become thinner. Eventually, the natural bridge may collapse.

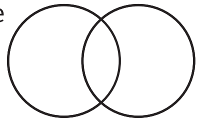
Reading Check **How are sinkholes related to natural bridges?**

Figure 4 This natural bridge near San Antonio, Texas, formed when the roof of a large cavern room collapsed.

Figure 5 The Stone Forest in Yunnan, China, is a dramatic example of karst topography.

READING TOOLBOX

Venn Diagrams
Draw a Venn diagram with two circles, and title it "Karst Topography." Label one circle "Humid climate" and the other circle "Dry climate." In each circle, write characteristics that are unique to the landscape in each type of climate. In the area where the circles overlap, write shared characteristics.



Karst Topography

Irregular topography caused by the chemical weathering of limestone or other soluble rock by groundwater is called **karst topography.** Common features of karst topography include many closely spaced sinkholes and caverns. In karst regions, streams often disappear into cracks in the rock and then emerge in caves or through other cracks many kilometers away. In the United States, there is extensive karst topography in Kentucky, Tennessee, southern Indiana, northern Florida, and Puerto Rico.

Generally, karst topography forms in regions where the climate is humid and where limestone formations exist at or near the surface. The plentiful precipitation in these regions commonly becomes groundwater. The groundwater flows through the limestone and reacts chemically with the calcite in the limestone. As the groundwater dissolves the limestone, cracks in the rock enlarge to form cave systems. Features of karst topography can form in relatively dry regions, too. In these areas, sinkholes may form very close together and leave dramatic arches and spires, as shown in **Figure 5.** Karst topography in these regions may indicate that the climate is becoming drier.

karst topography a type of irregular topography that is characterized by caverns, sinkholes, and underground drainage and that forms on limestone or other soluble rock

Academic Vocabulary

feature (FEE chuhr) the shape or form of a thing; characteristic

Section 2 Review

Key Ideas

1. **Describe** how water chemically weathers rock.
2. **Explain** how caverns form.
3. **Explain** the difference between stalactites and stalagmites.
4. **Identify** three common features of karst topography.
5. **Describe** two ways in which a natural bridge might form.
6. **Compare** sinkholes and caverns.

Critical Thinking

7. **Making Inferences** If an area has a dry climate, how can the area have karst topography?
8. **Identifying Relationships** Why might you expect to find springs in regions that have karst topography?

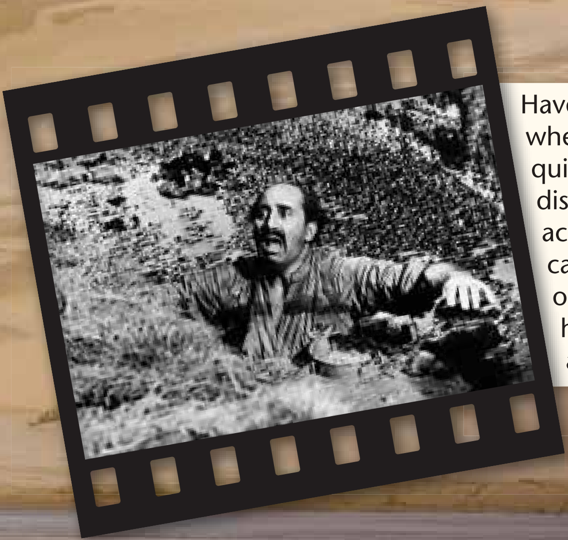
Concept Mapping

9. Use the following terms to create a concept map: *groundwater, stalagmite, stalactite, natural bridge, cavern,* and *sinkhole.*

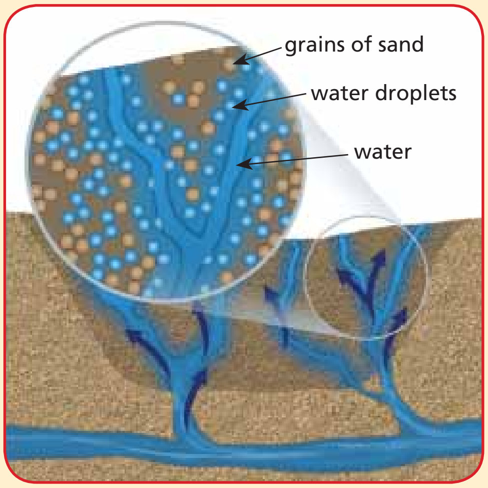
Why It Matters

Is it Possible to Drown in Quicksand?

In certain areas where groundwater is near the land surface, quicksand can form. Quicksand is made of fine grains of sand and clay saturated with water. When a person steps on quicksand, the pressure causes water below the sand to move up, turning the sand into a thick jelly-like substance.



Have you ever seen a movie where a character falls into quicksand and completely disappears? This could not actually happen. A person can sink in quicksand, but only to the waist, because humans are not as dense as quicksand.



When force is applied to quicksand, groundwater moves up, resulting in a thick and sandy fluid.

It is easy, however, to become trapped in quicksand. If you were stuck in quicksand, you could not simply be pulled out. Instead, you should wiggle your legs to slowly make a space around your body. Water can flow into this space and let you pull yourself free.

YOUR TURN

UNDERSTANDING CONCEPTS
What happens when someone steps on quicksand?

APPLYING INFORMATION
Describe the porosity and permeability of quicksand.

45 min

Porosity

Whether soil is composed of coarse pieces of rock or very fine particles, some pore space remains between the pieces of solid material. Porosity is calculated by dividing the volume of the pore space by the total volume of the soil sample. Thus, if 50 cm^3 of soil contains 5.0 cm^3 of pore space, the porosity of the soil sample is

$$5.0\ cm^3/50\ cm^3 = 0.10 \times 100 = 10\%.$$

The result is generally written as a percentage. In this lab, you will measure and compare the porosity of three samples that represent rock particles.

What You'll Do

- **Measure** the porosity of a given volume of beads for each of three samples: large beads, small beads, and a mix of large and small beads.
- **Describe** how particle size and sorting of a material affect porosity.

What You'll Need

beads, plastic, 4 mm (400)
beads, plastic, 8 mm (200)
beaker, 100 mL
graduated cylinder, 100 mL

Safety

Procedure

1. Fill a beaker to the top with water. Pour the water into a graduated cylinder and record the volume of water.
2. Dry the beaker, and fill it to the top with large (8 mm) plastic beads. Gently tap the beaker to settle and compact the beads. Add more beads to fill the beaker until the beads are level with the top. Record the total volume of the beads, which includes the pore space volume.
3. Fill the graduated cylinder with water to the top mark, and record the volume of water. Carefully pour the water from the cylinder into the beaker filled with the large beads until the water level just reaches the top of the beads.

Step 3

4. To determine the amount of water that you added to the beaker, subtract the volume of water in the graduated cylinder from the volume that you recorded in step 3. This difference is the volume of the pore space between the beads. Record the volume of the pore space.
5. Calculate the porosity of the beads. Record the porosity as a decimal and as a percentage.
6. Repeat steps 2 to 5 using small (4 mm) beads.
7. Drain and dry both sets of beads. Mix together equal volumes of the small and large beads. Using the mixed-size beads, repeat steps 2 to 5.

Step 4

Analysis

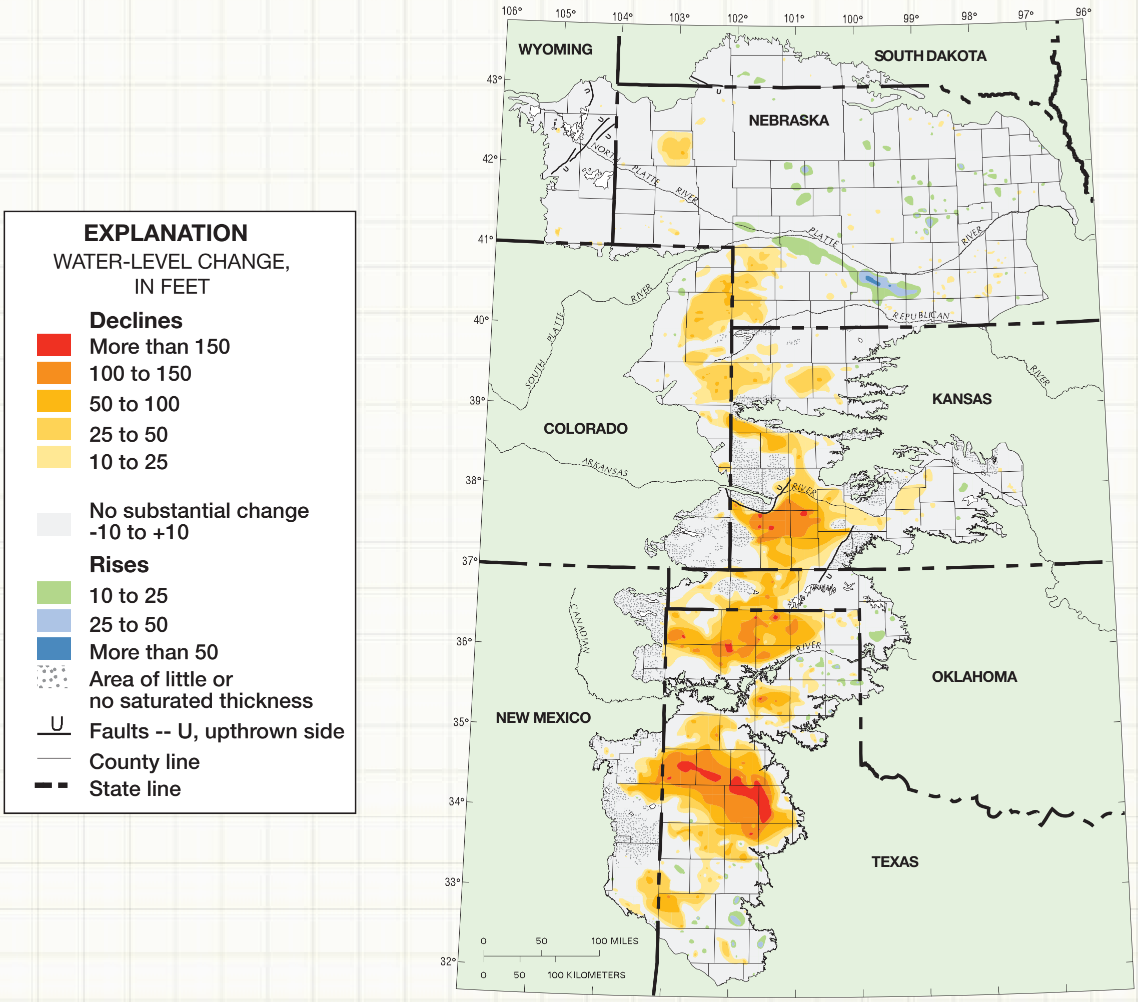
1. **Analyzing Methods** Do the 8 mm beads in step 2 represent well-sorted large rock particles, well-sorted small rock particles, or unsorted rock particles?
2. **Analyzing Methods** Do the 4 mm beads in step 6 represent well-sorted large rock particles, well-sorted small rock particles, or unsorted rock particles?
3. **Analyzing Methods** Do the mixed beads in step 7 represent well-sorted or unsorted rock particles?
4. **Making Graphs** Compare your measurements of the porosity of the large beads with your measurements of the porosity of the small beads. Make a graph that shows bead size on the *x*-axis and porosity on the *y*-axis.
5. **Drawing Conclusions** In well-sorted sediment, does porosity depend on particle size? Explain your answer.
6. **Determining Cause and Effect** How did mixing the bead sizes affect the porosity? Explain the effect.

Extension

Designing Experiments How would mixing coarse gravel with fine sand affect the porosity of the gravel? Conduct an experiment to find out if your answer is correct.

MAPS in Action

Water Level in the Southern Ogallala



Map Skills Activity

This map shows water-level change from predevelopment to 2005 in regions of the Ogallala Aquifer, which supplies much of the drinking water in the midwestern United States. Use the map to answer the questions below.

1. **Using a Key** From predevelopment to 2005, how many states had areas in which the water level declined more than 150 feet?
2. **Using a Key** From predevelopment to 2005, how many states had areas in which the water level rose?
3. **Identifying Trends** How has the water level changed overall, from predevelopment to 2005?
4. **Analyzing Relationships** What may have caused the trend that you identified in question 3?
5. **Making Predictions** How do you think the aquifer's overall water level will change over the next 50 years? Explain.

Summary

THINK central
SUPER SUMMARY
Keyword: HQXGWES

Key Ideas | Key Terms

Section 1

Water Beneath the Surface

- The porosity and permeability of an aquifer affect the flow of groundwater.
- The water table is the upper surface of the zone of saturation, beneath the land surface and the zone of aeration.
- A well is a hole dug to below the water table, while a spring is a natural flow of groundwater to Earth's surface. Water also may flow naturally to Earth's surface through artesian formations.
- Hot springs and geysers are two land features formed by hot groundwater.

Key Terms

groundwater, p. 431
aquifer, p. 431
porosity, p. 431
permeability, p. 432
water table, p. 433
artesian formation, p. 437

Section 2

Groundwater and Chemical Weathering

- Water combines with carbon dioxide to form carbonic acid, which breaks down and dissolves minerals in rock that the water passes through.
- Caverns and sinkholes form as limestone or other rock is slowly dissolved by chemical weathering.
- Features of karst topography include caverns, sinkholes, and underground drainage.

Key Terms

cavern, p. 440
sinkhole, p. 441
karst topography, p. 442

Chapter 16 Review

1. Temporal Language Create a temporal language table for the page in Section 1 that discusses hot springs and geysers. Find at least five words or phrases that refer to time and record them in the table. Use the table shown in the Reading Toolbox at the beginning of the chapter as a model.

USING KEY TERMS

Use each of the following terms in a separate sentence.

2. *groundwater*

3. *water table*

4. *karst topography*

For each pair of terms, explain how the meanings of the terms differ.

5. *geyser* and *hot spring*

6. *porosity* and *permeability*

7. *well* and *spring*

8. *ordinary well* and *artesian well*

9. *stalactite* and *stalagmite*

UNDERSTANDING KEY IDEAS

10. Any body of rock or sediment in which water can flow and be stored is called a(n)
a. well.
b. aquifer.
c. sinkhole.
d. artesian formation.

11. The percentage of open space in a given volume of rock is the rock's
a. viscosity.
b. capillary fringe.
c. permeability.
d. porosity.

12. The ease with which water can pass through a rock or sediment is called
a. permeability. **c.** porosity.
b. carbonation. **d.** velocity.

13. The slope of a water table is called the
a. gradient. **c.** permeability.
b. porosity. **d.** aquifer.

14. A natural flow of groundwater that has reached the surface is a(n)
a. spring. **c.** aquifer.
b. well. **d.** travertine.

15. Pumping water from a well causes a local lowering of the water table known as a
a. cone of depression.
b. horizontal fissure.
c. hot spring.
d. sinkhole.

16. Calcite formations that hang from the ceiling of a cavern are called
a. stalagmites.
b. sinks.
c. stalactites.
d. aquifers.

17. Caverns and sinkholes are typical in areas of
a. sink topography.
b. karst topography.
c. low porosity.
d. artesian formations.

18. When the roofs of several caverns collapse, the uncollapsed rock between sinkholes can form
a. natural bridges.
b. stalactites.
c. limestone topography.
d. artesian formations.

19. A layer of permeable rock that is sandwiched between layers of impermeable rock is called
a. a natural bridge.
b. karst topography.
c. limestone topography.
d. an artesian formation.

SHORT ANSWER

20. In regions where the water table is at the surface of the land, what type of terrain would you expect to find?

21. Explain the process that forms stalactites and stalagmites. Name another process in nature that produces shapes similar to the shapes of stalactites.

22. How does a mud pot form?

23. Describe the zones of an aquifer.
24. What are two ways that groundwater reaches Earth's surface?
25. How are caverns and sinkholes related?
26. What causes a geyser to erupt?
27. Why does it take a long time to replenish a depleted aquifer?

CRITICAL THINKING

28. **Making Inferences** In what type of location might pumping too much water from an aquifer lead to contamination of the groundwater supply? Explain how the water becomes contaminated.
29. **Analyzing Relationships** Describe an artesian formation, and explain how the water in an artesian well may have entered the ground many hundreds of kilometers away.
30. **Analyzing Ideas** Explain how a rock can be both porous and impermeable.
31. **Identifying Relationships** Do you think that an area that has karst topography would have many surface streams or few surface streams? Explain your answer.

CONCEPT MAPPING

32. Use the following terms to create a concept map: *porosity, sorting, permeability, ordinary well, artesian formation, highly permeable rock,* and *impermeable rock.*

MATH SKILLS

Math Skills

33. **Evaluating Data** People in Oklahoma use 11 billion gallons of water every day. The renewable water supply in Oklahoma is 68.7 billion gallons per day. What percentage of the renewable water supply do Oklahomans use every day?
34. **Making Conversions** In an average aquifer, groundwater moves about 50 m per year. At this rate, how long would the groundwater take to flow 1 km?

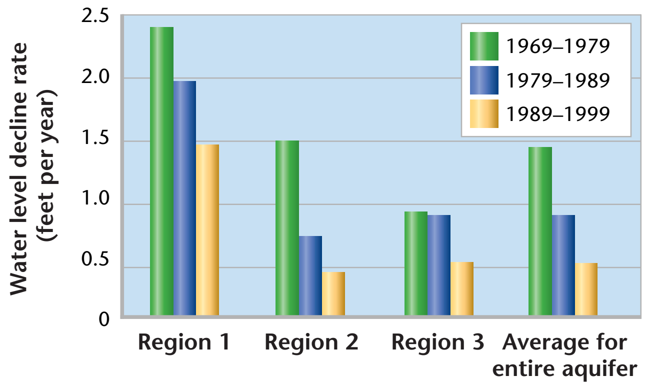
WRITING SKILLS

35. **Writing Persuasively** Write a persuasive essay about the importance of conserving groundwater.
36. **Communicating Main Ideas** Explain how overpumping at one well can affect groundwater availability in surrounding areas.

INTERPRETING GRAPHICS

The graph below shows the average annual decline in water level for the Ogallala Aquifer over 30 years. Use the graph below to answer the questions that follow.

Average Annual Rate of Decline by Decade for the Ogallala Aquifer, 1969–1999



37. Which region had the highest rate of decline from 1969 to 1999?
38. Over which decade did the aquifer have the lowest rate of decline?
39. Which years would you expect to have a higher rate of decline: the years 1999 to 2009 or the years 1989 to 1999? Explain your answer.

Standardized Test Prep

Understanding Concepts

Directions (1–5): For each question, write on a separate sheet of paper the letter of the correct answer.

1. Which of the following statements is false?
- **A.** Permeability affects flow through an aquifer.
- **B.** Groundwater can be stored in an aquifer.
- **C.** Aquifers are always a single rock layer.
- **D.** Well-sorted sediment holds the most water.

2. The amount of surface water that seeps into the pores between rock particles is influenced by which of the following factors?
- **F.** rock type, land slope, and climate
- **G.** rock type, land slope, and capillary fringe
- **H.** rock type, land slope, and sea level
- **I.** rock type, land slope, and recharging

3. Shanghai removed 96.03 million cubic meters of groundwater in 2002 but replaced only 13.75 million cubic meters. What was the rate of groundwater depletion in Shanghai that year?
- **A.** 109.78 million cubic meters per year
- **B.** 1,320.41 million cubic meters per year
- **C.** 6.98 million cubic meters per year
- **D.** 82.28 million cubic meters per year

4. The formation of karst topography is caused by
- **F.** the physical weathering of limestone.
- **G.** the chemical weathering of limestone.
- **H.** closely spaced sinkholes.
- **I.** irregular topography.

5. What quality distinguishes an ordinary well from an artesian well?
- **A.** Water flows freely from an ordinary well.
- **B.** Water is pressurized in an ordinary well.
- **C.** Water must be pumped from an ordinary well.
- **D.** Water comes from rainfall in an ordinary well.

Directions (6–7): For each question, write a short response.

6. What is a watershed?

7. What is the term for a local lowering of the water table caused by the pumping of water from a well?

Reading Skills

Directions (8–10): Read the passage below. Then, answer the questions.

Land Subsidence

Land subsidence is the settling or sinking of earth in response to the movement of materials under its surface. The greatest contributor to land subsidence is aquifer depletion. As groundwater is removed, the surface above may sink. Rocks may settle and pores may close, which leaves less area for water to be stored. In areas where aquifers are replenished, the surface of Earth may subside and then return almost to its previous level. However, in areas where water is not pumped back into aquifers, subsidence is substantial and whole regions may sink. Human activites can contribute to land subsidence. These activities include the pumping of water, gas, and oil from underground reservoirs and the collapse of mine tunnels.

8. According to the passage, which of the following statements is not true?
- **F.** Land subsidence is the settling or sinking of earth.
- **G.** As groundwater is removed, the earth above may sink.
- **H.** The greatest contributor to land subsidence is aquifer depletion.
- **I.** Rocks settle and pores close, which leaves more area for water to be stored.

9. Which of the following statements can be inferred from the information in the passage?
- **A.** Subsidence sinkholes occur most often in rural areas.
- **B.** The majority of all subsidence sinkholes are formed through natural processes.
- **C.** Subsidence sinkholes form both naturally and because of the activities of humans.
- **D.** Older sinkholes are easily recovered by refilling the area with water.

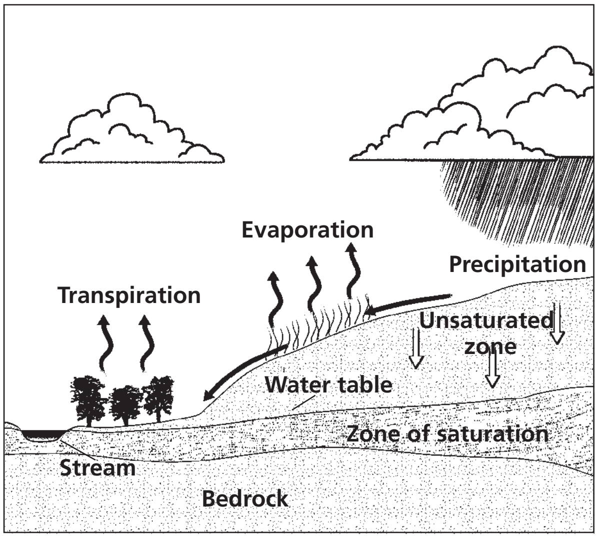
10. Subsidence due to groundwater depletion may occur slowly or very abruptly. Which type of subsidence presents a greater chance for recovery? Why?

Interpreting Graphics

Directions (11–13): For each question below, record the correct answer on a separate sheet of paper.

This graphic shows an example of the water cycle. Use this graphic to answer question 11.

The Water Cycle

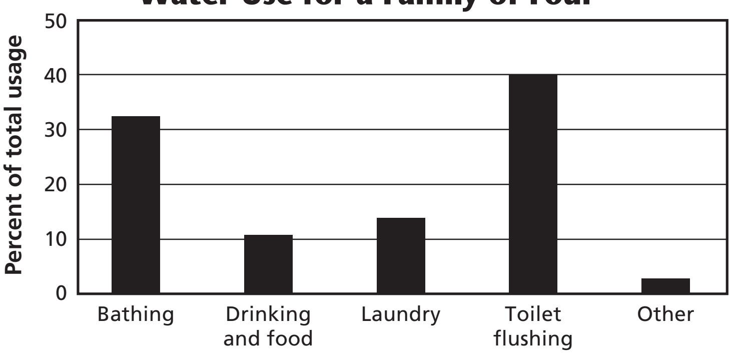


11. Which process occurs where the water table intersects the surface?

F. stream formation
G. runoff
H. groundwater movement
I. saturation

The graph below shows indoor water use for a typical family in the United States. Use this graph to answer questions 12 and 13.

Water Use for a Family of Four



12. According to the graph, what is the largest use of indoor water for a family in the United States? Name some ways that people can reduce the amount of water consumed by this task.

13. What total percentage of household indoor water is consumed by the two largest uses of indoor water? Round your answer to the nearest 10. How could this knowledge be used to help people reduce water usage?

Test Tip

Remember that if you can eliminate two of four answer choices, your chances of choosing the correct answer will double.