CHAPTER 4

GROUNDWATER HYDROLOGY

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> *For two decades scientists have debated whether liquid water might have existed on the surface of Mars as recently as a few billion years ago. With today's discovery, we're no longer talking about a distant time. The debate has moved to present-day Mars. The presence of liquid water on Mars has profound implications for the question of life not only in the past, but perhaps even today. If life ever did develop there, and if it survives to the present time, then these landforms would be great places to look.*[1]
>
> Dr. Ed Weiler, Jet Propulsion Laboratory,
> National Aeronautics and Space Administration,
> Pasadena, California, June 22, 2000

Interplanetary explorers may soon prove that life exists on Mars, and groundwater could provide the vital clue to such a discovery. The National Aeronautics and Space Administration's (NASA) Mars Global Surveyor spacecraft entered Martian orbit in 1999 and gathered photographic evidence that liquid water may exist on or just beneath the surface of the Red Planet. Analysis of these photos has led NASA scientists to believe that gullies and other channels on the Martian surface were formed by running water. The images also show fluvial landforms that could indicate the presence of water beneath the surface (Figure 4.1).

In the 1970s, photos from *Mariner 9* also showed ancient geologic features shaped by flowing water on Mars. However, the more detailed Global Surveyor images display fairly recent flows. If surface water actually did exist on Mars billions of years ago, where did the water go? The best hypothesis provided by scientists is that it percolated below the Martian surface and could still exist there today. NASA's 2008 Phoenix Mars Lander provided more information when water ice was found just beneath the Martian surface.[2]

On Earth, groundwater accounts for only 0.6 percent of the total water supply and yet represents 98 percent of all freshwater readily available to humans. Abundant freshwater is tied up in glaciers and polar ice, making it essentially unavailable. Other water sources, such as rivers, lakes, and reservoirs, have local importance but are much less significant on a global scale.

In the United States, groundwater provides drinking water to approximately half of the

FIG. 4.1 Mars appears very dry today, but images of gullies like these led scientists to suspect the presence of water in the past on the Red Planet. Such channels may have formed as a result of the sudden release of frozen groundwater to the planet's surface. In this NASA photo, note how some channels cut through craters, which indicates that water flowed after the craters were formed.

population; in Canada, the figure is approximately 30 percent. These figures are high because most groundwater is readily accessible and can often be used without any treatment. Irrigators in the United States obtain 37 percent of all irrigation water from groundwater sources. In some states, including Nebraska, Mississippi, Nevada, Oklahoma, and Texas, the figures are in the range of 69 to 94 percent.

Our extensive reliance on groundwater can be tenuous at times, owing to its vulnerability to pollution. Just 1 gallon (4 l) of gasoline can contaminate 1 million gallons (4 million l) of groundwater for drinking-water purposes. Hazardous-waste spills and percolation of fertilizer, pesticides, and other chemicals can pollute vast quantities of groundwater supplies. For more details on groundwater pollution, see Chapter 5.

WHAT IS GROUNDWATER?

Groundwater is water found within the pore spaces of geologic material beneath the surface of the Earth. It exists in saturated layers of sands and gravels, in certain types of clay material, and in cracks within crystalline rock. Moving water, wind, ice, and tectonic forces create opportunities for surface water to seep into underground material. Groundwater moves through porous geologic materials under the force of gravity or sometimes by the sheer weight of atmospheric pressure. This movement continues downward until an impervious layer of rock, shale, clay, or other watertight formation is encountered. These geologic barriers can cause a localized area to remain completely saturated with groundwater, sometimes up to the land surface. Such a wet, underground geologic setting can create a wetland, pond, or base flow for a river at the land surface.

As discussed in Chapters 2 and 3, groundwater can be replenished from surface water runoff, or through the beds or banks of rivers, lakes, ponds, or wetlands. It can also be supplied by seawater through saltwater intrusion into an aquifer. Groundwater is sometimes found within a few feet (or meters) of the Earth's surface and can be hydraulically connected to rivers, lakes, wetlands, and oceans. In other locations, well drillers must core hundreds of feet (100 m or more) to reach usable supplies. Large quantities of groundwater are not generally found below 10,000 feet (3000 m). This is due to the tremendous pressures at such depths, which cause any small openings between geologic material to be tightly pressed together and closed.

SIDEBAR

The word *groundwater* is often written as two words (*ground water*) to correspond to the term *surface water*. However, many scientists prefer to write *groundwater* as a single word to represent a technical term. Either form is appropriate, although we will use the single-word form in our discussions.

Groundwater is a small but integral part of the hydrologic cycle. According to the U.S. Geological Survey, there are an estimated 1 million cubic miles (4 million km^3) of groundwater within one-half mile (800 m) of the Earth's surface. This compares with only 30,000 cubic miles (125,000 km^3) of water in freshwater lakes and a mere 300 cubic miles (1250 km^3) in streams.[3]

Groundwater is the largest source of freshwater on Earth and provides drinking water to 53 percent of the people in the United States.[4] Cities such as San Antonio and El Paso, Texas; Albuquerque, New Mexico; Dayton, Ohio; and Lincoln, Nebraska, rely almost exclusively on groundwater. In many regions of the world, however, groundwater cannot be obtained in sufficient quantities to economically justify installation of a single well (sometimes called a *bore hole* outside the United States). The spatial distribution of groundwater can be quite irregular and variable in supply (see Figure 4.2).

The United Nations, during its observance of World Day for Water in 1998, described

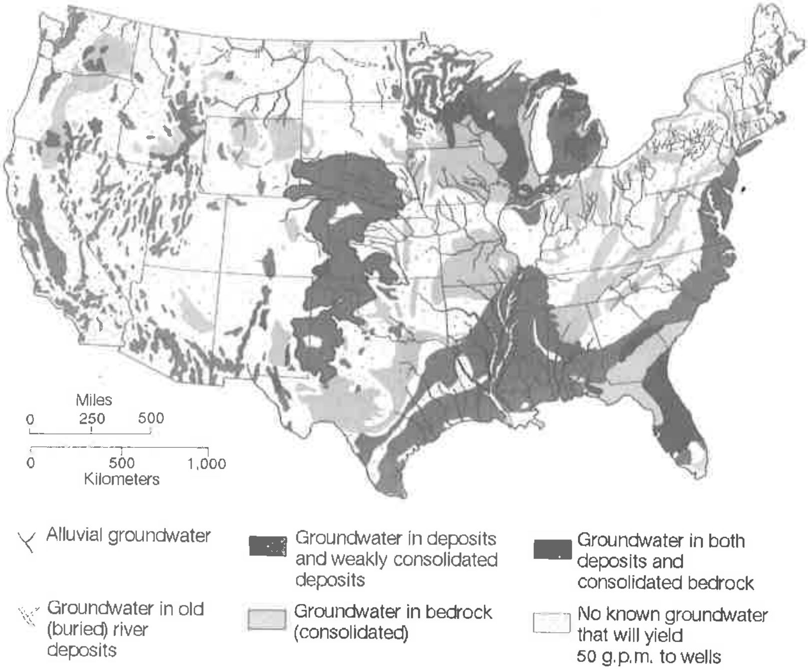

FIG. 4.2 This map of major aquifers in the United States shows an interesting distribution of groundwater formations. Do any regional surface features coincide with the geographic distribution of groundwater? Which region appears to have the greatest concentration of groundwater? Can any correlations be made between climate and the distribution of groundwater in the United States? The various types of groundwater shown on this map will be explained later in this chapter.

groundwater as the "Invisible Resource." Though unseen, groundwater is playing a decisive role in global economies, political conflicts, and personal health around the world. This focus on groundwater is inevitable as population increases and as demand for water supplies accordingly escalates.

The study of groundwater requires an understanding of many physical processes. Knowledge of these attributes and methods is critical in determining groundwater availability, trends, and characteristics to meet the needs of our natural and developed environment. Several questions surround these physical processes:

How is groundwater formed?

What role does geology play in the movement of surface water into groundwater settings?

How does groundwater interact with surface water?

What role does geology play in the movement of groundwater?

What methods are used to measure the movement of groundwater?

How are groundwater quantities determined?

WHAT IS GROUNDWATER HYDROLOGY?

Groundwater hydrology is the study of the characteristics, movement, and occurrence of water found beneath the surface of the Earth. Groundwater professionals have expertise in engineering, geology, earth science, or other scientific fields that require knowledge of Earth systems, mathematics, and chemistry. Groundwater hydrologists provide water managers, planners, and others involved in water resource management with invaluable information regarding groundwater attributes.

The hydrology of groundwater has some characteristics similar to those of surface water. In

Chapter 3, we discussed how watersheds are a basic geographic unit for the study of surface water. Groundwater and aquifers are somewhat analogous to surface water and watersheds. We've seen how the movement of surface water is affected by the gradient of the land surface. Groundwater movement, in turn, is affected by subsurface geologic material and the gradient of water found at such depths. Surface water discharge can be measured by using a flow meter, gaging station, or mathematical equations such as the rational formula. Groundwater levels (elevations below the land surface) can be measured by inserting a tape measure or electronic device down a well or by using mathematical formulas developed in the 1800s.

The study of groundwater existed even during ancient times. Although the level of scientific knowledge was then limited, the development of *qanats* in Africa, the Middle East, China, and South America provides an impressive record of hydrologic insight. Hydrologists and engineers of the Roman Empire utilized groundwater from springs (which will be discussed later in this chapter) as water sources for aqueducts to their cities.

These impressive ancient groundwater supply systems notwithstanding, the ancients also propagated certain bizarre theories regarding the origin of groundwater, some of which continue today. Early Greek philosophers, including Homer (c. 800 B.C.), Thales (636–546 B.C.), and Plato (427–347 B.C.), believed that groundwater originated as seawater. These learned scholars deduced that water moves through subterranean channels beneath mountains and is then purified as it moves to the land surface. The Roman architect and water manager Marcus Vitruvius Pollio (c. 70–25 B.C.) corrected this misconception and hypothesized that precipitation and surface water percolation serve as the source of all groundwater. In the 17th century, Pierre Perrault (1611–1680) measured precipitation and its relationship to runoff in the upper Seine River watershed of France and discovered that regional precipitation exceeded the discharge of the Seine River by 600 percent. His research supported the theory of Vitruvius developed in Rome nearly 1700 years earlier.[5]

THE GEOLOGY OF GROUNDWATER

Groundwater is found in a variety of geologic settings constrained by lithology, stratigraphy, and the structure of geologic deposits and formations. *Lithology* is the study of the physical characteristics of rocks, including mineralogy, composition, grain size, and density of geologic materials; *stratigraphy* describes the composition and age of deposit beds (such as sediments), lenses, and other formations; and *structure* refers to cracks, folds, and other deformations of geologic systems. In some locations, wind and erosion created opportunities for surface water to fill underground layers of sand, gravel, and other sediments. In other regions, deep geologic faults allowed surface water to migrate (travel) to depths of hundreds and even thousands of feet (or meters). Understanding regional geology is the road map to finding groundwater.

SEDIMENTARY ROCKS

Sedimentary rocks are made up of particles created through weathering and erosion of igneous and metamorphic rock. Such materials can form underground layers of **conglomerate** (boulders, gravels, pebbles, cobbles), **sandstone** (sand), **siltstone** (silt), or **shale** (clay). These layers, or formations, can have a thickness of just a few inches (or centimeters) or as much as hundreds of feet (over 100 m).

Conglomerate is often rice- to pea-sized and may have irregular or smooth surfaces. An irregular surface means the conglomerate was not transported far from its origin and was not exposed to the smoothing action of water. Sandstone is generally of uniform size and may have irregular or smooth surfaces, depending on the method of transport and exposure to wind and water. Siltstone consists of very small particles, often called **fines**, which are smaller than grains of sand. Shale contains an abundance of tightly bound, adhesive clay materials but may also include numerous fines dispersed throughout such a formation.

Sediments can be transported by wind, gravity, ice, and water. Such materials are deposited when the carrying capacity of the transportation method is exceeded (as discussed in Chapter 3). Common locations of sediment deposition are in river valleys (deposits of gravels, sands, and fines), lake shores and bottoms (well-sorted sands), and glaciated regions (random-sized materials ranging from clay particles to boulders). Sediments can also be carried by the wind to create large deposits of sand and smaller-grained materials called *eolian deposits* (named after Aeolus, the Greek god of wind). The Great Sand Dunes National Park in the San Luis Valley of southern Colorado, and the Sandhills of north-central Nebraska, are excellent examples of eolian deposits.

Limestone formations are generally composed of consolidated (hardened) lime mud, marine algae, and sand. Tremendous pressures from overburden compressed these materials into hardened deposits. Limestone tends to dissolve and can create large openings for groundwater movement. Some dissolved limestone areas can be so extensive that people can walk through caves formed by this process—such as at Carlsbad Caverns in New Mexico, which has one dissolved chamber more than one-half mile (800 m) long, 650 feet (200 m) wide, and almost 330 feet (100 m) high. The Mammoth Cave system in Kentucky is another example of underground passageways created from dissolved limestone.

Karst (a German word meaning "bare, stony ground," named for the Karst region in Slovenia) landscapes are located around the world, and vary from rolling hills dotted with depressions to jagged hills and pinnacle karst. Karst landforms require the presence of rock capable of being dissolved by surface or groundwater. Karst terrain is commonly associated with carbonate rocks (limestone and dolomite), but highly soluble rocks (such as gypsum and rock salt) can also be sculpted into karst terrain. These regions can contain numerous caves, sinkholes, and rivers that disappear underground. Karst terrain is commonly found in Florida, Texas, Kentucky, China, Slovenia, and Turkey. Ten percent of the Earth's surface is composed of karst landscape, and nearly 25 percent of the world's population relies on water supplied from karst areas.[6]

Sinkholes are smaller features on the landscape where limestone, carbonate rock, or salt beds naturally dissolve with water. Although deterioration is very slow, formation of a sinkhole can be sudden and dramatic. Vehicles and houses have fallen into sinkholes with little or no warning. In the United States, most sinkholes occur in Florida, Texas, Alabama, Missouri, Kentucky, Tennessee, and Pennsylvania. Sinkholes are also found in the Shan Plateau of China, Nullarbor Region of western Australia, Atlas Mountains of northern Africa, Belo Horizonte of Brazil, and the Carpathian Basin of southern Europe.

GUEST ESSAY

Sinkholes

by **Carlos Herd, P.G.**
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Sinkholes are features that indicate an area of karst topography. Karst topography is a terrain formed by the dissolution of underlying limestone. There is a lot involved with how the dissolution of limestone occurs. Basically, low-pH rainwater enters the groundwater system and reacts with the carbonate limestone, eventually forming karst features on land surface and open conduits through the underground aquifers. Sinkholes form as a result of the removal of material (limestone) lying underneath surficial, unconsolidated deposits of clays, silts, sands, etc. There are many types of sinkholes, but the two most common occurrences, at least in north central Florida, are *collapse* and *solution* sinkholes.

Over time, underlying limestone dissolves to the point where there is no longer sufficient structural integrity to hold up the overlying, unconsolidated materials. A collapse sinkhole forms suddenly as the weight of the overlying soil suddenly becomes too great, and the earth collapses until it fills a limestone cavity formed by the dissolution process previously described. It is difficult to predict where collapse sinkholes will form, due to the random occurrence of underground cavities and conduits and our lack of ability to "see" underground. At land surface, a circular, steep-sided hole appears, which may or may not contain water. Collapse sinkholes have been known to drain lakes and swallow houses, roads, etc. over a matter of hours. Although sinkholes form naturally, increasing development in sinkhole-prone areas brings more attention to their occurrence. If a sinkhole forms in a pasture, it does not get the same level of attention it would if the pasture were converted into a residential subdivision and a house were damaged by its occurrence. Factors that may contribute to or increase the likelihood of the formation of collapse sinkholes include:

- Large changes in the water table caused by too much or too little rain;
- Drilling a well into the cavity;
- Pumping groundwater from near the cavity; and
- Diverting drainage to the areas where a cavity exists.

A solution sinkhole develops slowly and continuously. It forms where sand or other relatively thin materials slowly and steadily move downward to fill expanding cracks and joints that occur in the underground limestone layers as a result of dissolution. As a sinkhole gets bigger, it collects more surface water runoff, which commonly carries sand, silt, and clay particles. This material can sometimes plug the sinkhole, thereby creating a lake or pond. Lakes that once were collapse sinkholes can sometimes unplug and drain into the underground aquifer. If the lake becomes polluted, this can be a health hazard to people whose drinking water wells tap into the connected aquifer.

Depending upon their occurrence, sinkholes may be referred to by different names. Sinkholes occurring in riverbeds that take a portion of the flow are referred to as siphons. A swallow hole (sinking stream, ponor, or lost river) is basically a sinkhole that has the ability to capture all or a majority of the flow of a river or stream (see Figure 4.3). A karst window is basically a collapse sinkhole within a cave conduit where the overburden has been removed by the flow in the conduit, revealing a view into the aquifer. It is a combination of a spring and a sink in the same feature. These are only a few types of sinkholes and names associated with them.

Karst systems provide a complicated and fascinating perspective on surface and groundwater interaction. Let's follow water through a karst system and see what happens. A surface water stream or a portion of it may disappear into a sink feature where the water goes immediately from surface water to groundwater (see Figure 4.4); this is where things start to get interesting. The concept of how the water flows through the

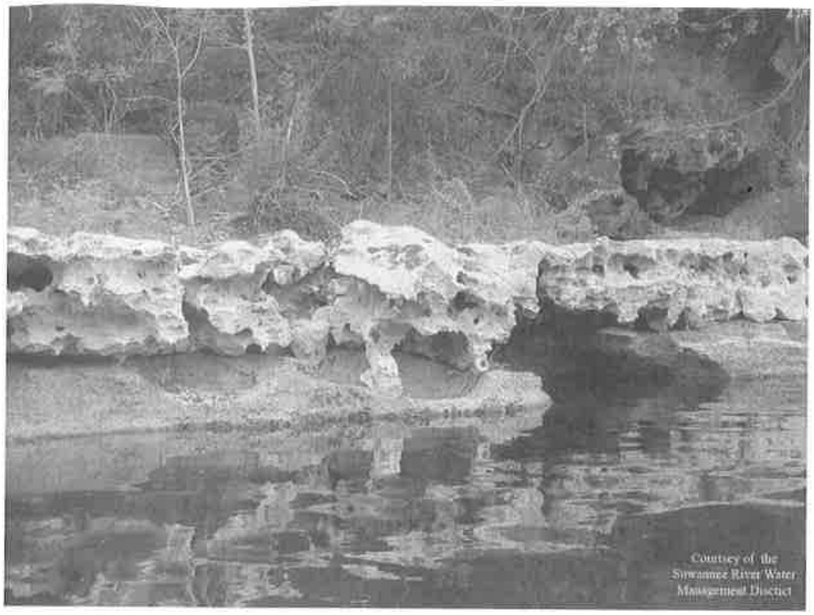


FIG. 4.3 This picture shows an example of limestone dissolution. The location is along the Suwannee River in northern Florida.

system is not as complicated as trying to predict where it goes and where it may surface again.

Once the water goes underground, it can take a couple of different paths. It can flow through open conduits and through the pores in the aquifer, making its way down gradient to discharge in a spring, seep, or well. A portion of the water may stay in the conduit and reemerge to surface water within a matter of hours or days with little change to its chemical and physical properties. Another portion of the water may enter small fractures or pore spaces

FIG. 4.4 This photograph shows the terminus of the Dead River located in Hamilton County, Florida. The feature shown is an excellent example of a swallow hole or sinking stream.

of the formation that make up the aquifer and move much slower through the system. This water will take longer to get through the system because of the relatively slow movement caused by the flow through the aquifer matrix rather than flowing freely through the conduit system. Based on the proximity of the recharge area (area where the water enters the ground) to the spring or discharge point, this water could take days to decades to reach the surface again. Once the water returns to the surface through a spring or seep, it has become surface water again and contributes to the flow in rivers and streams. While the water is in the ground, it can be captured by various pumping sources, such as commercial, residential, irrigation, or public supply wells. Once the water returns to the surface in a spring or seep, it once again becomes surface water and can provide a small or even significant percentage of flow to surface water bodies, such as rivers, streams, lakes, etc., playing a big role in sustaining natural systems.

Many of the most productive drinking-water aquifers are made up of limestone units; therefore, it is important to remember that sinkholes are directly connected to our sources of drinking water. Historically, sinkholes were used as waste disposal sites to dispose of many types of waste materials. Everything from bowling balls to batteries have been "disposed" of in sinkholes. Now that we have a better understanding of how groundwater systems work and the importance of keeping our drinking-water supplies clean, we are doing a better job of properly disposing of waste materials. Strict federal and state regulations for the disposal of wastes have helped stop disposal of wastes in sinkholes, which affects not only our drinking-water supplies but also other natural systems. There is still the need for education of the general public to increase awareness and understanding of our natural systems to prevent dumping into sinkholes and other natural systems.

OUR ENVIRONMENT

Karst systems are very vulnerable to groundwater pollution due to the relatively rapid rate of water movement and the lack of a natural filtration system. Local water supply systems located in karst regions are at risk of being contaminated. In the 1980s, caves were flooded in a highly populated area around Bowling Green, Kentucky, and allowed industrial waste to contaminate a vast region of underground fissures that supplied local wells.

GLACIATED TERRAIN

Glaciers have carved many surfaces of the Earth, particularly in the Northern Hemisphere. These ancient ice sheets also left deposits of material that today often contain groundwater. During the Pleistocene epoch, much of Canada, the northern United States, Scandinavia, Russia, and Siberia were covered by massive sheets of ice. These ice layers were as much as 1 to 2 miles (1600 to 3200 m) thick. Glaciers increased in size during periods of global cooling and then receded as global warming occurred. More glaciers existed in the Northern Hemisphere than other parts of the world, probably because the larger landmasses cooled more quickly than the large expanses of ocean that existed in the Southern Hemisphere. The ice sheets of the Northern Hemisphere could move along landmasses to the south, while the glacial ice in the Southern Hemisphere tended to break off along the coast of Antarctica and formed icebergs before reaching nearby southern continents. Scandinavian ice sheets moved southward to present-day Germany, Ukraine, and Kazakhstan, while glaciers in North America extended as far south as the Midwestern states of Indiana, Iowa, and Illinois (Figure 4.5). Surface water drainage patterns changed, valleys were created, and huge sedimentary deposits of glacial materials were left behind.

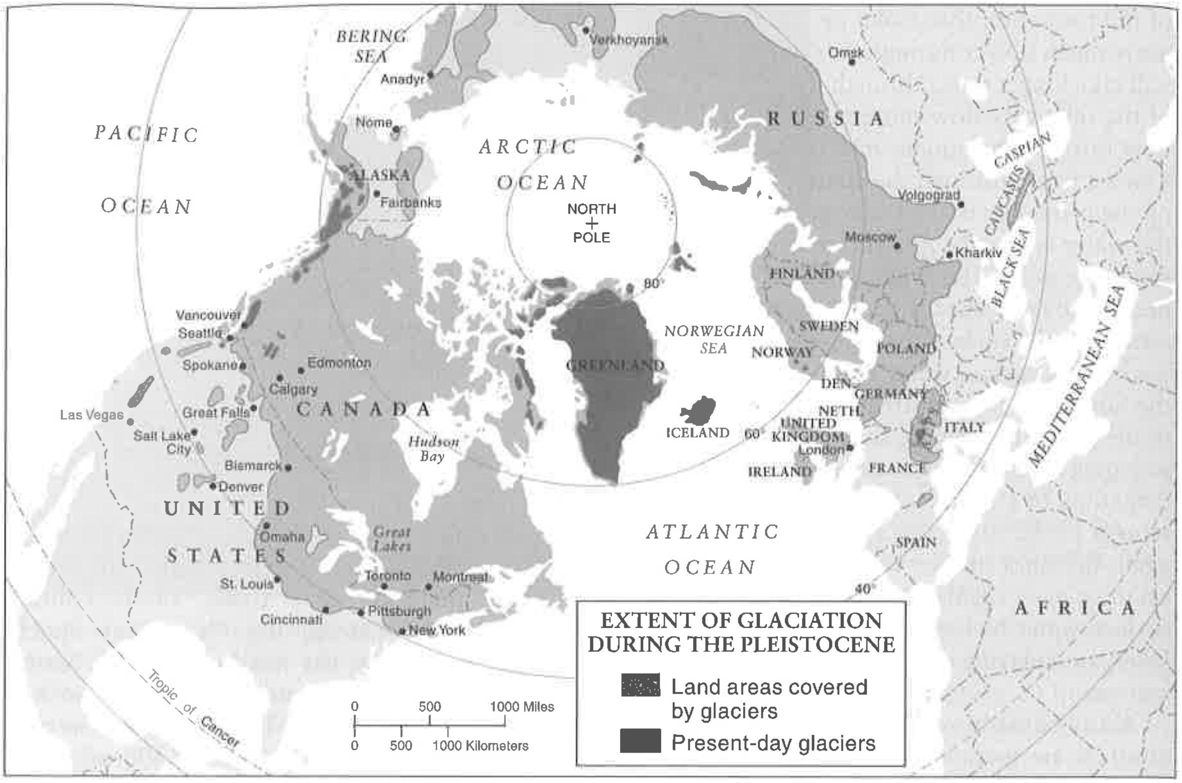


FIG. 4.5 Continental glaciers of the most recent Ice Age in North America (approximately 20,000 years ago) reached as far south as the Ohio and Missouri river valleys. Most of Canada and the northern United States were covered with ice sheets between 500 and 2500 feet (150 to 760 m) deep. Much of the world's water supply was frozen at that time in glaciers, and sea level fell about 300 feet (90 m). *Geography: Realms, Regions, and Concepts*, 10th Edition, by Harm de Blij and Peter O. Muller. Copyright © 2002 H. J. de Blij and John Wiley & Sons, Inc. This map was originally produced in color. Adapted and reprinted by permission of John Wiley & Sons, Inc.

Several glacial epochs have occurred throughout Earth's history. The most recent period of deglaciation began about 15,000 years ago, following global warming, and continues today.

During times of glacial activity, underlying terrain was scraped, carved, and reshaped through the plowing and grinding action of moving glacial ice, rocks, and boulders. Rocks and boulders were carried at the base of the ice sheet and were deposited as a glacier melted. In North America, materials were carried from the Canadian Precambrian Shield regions of Ontario and Quebec to the northern United States (Figure 4.6). In Europe, rocks from Scandinavia were dragged into Germany, Poland, and the former Soviet Union. Mountain glaciers in the Rockies, Alps, and Andes altered local landscapes in much the same way, though on a much smaller scale.

Rock debris that is transported by glaciers and then deposited is called **glacial till**. Glacial deposits often contain boulders intermixed with sand and silt (material between the size of fine sand and clay particles), gravel, and large rocks. Some buried valleys of glacial material are not apparent from surface topography, and coring (drilling) is necessary to

FIG. 4.6 A piece of Canadian rock, called an *erratic* (so called because of its "erratic" occurrence) sits in central Illinois. Farmers in regions where erratics are found were forced to clear fields of rock obstructions before plowing or other cultivation. Some erratics were used to build fences and foundations, while others were simply piled out of the way in the corners of fields.

locate these potential sources of groundwater. As glaciers melted, some boulders, cobbles, pebbles, gravel, sand, and fines were carried by floodwaters and deposited as **glacial outwash**. These materials can sometimes be found in buried valleys tens of miles (over 16 km) long and several miles (over 3 km) wide.

A CLOSER LOOK

Sir Charles Lyell (1797–1875) was an esteemed British geologist who announced the theory of the Pleistocene epoch in 1839. His study of fossil mollusks, as well as his profound understanding of geology and geologic processes, led to his explanation of the natural glacial forces that caused erosion and other terrestrial changes during the most recent Ice Age. Others of that same era developed the glacial theory through research of the odd and erratic occurrence of boulders in regions far from native bedrock. Scientists of the 18th and early 19th centuries had argued that a great flood deposited these freak boulders around the world. Later, another theory proposed that these boulders were first frozen within drifting icebergs and then deposited in wild patterns as melting occurred during a great flood. These out-of-place boulders were called *drift*, a term still used today even though the theory of drifting boulders was discredited over 150 years ago.[7]

ALLUVIAL VALLEYS

Flowing rivers deposit sediments called **alluvium** (also called alluvial or fluvial material). In Chapter 3 we discussed the process of sediment transport and deposition during flood events. During a flood, gravels and larger materials are typically deposited and settle on a riverbed. Smaller materials—sand and clay particles—are generally transported greater distances and deposited across a floodplain during high-water events. As geologic time passed, alluvial material could build to a thickness of hundreds of feet (over 100 m).

Rivers that flow through an alluvial valley are often hydraulically linked to groundwater. This physical connection creates opportunities for surface water in a river to recharge groundwater or for groundwater to replenish flows in a river as baseflow. The direction of water movement between groundwater and surface water is dependent on gradients, climatic conditions, and water volume, as discussed in Chapter 3.

TECTONIC ACTIVITY

Tectonic activity—the movement of rock formations—can create fissures and fractures that hold groundwater. A **fracture** is the separation of a rock surface, which creates a hairline crack in the rock (Figure 4.7). A **fissure** is a location where the walls of a fracture have become separated and moved apart. Some fissures are filled with materials (veins) such as rocks, sediments, minerals, or water.

Many homeowners in mountainous regions rely on groundwater found in fissures (called *l'eau des roches* or "rock water" in France) for water supplies. Variability is a problem, however. A well driller may find groundwater at one location but be unsuccessful only a few hundred feet (100 m) away. Fissures in igneous rocks are generally not extensively interconnected and often provide limited sources of groundwater because of the limited open space within fissures.

FIG. 4.7 Ms. Cech inspects rock fractures along the Big Thompson River near Estes Park, Colorado.

GROUNDWATER RECHARGE

The hydrologic cycle has a major impact on groundwater storage. Precipitation and surface water slowly move belowground until they are intercepted by plant roots or stopped by an impervious layer of material such as clay or shale. This naturally occurring process of downward water migration is called **groundwater recharge** or **percolation.**

Groundwater recharge rates depend on climate, terrain, geology, and vegetative ground cover. Percolation occurs slowly if geologic materials are tight (somewhat impervious) and limit movement of percolating water. It has been estimated that groundwater in some regions of the High Plains in the central United States and Canada could take centuries to recharge if depleted. This is due to the slow rate of groundwater recharge. By contrast, a small, shallow body of groundwater, located in geologic material with high recharge capacity, could refill after one significant rainstorm.

Groundwater recharge is greatly reduced in urban areas. Paved roads, rooftops, and other impermeable surfaces prevent surface water from percolating to groundwater. Reduced recharge rates in such developed locations can cause downstream flooding problems as a result of increased surface water runoff. Preservation of wetlands along streams, stormwater detention ponds, and open space such as parks, golf courses, and wildlife areas can help preserve groundwater recharge zones.

High-precipitation events do not always lead to increased percolation rates. Arid locations, in particular, can have low percolation rates due to hard, sun-baked land surfaces. A heavy thunderstorm in a desert may generate significant volumes of surface water runoff that rapidly collect in an arroyo (a creek or gulch). The result is usually a flash flood but negligible groundwater recharge.

When precipitation or surface water begins to recharge, it enters an area just below the land surface called the **vadose** (from the Latin word *vadosus*, meaning "shallow") **zone**. The vadose zone (also referred to as the **unsaturated zone**) extends vertically from the land surface down to the area completely saturated with groundwater (called the **saturated zone**). The top of the saturated zone is known as the **groundwater table**. The slope of the groundwater table generally (but not always) follows the topography of the land surface, though usually in less detail (Figure 4.8).

Soil is a combination of inorganic weathered geologic material, decomposed organic material, bacteria and other living organisms, air, and water. Water found in the small openings between soil particles is called **soil moisture** (also called *soil water*). Soil moisture resides between soil particles in quantities that vary with precipitation and evapotranspiration. Plant roots capture soil water through **capillary action**. This process draws water into a root system (called the **root zone**) and moves it upward to all parts of the plant. Surface tension within the root causes water molecules to be attracted upward into the plant. Surplus soil water percolates downward past the root zone until it reaches a saturated zone. These processes are of particular interest to soil scientists, agronomists, and botanists in determining plant water requirements and groundwater recharge rates.

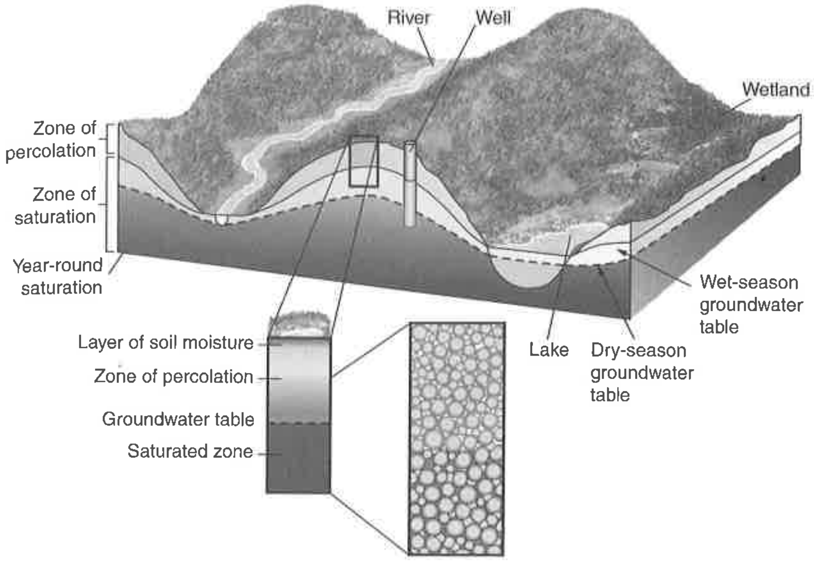


FIG. 4.8 Lakes and wetland complexes often exist in areas with shallow groundwater elevations that intercept the land surface. Variations in precipitation, between seasons and during wet or dry cycles, can greatly affect the elevation of shallow groundwater.

POLICY ISSUE

Groundwater recharge is an important natural process for replenishing groundwater supplies. In some areas of the world, however, drought and overuse of groundwater for urban and rural uses have led to alarming declines. Coupled with these conditions is ongoing urban sprawl, which effectively seals potential recharge zones with paved streets, sidewalks, and rooftops.

If you were a groundwater hydrologist, how would you collect and develop data in an urban area to prove the need to preserve open space for groundwater recharge? What information would be necessary to convince a city council, development community, or homeowners of the importance of groundwater recharge? Suppose your community relied solely on surface water for its water supplies. How would this change your argument regarding the need to protect groundwater recharge zones?

AQUIFERS

An **aquifer** is a water-bearing geologic formation that can store and yield usable amounts of water. The word *aquifer* comes from the Latin words *aqua*, meaning "water," and *ferre*, meaning "to bear or carry." Aquifer materials include sand, gravel, sandstone, limestone, and fractured rock such as granite, which has sizable fissures. Aquifers are analogous to surface watersheds in that both are basic units of water management.

An aquifer is identified by characteristics such as type, areal extent, depth from the land surface, thickness, yield, and direction of groundwater movement. Some jurisdictions manage an aquifer by implementing rules (laws) that can regulate pumping rates, as is done in Nebraska, for example, and by spacing (spatial separation) of groundwater wells, as is required in Kansas. In Colorado, some groundwater users are required to provide alternative water supplies to surface water users in locations where a hydraulic connection exists between surface water and groundwater. (Groundwater allocation laws will be discussed in Chapter 8.)

AQUIFER TYPES

Aquifers are classified as consolidated or unconsolidated rock. **Consolidated rock** includes sandstone, limestone, granite, or other rock. Some are very low water-yielding formations, since the material is almost impervious and does not allow groundwater to move easily through the geologic material. Limestone aquifers, however, can yield large amounts of groundwater because of extensive porous space created by solution. The Floridian Aquifer in Florida is an excellent example of a high water-yielding limestone aquifer. **Unconsolidated rock** consists of granular material such as sand and gravel and generally yields larger amounts of groundwater.

Aquifers can range in size from very small formations of a few feet (1 m) thick that extend less than 1 mile (1600 m) to massive systems that extend hundreds of miles (hundreds of kilometers) across multiple state, provincial, or international borders. Aquifers can vary greatly in depth from the land surface. In some locations, the top of an aquifer may extend to the land surface and then tilt gradually downward for hundreds of feet (over 100 m). Again, regional geology provides the setting for groundwater and aquifers.

The **saturated thickness** of an aquifer is the total water-bearing thickness of a geologic formation. An aquifer may be a few feet (1 m) thick or hundreds of feet (over 100 m) thick. The saturated thickness of an aquifer significantly affects its potential water yield.

Numerous types of aquifers exist around the world. A **perched aquifer**, for example, is often found in formations of glacial outwash where clay layers (sometimes called *lenses*) form impermeable layers above a primary aquifer. This upper or perched groundwater usually covers a small area but allows groundwater to exist above the saturated zone of a lower aquifer system. A perched aquifer is often located relatively close to the land surface, and in some cases, the upper limit of a perched aquifer (called a *perched water table*) can provide base flow for wetlands or streams. The process of drilling a well can actually puncture a perched aquifer and allow it to drain into lower geologic formations.

A **fractured aquifer** is found in rocks, such as granite and basalt, which contain usable amounts of groundwater in cracks, fissures, or joints. Limestone formations are sometimes found in fractured aquifers but often contain cracks or other openings enlarged by solution (dissolving of rock). Large channels or caverns can be created in this type of geologic setting, such as the limestone caves of Kentucky discussed earlier. An **aquiclude** (from the Latin word *claudere* meaning "to shut down") is a formation that contains groundwater but cannot transmit it at significant rates to supply a well or spring.

Groundwater exists in an aquifer under two different conditions: **confined** (also called *artesian*) or **unconfined** (sometimes called *water table*). An unconfined aquifer is generally located near the land surface and is recharged directly by surface water. Alluvial aquifers are excellent examples of unconfined aquifers. Recharge can occur from the downward seepage of surface water through the unsaturated zone or from lateral movement or upward seepage of groundwater from underlying geologic strata.

A CLOSER LOOK

A confined aquifer is similar to a volume of water in a pressurized container. The sides of the container act as an impermeable barrier that confines the water within a given space. If a small opening is made, water will flow out to release pressure built up inside the confined space of the container. A confined aquifer has similar properties. Water pressure caused by gravity will cause confined groundwater to find exit points anywhere in the geologic system. Occasionally, the path of least resistance is upward to the land surface. If enough pressure exists in the aquifer, a spring may form.

Confined, or artesian, conditions occur when an inclined water-bearing formation is located at

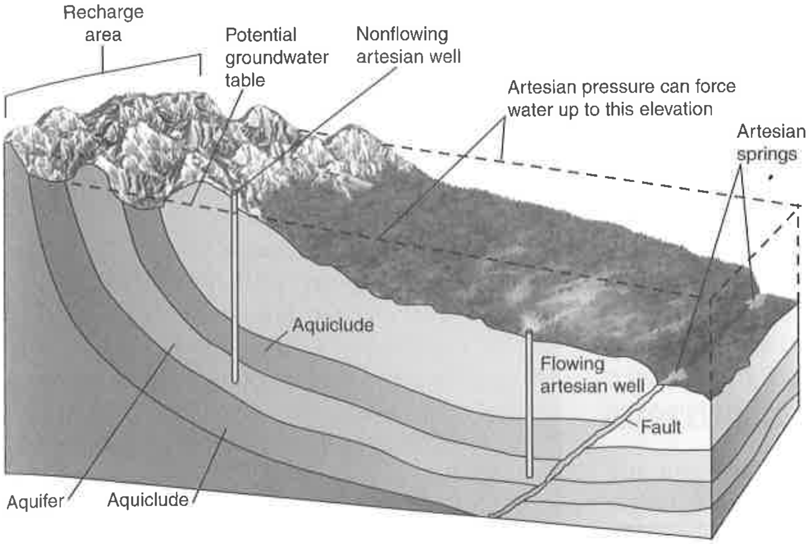


FIG. 4.9 Two conditions are necessary to create an artesian groundwater system: a confined aquifer and sufficient pressure in the aquifer to force groundwater in a well or other opening to rise above the static water level (or groundwater table) of the aquifer. If groundwater pressure is great enough to force water to the same elevation as the recharge zone (shown by the dashed line), water at the surface will flow out of the ground naturally and create artesian springs.

depth below an impermeable layer of geologic material such as rock, clay, or shale. This geologic barrier "confines" groundwater and causes it to be under pressure. If the pressure is great enough, groundwater can emerge at the land surface as an **artesian spring**. A spring can also occur if groundwater in an unconfined aquifer moves from a higher to a lower elevation and emerges on the land surface (Figure 4.9).

If pressure is great enough, confined groundwater will flow up a well to the land surface, called a *flowing artesian well* (Figure 4.10). If the pressure in a confined aquifer is less, groundwater may travel only partially up a rock fissure or well but not reach the surface. Confined aquifers generally have small recharge zones and yield small amounts of water. However, an exception is the Dakota Sandstone Aquifer of South Dakota. This formation is recharged by surface water from across the Black Hills in western South Dakota and from adjacent formations, and supplies groundwater to much of the state. Pressure in this confined aquifer was as high as 130 pounds per square inch (9 kg/cm^2) in the early 1900s. The

FIG. 4.10 The citizens of Bad Oeynhausen, Germany, owe a large portion of their prosperity to a local farmer and his pigs, who discovered the first flowing artesian spring in the area. *Bad*, German for *spa*, was added to the town name, and the community was soon discovered by thousands seeking therapeutic relief from the minerals contained in the hot waters, called *Heilwasser*, or "healing waters," by Germans. The grateful residents erected this *Schweinebrunnen* (pig fountain) in honor of their discovery.

first wells were drilled into the Dakota Sandstone Aquifer in 1882 and required coring through overlying layers of shale that varied in thickness from 985 feet (300 m) to 1640 feet (500 m). These shale layers acted as the confining beds of the aquifer. Artesian pressure was so great at the time that groundwater jetted over 100 feet (30 m) into the air in some locations. However, as more wells were drilled in the late 1800s, artesian pressure decreased. By 1915, 10,000 artesian wells had been drilled into the formation, with a corresponding head reduction (drop in groundwater levels) of approximately 13 feet (4 m) per year between 1902 and 1915.[8]

A CLOSER LOOK

The word *artesian* comes from the province of Artois in northwestern France, where the first artesian well was drilled by Carthusian monks in A.D. 1126. The monks used a percussion method to drill their well (they hit a sharp metal rod with a heavy hammer). The bore hole was only a few inches (or centimeters) in diameter, but the confined groundwater was under enough pressure that it flowed out of the ground.

The bottling of such artesian spring water has become a huge business worldwide. According to UNICEF (the United Nations Children's Fund), the consumption of bottled water was almost nonexistent in the 1950s but grew to 843 million gallons (3.2 billion l) in 1984. It reached a staggering 3 billion gallons (11 billion l) in 1997. Bottled water may seem like a luxury in the United States and other more-industrialized countries, but in less-industrialized regions, where water pipelines may not extend to poorer neighborhoods, bottled water can be a necessity.

In the mid-1900s, many artesian wells in the San Luis Valley of south-central Colorado (elevation 8000 feet, or 2400 m) flowed as "fountains" aboveground due to the high artesian pressure of groundwater in the area. As the weather cooled in the fall, the artesian water froze, creating beautiful ice sculptures. Valley farmers sometimes placed food coloring in the nearly frozen water to create colored fountains—a unique tourist attraction throughout the valley. Today, artesian pressures have declined significantly, owing to increased groundwater pumping in the area. Groundwater recharge from the nearby Sangre de Cristo Mountains no longer provides enough pressure to maintain historic artesian conditions. Today, the rainbow artesian fountains of the San Luis Valley are only memories.

Thermal springs discharge groundwater that has a higher temperature than normal ambient (native) groundwater (an average of approximately 50°F, or 10°C, in the United States). Thermal spring water is found only in locations where groundwater has been heated by the Earth's hot interior. Steam pressure then forces superheated groundwater back to the surface through fault zones. Warm Springs in Georgia, Hot Springs in Arkansas, Yellowstone Park in Wyoming, Glenwood Hot Springs in Colorado, and Bath, England, are famous resorts where groundwater is heated by thermal activity. It has been estimated that some thermal spring water may circulate as deep as 2.5 miles (4 km) before returning to the Earth's surface with temperatures as high as 115°F (46°C).[9]

Mud pots, such as those found in Yellowstone National Park, are similar to thermal springs. The addition of clay and other undissolved particles in suspension creates the mud effect. A *geyser* is a thermal spring that intermittently builds up pressure from thermal expansion and steam to force heated water out of its crater and into the air. Geyser water is forced up narrow plumbing systems of fissures, vents, and shafts until it reaches the surface in a wild, steamy explosion (see Figure 4.11).

The Ogallala Aquifer, an unconfined aquifer located in the central United States, is the largest groundwater aquifer in North America (Figure 4.12). Also known as the High Plains Aquifer, it stretches from South Dakota to the Texas Panhandle. It consists of sediments that eroded off the ancient Rocky Mountains and deposited about 3.8 million years ago (during the Tertiary Period). The aquifer covers nearly 175,000 square miles (453,250 km^2) and contains enough groundwater to fill Lake Huron.

FIG. 4.11 Groundwater can sometimes be seen at unique geologic locations. Thermal heating far beneath the Earth's crust has created hundreds of geysers, mud pools, fumaroles, and boiling chloride pools here at the Whakarewarewa Thermal Area at Rotorua on the North Island of New Zealand. Pohutu Geyser, shown here, is the largest in New Zealand. It usually erupts 20 times a day to a height of 60 feet (18 m) and at times exceeds 100 feet (30 m). Go to http://www.youtube.com and type in "Pohutu Geyser" for a short video of the eruption.

The thickness of the Ogallala varies from less than a foot (30 cm) at its edges to over 1300 feet (400 m) in central Nebraska. In the Sandhills of Nebraska, the aquifer has springs that actually bubble, and some even form geysers several feet (meters) in height. In other locations, the saturated zone of the aquifer can be seen along eroded bluffs at the base of small spring-fed ponds.

Most water use from the Ogallala Aquifer is for irrigation. **Groundwater mining** has occurred in some areas where more groundwater is withdrawn than is recharged. Declines of over 100 feet (30 m) are common in many locations of north Texas, while smaller declines have occurred in South Dakota, Nebraska, Kansas, Colorado, and Oklahoma. Some irrigation wells have been abandoned because the expense of pumping groundwater from such depths exceeds the economic benefits from crop production.

PROPERTIES OF AQUIFERS

The amount of groundwater that is contained within aquifers varies tremendously with the pore spaces created between geologic materials. That portion of the rock not occupied by solid matter is called the **void space** (also **pore space**, **pores**, **voids**, **interstices**, and **fissures**). This space contains groundwater or air. Only interconnected void spaces provide opportunities for groundwater to move through under the force of gravity. Voids range in size from microscopic openings between very fine materials of chalk formations (found in Great Britain) to dissolved limestone caverns (found in Kentucky). Interconnected pores provide residence sites for groundwater, and in enough quantity, they combine to form an aquifer.

Porosity is the percentage of the total volume of pore spaces within a geologic formation that can fill with water. An aquifer that contains a relatively high percentage of void space is considered to be porous or to possess a high porosity. Porosity is defined by the following equation:

$$n = V_v/V_t$$

where n = porosity
V_v = volume of void space in a unit volume
V_t = total unit volume of earth material within a geologic formation

In principle, porosity can be determined in a laboratory by taking a known volume of geologic material V_t, drying the material in an oven until all water is removed, and then submerging the dried matter in a known volume of water. The difference between the original water volume and the amount remaining after removal of geologic material is the volume of the void space. Dividing void space by the known volume gives the porosity of the material.

EXPERT ANALYSIS

Calculate the porosity of a sample of sand, given the following information:

Total volume of sand = 12 cu. in. (or 197 cm^3)

Initial water level in a graduated cylinder = 26 cu. in. (or 426 cm^3)

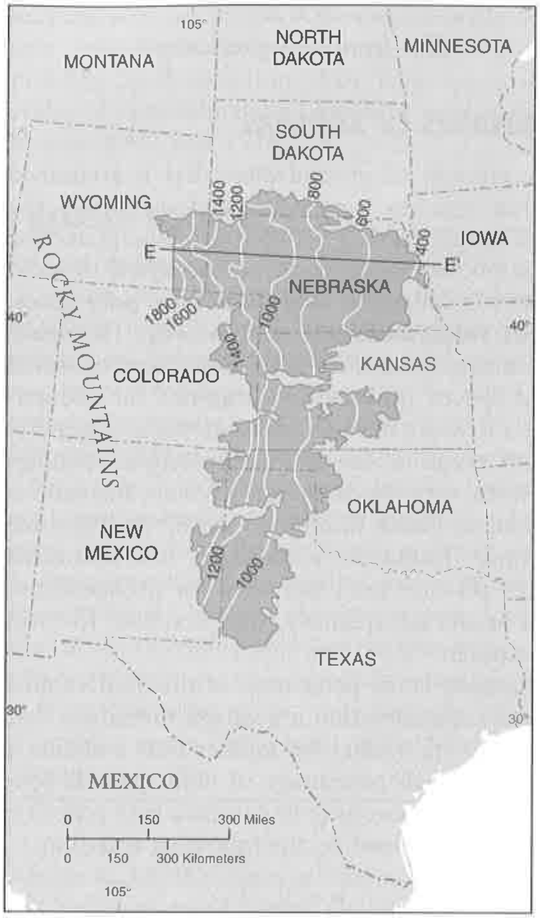
Displaced water level after dried sand is placed in graduated cylinder = 34 cu. in. (or 557 cm^3)

Displaced water level (34 cu. in.) minus Initial water level (26 cu. in.) = 8 cu. in.

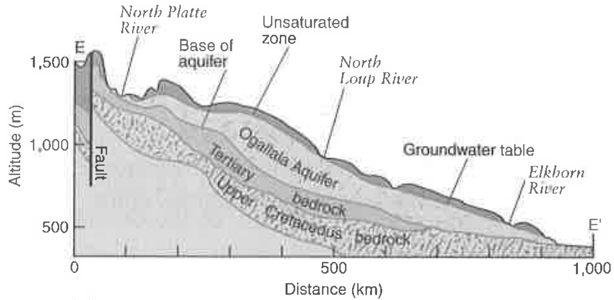
Using $n = V_v/V_t$, substitute the given values:

$$\begin{aligned} n &= (12\text{ cu. in.} - 8\text{ cu. in.})/12\text{ cu. in.} \\ &= 4\text{ cu. in.}/12\text{ cu. in.} \\ &= 0.33\text{ or }33\% \end{aligned}$$

Grains of sand of uniform size are considered to be well sorted and provide many open spaces for water to accumulate. However, if grains are poorly sorted, smaller particles of sand can fill in the pore spaces between larger grains. This intermixing results in fewer voids available for water storage. A porosity of 30 percent (often found in sand and gravel formations) provides significant storage space for groundwater. A porosity of 15 percent, found in a formation of silt



(a)



(b)

FIG. 4.12 The Ogallala Aquifer provides water to irrigators, cities, and other groundwater users in parts of South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, Texas, and New Mexico. The thickness of the aquifer varies generally from 20 to 1000 feet (6 to 305 m), while the elevation of the land surface in the region ranges from approximately 5900 feet (1800 m) in Wyoming to 1300 feet (400 m) in eastern Nebraska. Note the land surface elevation contour lines in the map (a) and the corresponding profile view across Wyoming and Nebraska (b). The edges of the Ogallala Aquifer, particularly in northern Texas, western Kansas, and eastern New Mexico and Colorado, tend to have significantly less saturated thickness than areas at the center of the aquifer in the Sandhills of central Nebraska.

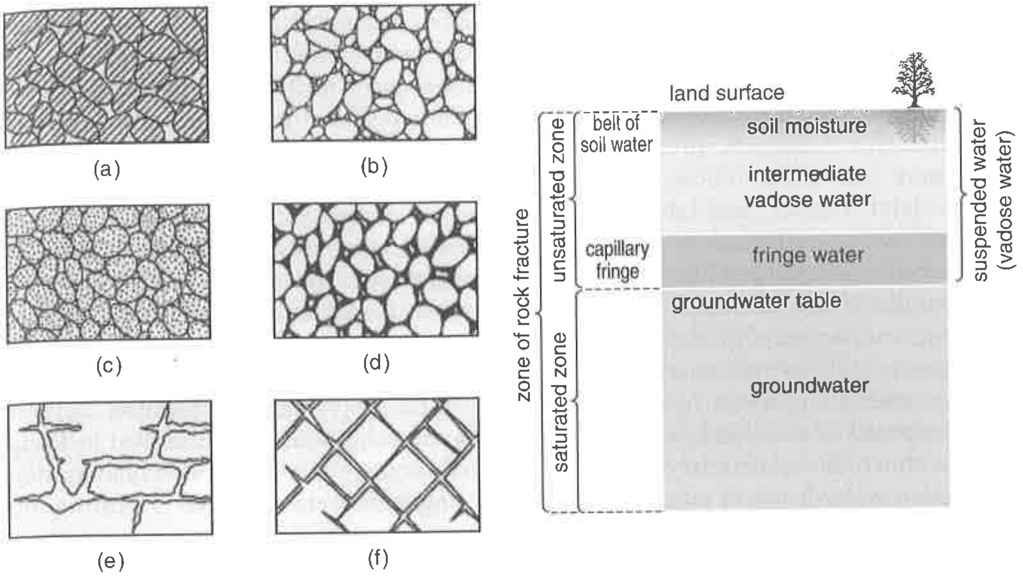


FIG. 4.13 Examples of rock interstices. (a) Well-sorted sedimentary deposits with a high porosity. (b) Poorly sorted sedimentary deposits with a much lower porosity. (c) Well-sorted material containing pebbles. (d) Well-sorted material that has a low porosity due to nonporous sediments found between pore spaces. (e) Porous rock due to solution. (f) Porous rock due to fracturing. These types of rock interstices form the zone of rock fracture illustrated on the right.

and clay materials, is fairly tight and restrictive. Materials such as igneous rock or sedimentary material like clay may have a porosity of less than 1 percent. See Figure 4.13 and Table 4.1.

Clay and shale formations contain numerous porous openings, but the voids are often too small to allow movement of water. Therefore, impervious formations of clay and shale act as barriers to groundwater percolation and can greatly influence groundwater location and movement.

GROUNDWATER MOVEMENT

Through the force of gravity, groundwater naturally moves to lower elevations. However, the direction and rate of movement are determined by the lithology, stratigraphy, and structure of geologic deposits. For example, in the Great Plains of the United States and Canada, several formations of Paleozoic, Mesozoic, and Cenozoic

TABLE 4.1 Grain-Size Classification

Material	Size (in.)	Size (mm)	Example
Boulder	12	300	Basketball
Cobbles	3–12	75–300	Grapefruit
Coarse gravel	0.7–3.0	18–75	Grape
Fine gravel	0.2–0.7	5–18	Pea
Coarse sand	0.08–0.20	2–5	Water softener salt
Medium sand	0.02–0.08	0.5–2.0	Table salt
Fine sand	0.003–0.020	0.075–0.500	Powdered sugar
Fines	0.003	0.075	Talcum powder

sandstones warp up along the foothills of the Rocky Mountains. This produces opportunities for artesian conditions as surface water from higher elevations is recharged into lower sandstone formations. In other locations, groundwater movement may generally follow the topography of the land surface and slowly move toward areas of lower elevation. A hydrologist may find conditions where the groundwater table is somewhat parallel to the land surface.

Within the intermountain basins of the western United States and Canada, alluvial valleys underlain with clay lenses and silt deposits provide excellent aquifers composed of sand and gravel. Groundwater levels within these aquifers are often closely linked to surface water levels in adjacent rivers. The direction of groundwater movement in these alluvial settings is typically in a relatively perpendicular direction toward local rivers. Why would a groundwater hydrologist be interested in understanding the direction of groundwater movement within such an aquifer?

Permeability is the ability of porous materials to allow fluids to move through it. Formations with low permeability (such as tight sands or clay) do not allow groundwater to move as rapidly as gravels that have a high permeability. Grain size, shape, and arrangement will have an effect on the ability of groundwater to move through an aquifer. Groundwater may move only a few inches (or centimeters) per *year* in clay, while it can move several feet or meters per *day* in gravel. Surface water in a river, by contrast, travels many miles (or kilometers) in a single day.

Aquifers that contain large openings, such as the dissolved limestone formations discussed earlier, may have low porosity but high permeability. Why? Because the large openings in these aquifers (such as are found in karst formations) allow groundwater to move at a high velocity even though the formation itself is impervious. The term *underground rivers* could actually be used to describe groundwater movement in these unique geologic settings.

Hydraulic conductivity is the actual measurement of the rate of flow of a fluid through porous material. For example, the permeability of sand remains the same whether water or maple syrup is present. However, the hydraulic conductivity (or permeability coefficient) would be much slower for syrup than it would be for groundwater. Permeability is expressed as a coefficient, while hydraulic conductivity is shown as a rate of discharge in feet or meters per day (similar to the measurement of surface water movement).

Tracer tests can be used to determine hydraulic conductivity by placing a dye in a monitoring well and then measuring the time necessary for the dye to move to the next monitoring station. Several test holes generally need to be installed in fairly close proximity to intercept the slowly migrating dye if exact groundwater movement patterns and directions are uncertain.

Hydraulic head (denoted as h in hydrology formulas) is the driving force that moves groundwater. The hydraulic head combines fluid pressure and gradient, and is the height of a column of water that can be supported by water pressure at the point of measurement. (It can also be thought of as the height that groundwater will rise inside a well.) Generally, groundwater elevations are the same as the hydraulic head in a well. Groundwater always moves from an area of higher hydraulic head to an area of lower hydraulic head. Therefore, not only does groundwater move downward under the force of gravity, but it can also move laterally and upward. The actual direction of groundwater movement depends on local conditions.

Hydraulic gradient—the slope of the top of the groundwater table—is a function of the hydraulic head within an aquifer. The gradient indicates the direction of groundwater movement. Hydraulic gradient is expressed with the following formula:

$$i = dh/dl$$

where i = hydraulic gradient
dh = change in head (elevation) between two points at the top of the groundwater table
dl = distance between the two points

Generally, the groundwater table will slope toward low spots on the land surface, often toward a river or lake. If the groundwater table is flat (a hydraulic gradient of 0), there will be no groundwater movement unless the water is withdrawn by wells or consumed by deep-rooted plants. If groundwater has no gradient, or if an inclined groundwater table has reached equilibrium between recharge and discharge, then an aquifer has reached a constant or steady state. This is analogous to a volume of water in a container filled with gravel and placed on a level surface. The water surface will have a hydraulic gradient of 0, and there is no water movement. If the container of gravel is tipped so that water flows over the edge, the water level will momentarily have a very slight incline or slope.

The direction of groundwater movement also depends on porosity and the connectivity of geologic voids. An aquifer of sand and gravel has elaborate networks of pores throughout the material. This allows unconfined groundwater to percolate down gradient (to a lower elevation) along the path of least resistance. If the aquifer is in a confined geologic setting, groundwater under pressure will seek a geologic pathway through voids in any direction. In a dissolved limestone cave, the direction of groundwater movement will be along the course of the bottom of the cave. Groundwater found at higher elevations will naturally seek exit points to land surfaces at lower elevations.

OUR ENVIRONMENT

Pollutants from industrial, urban, and agricultural sources can percolate into aquifers and then migrate (travel) great distances. The direction, speed, and extent of groundwater contamination can be predicted by groundwater hydrologists through the use of mathematical formulas. This type of analysis is vital to protect down-gradient (lower-elevation) wells used for drinking water and other purposes, or to determine the appropriate locations for well installation to remove contaminated water for cleanup (to be discussed in Chapter 5).

Depth of groundwater often changes with climatic conditions. For example, a prolonged drought may cause groundwater table declines owing to reduced recharge and increased groundwater use by cities, irrigators, and industry. A wet cycle could produce higher groundwater table levels because of increased recharge. Variations in shallow aquifers, as well as in hydraulically connected wetlands, ponds, rivers, and lakes, are often directly related to climatic patterns.

Transmissivity is a measure of the ability of an aquifer to transmit groundwater, and is the rate that water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is equal to the hydraulic conductivity of an aquifer multiplied by its saturated thickness. It is expressed in square feet (or square meters) per day:

$$T = Kb$$

where T = transmissivity (sq. ft./day or m^2/day)
K = hydraulic conductivity (ft./day or m/day)
b = saturated thickness of an aquifer (ft. or m)

EXPERT ANALYSIS

Calculate the transmissivity of a confined aquifer with a hydraulic conductivity of 5.1 feet (1.6 m) per day and a saturated thickness of 196 feet (59.7 m).

Using $T = Kb$, substitute the given values:

$$\begin{aligned} T &= 5.1 \text{ ft./day} \times 196 \text{ ft.} \\ &= 999.6 \text{ sq. ft./day (or } 92.9 \text{ m}^2\text{/day)} \end{aligned}$$

In 1855–1856, the French engineer Henry Darcy (1803–1858) conducted experiments showing that the water discharge through a uniform bed of sand could be expressed mathematically (Table 4.2). His discovery was the beginning of the science of groundwater hydrology and is still in use today. **Darcy's law** is known to groundwater hydrologists and hydraulic

TABLE 4.2 Results of Darcy's Experiments, Dijon, France, October 29, 30, and November 2, 1855

Experiment Number	Duration (min)	Mean Flow (l/min)	Mean Pressure (m)	Ratio of Volumes and Pressure	Observations
1	25	3.60	1.11	3.25	Sand not washed
2	20	7.65	2.36	3.24	
3	15	12.00	4.00	3.00	Weak movements
4	18	14.28	4.90	2.91	
5	17	15.20	5.02	3.03	
6	17	21.80	7.63	2.86	
7	11	23.41	8.13	2.88	
8	15	24.50	8.58	2.85	Very strong oscillations
9	13	27.80	9.86	2.82	
10	10	29.40	10.89	2.70	

Source: Henry Darcy, Inspector General of Bridges and Roads, "The Public Fountains of the City of Dijon," Report to the City of Dijon, 1856.

engineers as the following equation:

$$q = Ki$$

where q = specific discharge per unit area
K = hydraulic conductivity of the medium
i = hydraulic gradient

In 1855, Darcy designed an apparatus (see Figure 4.14) and used the plumbing system in a Dijon, France, hospital to test his theory. He made a tubular device 8 feet (250 cm) in height, with a diameter of 14 inches (35 cm). It was filled with sand from the Saône River, and then a hose was attached between the test apparatus and a water faucet in the hospital. The water tap allowed him to regulate the flow of water during the experiment. The bottom of the tube had a small pipe attached to a pressure gage. Darcy and his assistant packed the tube tightly with sand and then filled it with water to remove all air from the voids. Next, the height of the sand column was measured, and the faucet was turned on.

Darcy wrote in 1856 in "The Public Fountains of the City of Dijon Experience and Application Principles to Follow and Formulas to be Used in the Question of the Distribution of Water Work Finishes with an Appendix Related to the Water Supplies of Several Cities the Filtering of Water and the Manufacture of Strong Pipes of Lead, Sheet Metal and Bitumen,"

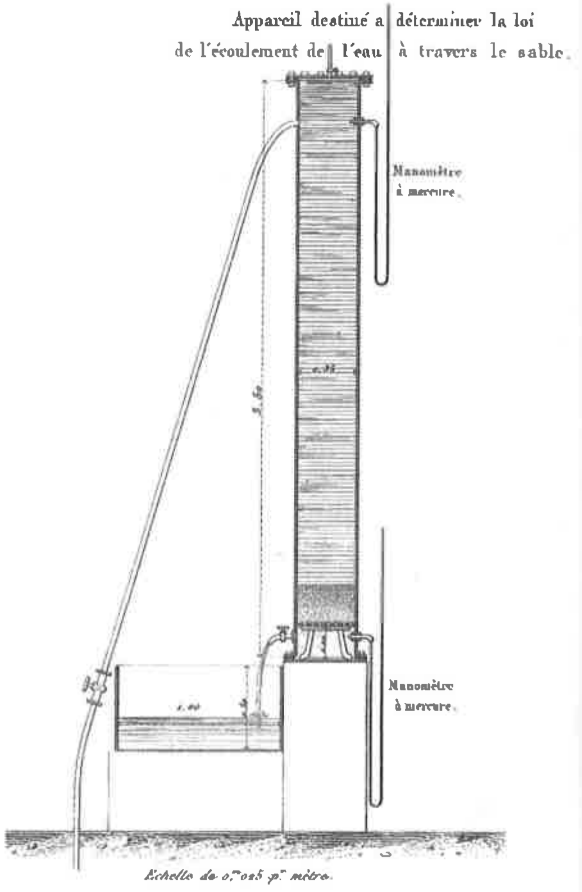


FIG. 4.14 Henry Darcy's apparatus intended to determine the law of water flow through sand.

> *The apparatus . . . consists of a vertical column 2.50 m in height, formed from a portion of conduit 0.35 m interior diameter, and closed at each of its ends by a bolted plate.*
>
> *In the interior and 0.20 m above the bottom, is a horizontal partition with an open screen, intended to support the sand, which divides the column into two chambers. This partition is formed by the superposition upwards on a iron grid with prismatic bars of 0.007 m, a cylindrical grizzly of 0.005 m, and finally a metal cloth with a mesh of 0.002 m. The spacing of the bars of each grid is equal to their thickness, and the two grids are positioned so that their bars are perpendicular to one another.*
>
> *The higher chamber of the column receives water by a pipe connected to the hospital water supply, and whose tap makes it possible to moderate the flow at will. The lower chamber opens by a tap on a gauging basin, 1 meter on a side.*
>
> *The pressure at the two ends of the column is indicated by mercury U-tube manometers. Finally, each of the chambers is provided with an air tap, which is essential for filling the apparatus.*

Darcy immediately encountered a small problem as every pipe in the hospital began vibrating violently when the water pressure was increased. Fortunately, the cause of the noise was determined to be simply the loose fittings in the water faucets of the facility. Deciding there were no negative effects on his experiment (or the hospital pipes), Darcy continued.

Measurements were recorded every minute after the flow of water through the packed sand became constant. The experiment was then altered by varying times, water pressures, and volumes and types of sand. Darcy discovered that the ratio between water pressure and the volume of water forced through his sand-filled device remained almost constant even as water pressure changed. This implied that groundwater movement through aquifers of uniform sands would have the same characteristics.

A CLOSER LOOK

Henry Philibert Gaspard Darcy (Figure 4.15) was born in Dijon, France, in 1803 and attended l'École Polytechnique (Polytechnic School) and l'École des Ponts et Chaussées (School of Bridges and Roads) in Paris, where he was an outstanding student. Soon after graduation, he began working on the water supply system for his hometown of Dijon.

FIG. 4.15 Henry Philibert Gaspard Darcy, the discoverer of Darcy's law for flow in a porous medium.

Water systems in 19th-century France were abhorrent. In Paris, the River Seine was a public sewer, and conditions during the summer months were unbearable. Conditions in Dijon weren't much better. The city relied on groundwater, but the wells often went dry, or sewage wastes contaminated the aquifer. In addition, the drinking water gave off terrible odors.

In 1844, Henry Darcy completed a new water delivery system for his hometown. It started with water from a 2000 gallon per minute (8 m^3/min) spring at Rosori. From there it flowed through a 7-mile (11 km) underground aqueduct that delivered spring water to a covered 1.5 million gallon (5700 m^3) reservoir. Buried distribution lines of over 17 miles (27 km) provided clean water to public fountains, hospitals, and major buildings throughout the city. A total of 142 public street fountains were also installed 300 feet (90 m) apart. The fountains provided the first dependable water supplies for the citizens of Dijon.

The townspeople were thrilled. Darcy received commendations from the Municipal Council and a bouquet of flowers from his workmen. Later, the City of Dijon provided him with free water for life. Unfortunately, Darcy died just a few years after his famous experiment in the hospital at Dijon.[10]

Specific yield of an unconfined aquifer is the ratio of the water that will drain freely from the geologic material to the total volume of

EXPERT ANALYSIS

How do groundwater hydrologists use Darcy's law? One of the most frequent and basic methods is to determine the natural movement of groundwater through an aquifer. Suppose an aquifer of uniform material has a hydraulic conductivity K of 180 feet per day and a hydraulic gradient i of 10 feet/1000 feet = 0.01. What is the specific discharge per unit area (q) in this aquifer? Using Darcy's law, solve for q:

$$\begin{aligned} q &= Ki \\ &= 180\ \text{ft./day} \times 0.01 \\ &= 1.8\ \text{ft./day (or 0.5 m/day)} \end{aligned}$$

This is the specific discharge per unit area of the aquifer.

We then must divide this result by the porosity of the aquifer, since not all of the cross-sectional area in the aquifer is open to water movement. Thus, the actual groundwater discharge (v) will be $v = q/n$, where n is porosity. If we use 33 percent for the porosity, $v = (1.8\ \text{ft./day}) \div 0.33 = 5.5\ \text{ft./day}$ (or 1.7 m/day). Note that the actual groundwater discharge is much higher than the specific discharge because water can only move through pore spaces and not the entire cross-sectional area of an aquifer.

---

the formation:

$$Y = V/T$$

where Y = specific yield
V = volume of water released
T = total volume of aquifer

Specific yield is always less than porosity because it is impossible to remove every drop of groundwater from an aquifer. The relationship of specific yield to porosity depends on the size of particles in a formation. The specific yield of a fine-grained aquifer will be small, while coarse grains will yield greater amounts of water (see Table 4.3).

POLICY ISSUE

Both the direction and speed of groundwater movement are extremely important in many facets of groundwater hydrology. For example, the states of Colorado and Nebraska share surface water supplies from the South Platte River as it flows from the plains of northeast Colorado into the panhandle of Nebraska. However, groundwater movement from the South Platte Alluvial Aquifer in Colorado, under the state line into Nebraska, was not addressed in an agreement between the two states (called an interstate compact) in 1923. As a result, in recent years disagreements have arisen between water officials in the two states over water delivery requirements for the endangered whooping crane in central Nebraska (to be discussed in Chapter 12).

AGE OF GROUNDWATER

Groundwater can remain underground for a few days, years, centuries, and up to many thousands of years, depending on geologic conditions and pumping by wells. By contrast, water in a surface stream may completely replace itself within just a few weeks. The period of time that groundwater remains in an aquifer is called its **residence time.** Table 4.4 shows that the residence time of groundwater can vary from weeks to thousands of years. Refer back to Table 2.1 in Chapter 2, and compare the residence times listed in Table 4.4 with the various water storage locations shown in Table 2.1. In Chapter 5, we'll discuss the implications of residence time, location of water storage, and water quality.

SIDEBAR

Age dating has determined groundwater beneath the Sahara Desert to be between 20,000 and 30,000 years old.[11] This groundwater was probably recharged during the more humid Pleistocene epoch in the region. This explains the availability of groundwater for *qanats* in other desert regions, as discussed in Chapter 1.

Tritium (^3H), a radioactive isotope of hydrogen with a half-life of 12.4 years, can be used to determine the age of water that has been underground since 1953. That year, hydrogen bomb explosions filled the atmosphere with tritium, a by-product of the testing program. Before the explosions, naturally occurring tritium resulted

TABLE 4.3 Specific Yield

Material	Maximum %	Minimum %	Average %
Clay	5	0	2
Sandy clay	12	3	7
Silt	19	3	18
Fine sand	28	10	21
Medium sand	32	15	26
Coarse sand	35	20	27
Gravelly sand	35	20	25
Fine gravel	35	21	25
Medium gravel	26	13	23
Coarse gravel	26	12	22

Source: A. I. Johnson, "Specific Yield—Compilation of Specific Yields for Various Materials," U.S. Geological Survey Water-Supply Paper 1662-D, Washington, DC, 1967.

in precipitation with only 2 to 4 tritium units (TU). After the testing began, levels greater than 10 to 20 TU were common.

The approximate age of groundwater can be determined by measuring levels of tritium in water samples. Levels above 10 to 20 TU indicate that the water was exposed to the atmosphere after 1952. Lower levels identify groundwater that was not exposed to tritium and was underground before the start of hydrogen bomb explosions.[12]

Radiocarbon analysis can also be used to date groundwater. Carbon activity can be measured to determine the time when surface water percolated belowground. Since the half-life of carbon-14 is 5730 years, a water sample with one-fourth the original carbon activity has an elapsed time of two half-lives, or 11,460 years underground. Adjustments must be made if carbonate or other organic materials are found in the groundwater to be tested, since it can alter results.

TABLE 4.4 Estimated Residence Time of the World's Water Supply

Water Type	Residence Time
Oceans and seas	~4000 yr.
Lakes and reservoirs	~10 yr.
Swamps	~1–10 yr.
Rivers	2 wk.
Soil moisture	2 wk.–1 yr.
Groundwater	2 wk.–10,000 yr.
Ice caps and glaciers	10–1000 yr.
Atmospheric water	10 days

Source: Adapted from R. Allen Freeze and John A. Cherry, *Groundwater* (Englewood Cliffs, NJ: Prentice-Hall, 1979), 5.

LOCATING AND MAPPING GROUNDWATER

Geologic history provides clues to the sources of groundwater. If a region has been glaciated, aquifers probably contain boulders, gravel, sand, and fines. The depth and quantity of groundwater may vary greatly, and some groundwater might be found beneath hills or within valley fill materials. A region with alluvial formations of sedimentary material can provide obvious locations to find groundwater. Such a formation would be composed of materials of uniform size, and the groundwater table would probably be somewhat horizontal to the water surface of an adjacent river. By contrast, a fractured rock region in mountainous terrain would be a much more difficult place to find groundwater. Numerous drilling attempts may be required before adequate supplies of groundwater are found in fissures.

Information regarding the elevation of a groundwater table (also called the **potentiometric surface** or *piezometric surface* of an aquifer) can be determined by measuring the depth to groundwater in surrounding domestic water wells, irrigation wells, or groundwater-monitoring wells. Monitoring wells are typically installed in areas where no water supply wells are available or where additional groundwater data are needed. Occasionally, monitoring wells are "nested" for water quality studies. Nesting occurs when several wells are installed in close proximity but are drilled to different depths. For example, monitoring well A may have a depth of 10 feet (3 m), monitoring well B a depth of 15 feet (5 m), monitoring well C 20 feet (6 m), and so on. This allows a groundwater researcher to collect groundwater quality samples at various depths through the saturated thickness of an aquifer.

Once groundwater data are collected, a **potentiometric map** of an aquifer can be produced to indicate the direction of groundwater movement within an aquifer (Figure 4.16). Well locations are plotted on a base map along with surface water features such as ponds, lakes, wetlands, and rivers. Land elevations are noted at each well location with data from either a global positioning unit (GPS) or a topographic map. Groundwater table elevations are also listed next to each well shown on the map. Contours can then be drawn between measurement points to give a general description of groundwater table elevations and hydraulic gradients. Readings will generally correspond to topographic features if the wells are within an unconfined aquifer.

Areas with a shallow gradient will have groundwater contours spaced far apart. A steep hydraulic gradient will be reflected in contours that are close together (similar to a topographic map of a land surface). A groundwater table map for a confined aquifer will generally not correspond with surface features, since confined groundwater is under pressure and has different properties than unconfined groundwater. It is not unusual for changes in atmospheric pressure to produce large fluctuations in wells drilled into confined aquifers. Therefore, accurate measurements can be difficult to obtain on a day-to-day basis in confined systems.

Computer software programs are used to model (generate maps based on mathematical equations) in order to show changes in groundwater elevations over time. This information can be extremely valuable in determining total groundwater in storage and groundwater use trends. The field of groundwater modeling is a highly specialized area of study generally performed by groundwater engineers, hydrologists, or computer scientists.

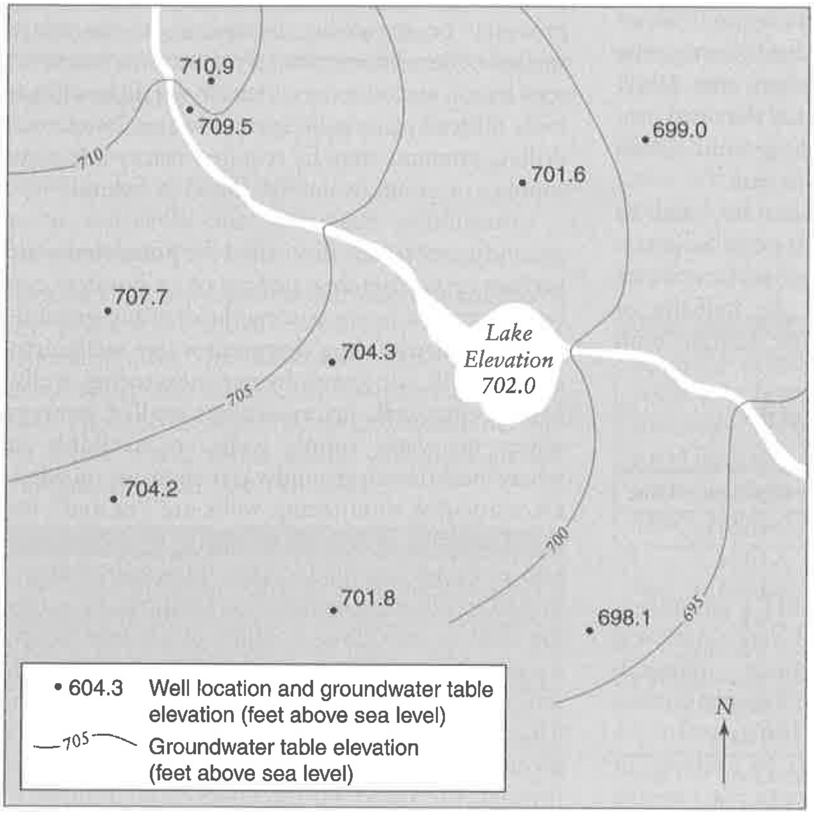


FIG. 4.16 Surface water bodies can be an important feature of a potentiometric map if they are hydraulically connected to the groundwater table. Note that groundwater contours cross the stream in this example, forming a V that points upstream. This indicates a gaining or "effluent" river. If the V on the contours were pointing downstream, the river would be a losing or "influent" system.

A CLOSER LOOK

Finding groundwater can be both an art and a science. Around 30 B.C., the Roman author Vitruvius wrote extensively on prospecting for groundwater. He recommended digging in locations where the mist rises from the ground in the early morning. He also noted that the quality and quantity of groundwater could be predicted based on surface topography and local geology.

Water dowsing is a technique that has been used for centuries to search for groundwater. Even today, many claim they can locate groundwater by holding a forked stick, metal rods, or a swaying weight at the end of a string. A particular movement, or pattern of movements, in the instrument signals the presence of groundwater to the dowser. During the 1977 drought in California, for example, a suburban water well was reportedly located using a bent coat hanger.[13]

In the late 1950s, an anthropologist and a psychologist conducted a well-documented study to assess the extent and credibility of water dowsing. The researchers surveyed county agricultural extension agents in the United States and found an average of 181 water dowsers per one million population. More were located in rural areas, particularly in regions where groundwater was difficult to locate. Although the authors of the study found no convincing scientific evidence that water dowsing worked, they concluded that it provided a process and belief system that relieved anxiety over groundwater availability and shortages.[14]

DRILLING A GROUNDWATER WELL

Groundwater wells are a vital component of many irrigation systems (in addition to providing drinking water, livestock watering, and urban uses). A well can be used to pump water into farm ditches, gated-pipe, lateral sprinkler systems, or center pivots (discussed in Chapter 6).

There are four main steps in constructing a well: (1) drilling; (2) casing; (3) developing; and (4) pump installation. The most common drilling methods are the auger, fluid, and percussion methods. A drilling rig mounted on a truck is used for each of these methods and usually requires a team of two or three technical people to complete the drilling operation (see Figure 4.17).

FIG. 4.17 Well-drilling rigs like this one are used around the world to tap precious groundwater supplies. Well drillers can use rotary drill bits, percussion bits that smash rock, or large auger bits if the ground is relatively soft.

The **auger drilling** method uses a bit attached to the end of a rotating column of pipe to drill and grind through geologic material. A drill bit has cutting "teeth" generally made of steel; for very hard geologic material, the teeth may be carbon, titanium, or diamond tipped. A hollow opening in the center of the bit allows lubrication with drilling mud. A well-drilling crew uses a large gasoline or diesel engine, mounted on the drill rig, to supply energy to rotate and lower the bit attached to the end of drilling pipe. As the drill bit rotates and moves downward, creating a bore hole, the drilling crew adds more lengths of 20-foot (6 m) pipe. This "string" of pipes is increased in length until the desired well depth is reached, often hundreds of feet (over 100 m) belowground. Typically, a well is drilled to the base of the saturated thickness of a water-bearing formation.

Drilling mud is forced inside the pipe stem, down to the drill bit, and back up to the land surface in a constant cycle. This recirculation of drilling mud cools the drill bit and forces tailings (geologic material) from the bore hole through the *annulus* (the space between the drilling pipe and the outside of the bore hole) up to the land surface. Drilling mud also exerts pressure on the walls of the bore hole and prevents it from caving in during the drilling process.

One member of the drilling team, called the *mud logger*, monitors tailings produced during the drilling process. This record (or log) gives a relatively accurate cross section of the formation being drilled and the elevation of the groundwater table. The landowner generally decides how deep to drill below the groundwater table, since the cost of a well is based on the number of feet drilled. Cost of drilling a well varies, but $80 to $100 per foot ($262 to $328 per m) is common for a completed, 8-inch-diameter (20 cm) irrigation well to depths of 100 to 250 feet (30 to 76 m).

Fluid drilling is similar to the auger method except that a high-pressure system of air or water, rather than a drill bit, is used to cut through geologic material. The **percussion drilling** method gets its name from the action of the drill, which raises and falls to smash geologic material, somewhat like a jackhammer breaking concrete. The method is simply an advanced method of the procedure used by the Carthusian monks of Artesia (discussed earlier in this chapter) to drill their artesian well in France in 1126.

After the desired depth is reached, well casing is installed. **Casing** is a plastic or steel pipe installed inside the bore hole to prevent the sides of the well from caving in. The bore hole is generally 2 to 3 inches (5 to 8 cm) larger than the casing to be installed. This extra space allows the well driller to place grout (a type of cement impervious to water) around the top section of the well, thereby preventing surface water contamination from percolating around the outer wall of the well casing and polluting groundwater. Many states require that wells be cased to specified depths for water quality purposes.

The bottom section of the casing, called the **well screen** (Figure 4.18), is perforated with numerous narrow slots (openings). This allows groundwater to move into the well casing but prevents most sand and gravel from entering the casing when the well is pumped. A well

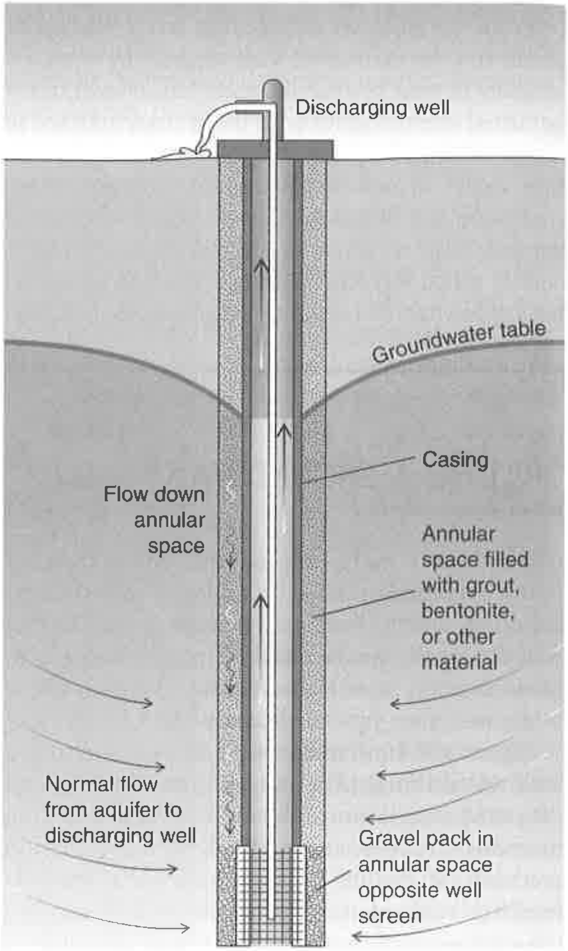


FIG. 4.18 Components of a completed groundwater well.

screen also prevents excessive unconsolidated material from being removed around the casing, which could cause the surrounding formation to subside (cave in). This could lead to collapse of the well or at least could damage the moving parts of a pump. The bottom 10 to 20 feet (3 to 6 m) of a well casing is usually screened, but 50 to 100 feet of screen (15 to 30 m) is not uncommon. The length of screening generally depends on the saturated thickness of the aquifer. Screen slots vary in size based on the grain size of aquifer material found during the drilling process. A 0.05-slot screen, for example, has openings of fifty thousandths (0.05) of an inch (1 mm).

The outside of the casing is often packed with large gravel. This prevents excessive pumping of sand and small gravel into the well and helps keep screen openings clear of sand buildup that could clog and plug the well screen slots.

After drilling is completed, the next step is to develop the well. This is accomplished by pumping or bailing (lifting groundwater out of the bore hole with a special bucket) to clean sediments, tailings, and other geologic material left inside the well. This process increases the transmissivity of the aquifer in the immediate proximity of the well screen by clearing pore spaces of the aquifer.

The final step in constructing a well is pump installation. The pump assembly generally consists of a power plant (pump), which is installed above the well casing on a concrete pad at the land surface. The pump rotates a shaft that turns impellers located near the base of the well inside the well casing. The impellers are similar in appearance to the propeller on a boat and are housed inside pump bowls (large cast iron cases). The pump turns a shaft that spins the impellers at a high rate of speed to lift water from the bottom of the well to the land surface. The power plant is usually operated by gasoline or diesel fuel engines or electric motors. The cost of a complete pump assembly can run approximately $10,000, depending on the horsepower of the power plant selected.

Pumping rates of groundwater can range from less than 15 gallons per minute (less than 57 l/min) to over 3000 gallons per minute (11,356 l/min). Pumping rates depend on the size of the well and power plant, depth to groundwater, and transmissivity of the aquifer. The cost of pumping groundwater is based on the amount of energy needed to "lift" groundwater to the surface. **Lift** can be defined as the total distance between the land surface and the depth to groundwater, within the well casing of a well being pumped, after the area of groundwater being pumped has reached equilibrium. Horsepower is the common power unit for discussing the energy required to lift water.

SIDEBAR

It takes 1 horsepower unit of energy to lift 2 cubic feet of water a vertical distance of 1 foot per second if the pumping plant is 100 percent efficient. If the pumping plant is only 50 percent efficient, it will require 2 horsepower units to lift 2 cubic feet of water a vertical distance of 1 foot per second.

Pump efficiencies vary based on friction and heat, much as a car engine runs less efficiently if it needs a tune-up or the tires are low on air. Pumping plants never run at 100 percent efficiency due to friction, engine wear, temperature, and other normal factors that affect mechanical engines. The efficiency of moving water will also be affected by friction created within the well casing, bowls, and impellers. Other factors that affect pumping efficiency include plugged well screens, worn impellers, and reduced aquifer transmissivity. Pumping plant efficiencies of 70 percent are very good, while 20 percent efficiency is considered very poor.

Pumping plants with greater horsepower needs require more energy to operate. Pumping groundwater from a depth of 80 feet (24 m) will require double the energy costs of a well operating at a depth of 40 feet (12 m) (Table 4.5). Therefore, static water levels (the depth to the groundwater table) and drawdown are extremely important factors to pump operators.

TABLE 4.5 Horsepower Required to Lift Different Quantities of Water to Elevations of 10 to 80 Feet[a]

		Elevation			
Gallons per minute	Cubic feet per second	10 ft.	30 ft.	50 ft.	80 ft.
100	0.22	0.5	1.5	2.5	4.0
200	0.45	1.0	3.0	5.0	8.1
300	0.67	1.5	4.6	7.6	12.1
400	0.89	2.0	6.1	10.1	16.2
500	1.11	2.5	6.7	12.6	20.2
600	1.34	3.0	9.1	15.2	24.2
700	1.56	3.5	10.6	17.7	28.3
800	1.78	4.0	12.1	20.2	32.3
900	2.01	4.6	13.6	22.7	36.4
1000	2.23	5.0	15.2	25.2	40.4
1250	2.78	6.3	18.9	31.6	50.5
1500	3.34	7.6	22.7	37.9	60.6

[a] All figures are for a pumping plant efficiency of 50 percent.
Source: A. S. Curry, *New Mexico Agricultural Experiment Station Bulletin* 237, New Mexico State University, Las Cruces, New Mexico, 1937. Reprinted with permission.

EXPERT ANALYSIS

Determine the cost of pumping an irrigation well for 60 days if the static groundwater level is 65 feet (20 m), drawdown is 15 feet (5 m), the pumping rate is 1500 gallons per minute (5678 l/min), pumping plant efficiency is at 50 percent, and the cost of a single horsepower unit is $0.50 per day. First, determine the lift:

65 ft. + 15 ft. = 80 ft.

(The static groundwater level was 65 ft. below the land surface, and well pumping created a cone of depression that lowered the groundwater level within the well casing an additional 15 ft.)

Next, use an appropriate table to determine the horsepower requirement for a pumping rate of 1500 gallons per minute, with a 50 percent pumping plant efficiency from a depth of 80 feet (24 m). Table 4.5 provides a requirement of 60.6 horsepower.

Finally, to determine the total cost, multiply the amount of horsepower required by the energy cost per day and number of days:

60.6 hp × $0.50/hp-day × 60 days
60.6 hp × $0.50/hp-day = $30.30/day
$30.30/day × 60 days = $1818

In this scenario, it will cost the irrigator $1818 to pump this well for 60 days. The actual cost per horsepower unit per day will vary greatly based on the type of energy used (such as diesel or gasoline fuel, or electricity) to operate the pump, and on current energy rates.

A CLOSER LOOK

Water in a well will reach a steady state (constant head) after the well is developed. However, once groundwater pumping begins, the water level in the well will decline. The difference between the original groundwater level and the reduced groundwater level caused by pumping is called **drawdown.** The pumping capacity of a well, and the hydraulics of the groundwater aquifer, will determine the discharge of a well. Pumping from an alluvial aquifer, for example, will create aquifer responses different from those associated with pumping from a fractured aquifer. A small drawdown means that plentiful supplies of groundwater exist in material of high transmissivity. A large drawdown can mean low transmissivity in an aquifer.

The yield (or pumping capacity) of a well divided by the drawdown is called the **specific capacity** of a well and is usually expressed as cubic feet/day/foot of drawdown or cubic meters/day/meter of drawdown. Specific capacity varies over several orders of magnitude for different geologic formations and provides an easily obtainable, useful measure of aquifer or well performance.

Groundwater pumping causes the hydraulic gradient to decline in the vicinity of the well casing and is called a **cone of**

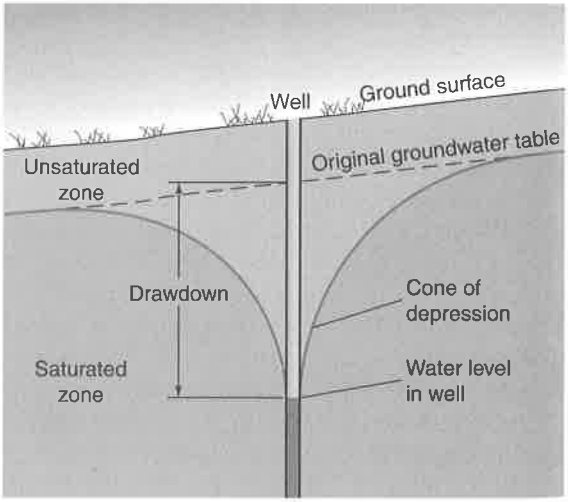


FIG. 4.19 A cone of depression is caused when the groundwater table is depressed due to pumping. Well pumping can interfere with streamflow if it pumps groundwater from an alluvial aquifer.

depression (see Figure 4.19). This area forms in a radial pattern around the intake point of the well screen. If wells are located in close proximity, well-to-well interference can occur if the wells are pumped simultaneously. Most states have well-spacing restrictions that regulate the distance required between wells.

EXPERT ANALYSIS

Well pumping can directly affect surface water if the groundwater system is hydraulically connected to a river, lake, or wetland system (see Figure 4.20). **Stream depletion** is the reduction of flowing water in a river caused by groundwater pumping of a well. A **stream depletion factor** is defined as the effect of well pumping on stream flow at any given time. It is expressed as follows:

$$\mathrm{SDF} = a - S/T$$

where SDF = stream depletion factor
a = distance of the well from the stream in feet (or meters)
S = specific yield of the aquifer
T = aquifer transmissivity

When a groundwater well is pumped continuously and the volume of stream depletion caused by the pumping reaches 28 percent of the volume pumped, the pumping time will be approximately equal to one SDF at the well. This analysis can be used to generate maps with contour lines (similar to topographic maps) that show the depletive effects of well pumping, located at various distances from a river, on flows in the river.

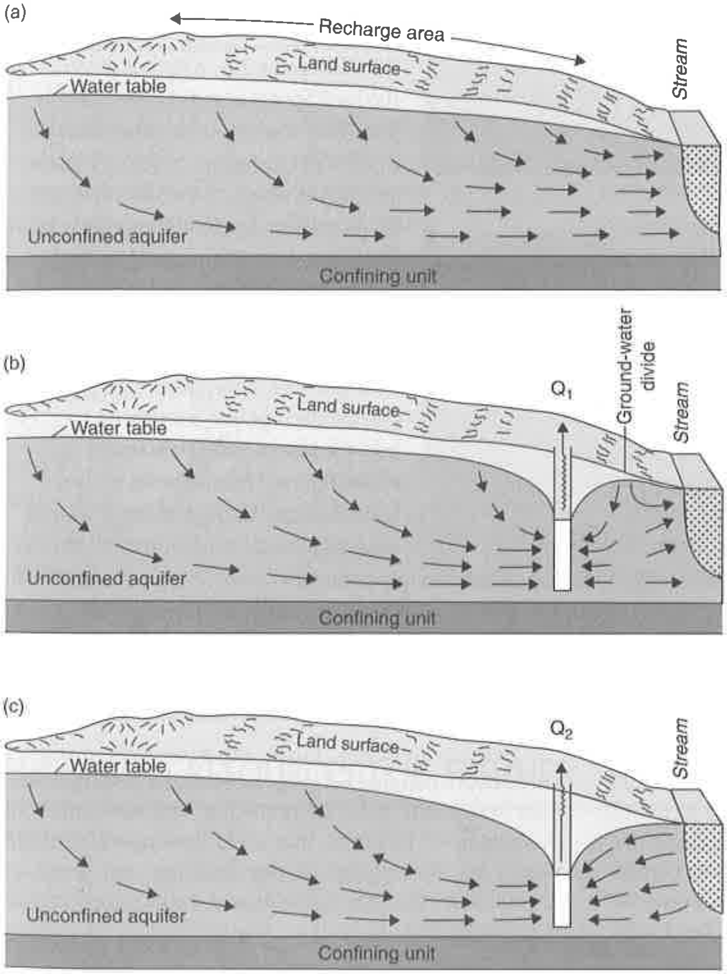
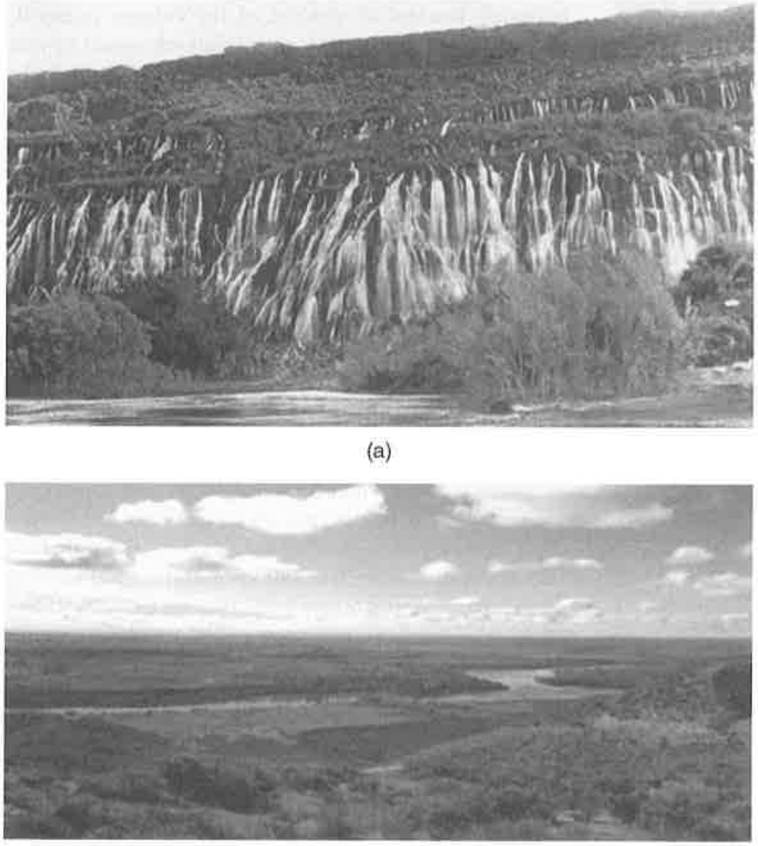


FIG. 4.20 Notice the affect that well pumping can have on streamflows if pumping from an alluvial aquifer. This is becoming a serious problem in many locations around the world, and has led to well shutdowns for irrigators in Colorado and Nebraska, and tenuous situations in Idaho and Georgia.

OUR ENVIRONMENT

Stream depletion factors are used in a variety of situations to assess the effects of well pumping on stream flow. In Nebraska, the U.S. Geological Survey, with the assistance of water officials in Wyoming and Colorado, are assessing the effects of groundwater pumping on stream flow in the Platte River between North Platte and Grand Island. This work is being conducted to determine the impacts of reduced stream flows on endangered species such as the whooping crane, least tern, and piping plover along the Platte River in central Nebraska (see Figures 4.21 and 4.22).



(a)

(b)

FIG. 4.21a and 4.21b A historic photo of the Thousand Springs waterfall area (a) and the Snake River in Idaho—a unique location where groundwater gushes out of porous volcanic rock canyon walls into the Snake River below (b). A significant legal battle erupted in 2007 when several trout farms along the Snake River were allegedly injured by groundwater pumping in the area. Fish hatcheries in this area raise approximately 70 percent of the trout produced in the United States. At issue are the effects of well pumping for irrigation, from the Eastern Snake Plain Aquifer, on stream flow and fish hatcheries along the Snake River, and the legal ability of a senior water right holder to be protected from injury by junior well users. This type of conflict will be discussed in Chapter 8.

CHAPTER SUMMARY

Groundwater can be found in a variety of geologic settings. Sedimentary rocks, alluvial landforms, glacial till, and tectonic formations can all provide suitable locations for groundwater. The hydrologic cycle provides the source of all groundwater through precipitation. Percolation from surface water runoff migrates downward as groundwater recharge. This migration eventually reaches a saturated zone or impervious geologic layer.

Groundwater may move short or long distances annually, depending on geologic material underground. This movement can be predicted with a variety of mathematical formulas that were developed over 100 years ago. Knowledge of the direction and speed of groundwater movement is critical in surface and groundwater management.

QUESTIONS FOR DISCUSSION

1. Why is it important to understand the relationship between surface water and groundwater?
2. What is groundwater hydrology?
3. What role has glacial activity played in the formation of aquifers?
4. What is the geologic area called where water collects underground, and how can we find it?
5. How did Darcy develop his theory of groundwater movement?
6. How can Darcy's law be used to determine groundwater movement?
7. What data are necessary to study potential overpumping of groundwater?
8. Explain the differences between an unconfined and a confined aquifer.
9. How can changes in atmospheric pressure cause the water level in a well to rise?
10. Discuss how the age of groundwater is determined.
11. What is groundwater mining?
12. Discuss the process of drilling a well to obtain groundwater.

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READINGS

Fetter, C. W. *Applied Hydrogeology*. 4th ed. Upper Saddle River, NJ: Prentice Hall, 2001.

Freeze, R. Allan, and John A. Cherry. *Groundwater*. Upper Saddle River, NJ: Prentice Hall, 1979.

McWhorter, David B., and Daniel K. Sunada. *Ground-Water Hydrology and Hydraulics*. Littleton, CO: Water Resources Publications, 1977.

Murck, Barbara W., and Brian J. Skinner. *Geology Today: Understanding Our Planet*. New York: John Wiley & Sons, 1999.

Price, Michael. *Introducing Groundwater*. 2nd ed. London: Chapman & Hall, 1996.

Rushton, K. R., and S. C. Redshaw. *Seepage and Groundwater Flow*. New York: John Wiley & Sons, 1979.

Skinner, Brian J., Stephen C. Porter, and Daniel B. Botkin. *The Blue Planet*. 2nd ed. New York: John Wiley & Sons, 1999.

Todd, David Keith. *Groundwater Hydrology*. 2nd ed. New York: John Wiley & Sons, 1980.

U.S. Department of the Interior, Geological Survey. "Ground Water." Washington, DC: U.S. Government Printing Office, 1986, 491–402/04.

WEBSITES

British Columbia Ministry of Environment, Water Stewardship Division, "Groundwater Resources of British Columbia." October 2008, http://www.env.gov.bc.ca/wsd

Environment ,Canada. Homepage, October 2008, http://www.ec.gc.ca/water

The Groundwater Foundation. "Groundwater Basics." October 2008, http://www.groundwater.org

UNICEF. "Groundwater: The Invisible and Endangered Resource." October 2008, http://www.unicef.org/wwd98

U.S. Geological Survey. *Ground Water Atlas of the United States*. October 2008, http://capp.water.usgs.gov/gwa

REFERENCES

1. Jet Propulsion Laboratory, "New Images Suggest Present-Day Sources of Liquid Water on Mars," news release, National Aeronautics and Space Administration, http://www.jpl.nasa.gov/news/releases/2000/marswater.html, June 22, 2000.

2. National Aeronautics and Space Administration, "NASA Phoenix Mars Lander Confirms Frozen Water," news release, June 20, 2008, http://www.nasa.gov/mission_pages/phoenix/news/phoenix-20080620.html.

3. U.S. Department of the Interior, U.S. Geological Survey, Ground Water (Washington, DC: U.S. Government Printing Office, 1993).

4. Groundwater Foundation, "Groundwater Basics," http://www.groundwater.org, September 20, 2000.

5. David Keith Todd, Groundwater Hydrology, 2nd ed. (New York: John Wiley & Sons, 1980), 5.

6. U.S. Geological Survey, "Karst," http://water.usgs.gov/ogw/karst, February 2008.

7. Richard Foster Flint, Glacial and Quaternary Geology (New York: John Wiley & Sons, 1971).

8. Michael Price, Introducing Groundwater (London: Chapman & Hall, 1985), 68–70.

9. Ibid., 167.

10. G. Fancher, "Henry Darcy—Engineer and Benefactor of Mankind," Journal of Petroleum Technology 8 (October 1956).

11. Todd, Groundwater Hydrology, 25.

12. C. W. Fetter, Applied Hydrogeology, 3rd ed. (Upper Saddle River, NJ: Prentice Hall, 1994), 419–20.

13. Ibid., 426.

14. E. Z. Vogt and R. Hyman, Water Witching U.S.A. (Chicago: University of Chicago Press, 1959).