CHAPTER 2

The Importance of Water

LEARNING OBJECTIVES

- Describe the hydrological cycle and where humans interact directly with it.
- List the major uses of water in the household.
- Define the saturated and vadose zones of groundwater.
- Identify the characteristics of surface water and groundwater, and why the distinctions are important.
- Learn how water is obtained.

KEY TERMS

- Artesian well
- Community water
- Groundwater
- Lentic
- Lotic
- Noncommunity water system
- Nontransient noncommunity water system
- Public water system
- Run-off
- Saturated zone
- Surface water
- Transient noncommunity water systems
- Unsaturated
- Vadose zone
- Water table

EVERYONE NEEDS WATER

Water is essential for life. Approximately 70% of the Earth's surface is covered with water, yet little of it is potable. Most is seawater and undrinkable (**Figure 2-1**). However, about 3% of the water on Earth is freshwater found in lakes, rivers, underground, as rainwater, and in the polar ice caps. An adequate supply of freshwater is necessary for the health of the population, and therefore great care is taken in the stewardship of this natural resource. In the past this was not always the case, and water sources were often polluted with many kinds of waste. However, changes in laws and in human attitudes have decreased water pollution greatly. While there is currently sufficient water in the United States, there is reason to be concerned about the future. Demand for water has increased, while supplies are finite. More effective use of water and cleaning of water once it has been used, will be needed.

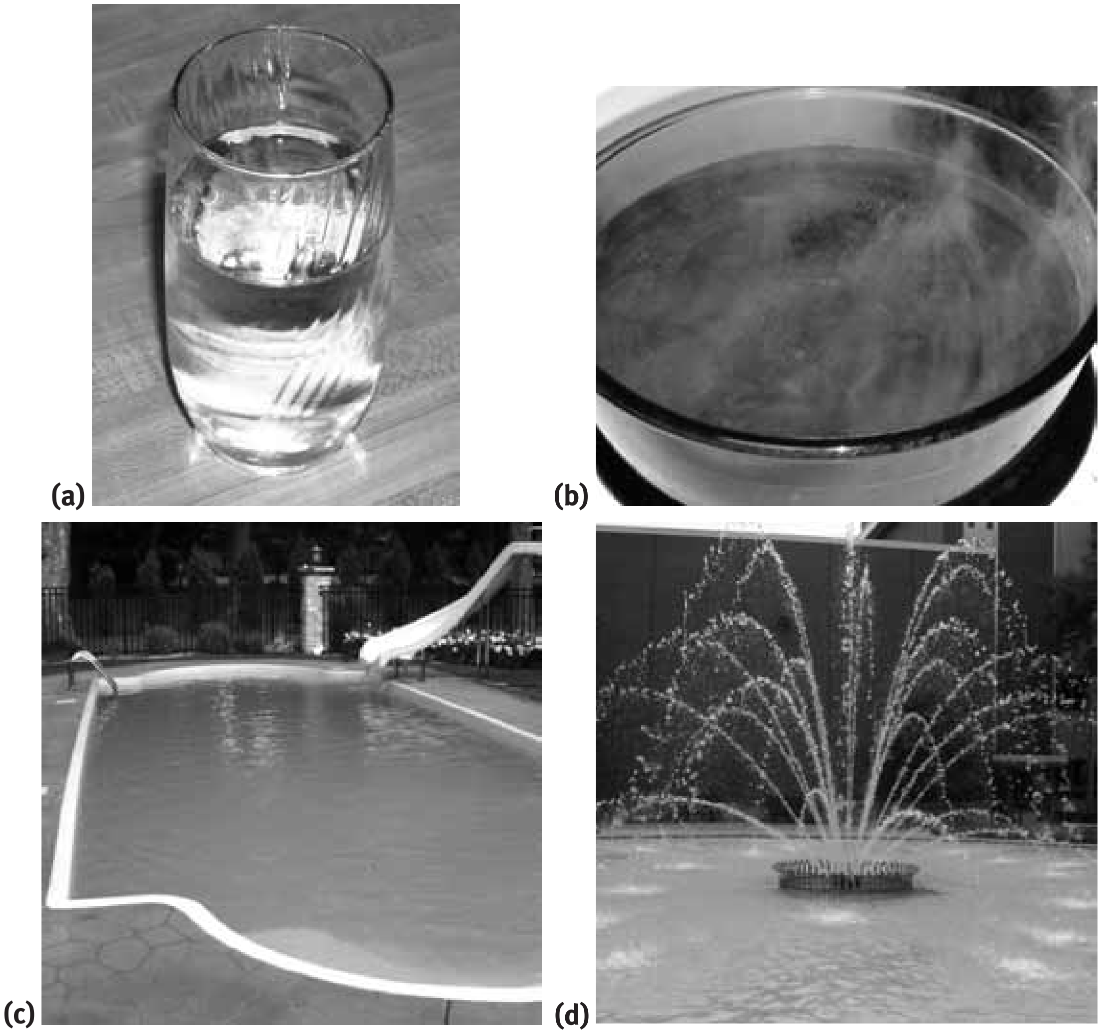
The importance of water is self-evident. Without it life cannot exist. NASA has devoted major projects to the detection of water elsewhere in our solar system, notably on Mars. If water is detected, then perhaps life exists there as well, but we are reasonably certain that without water there is no possibility of life. Human beings have always intrinsically understood the value of water (**Figure 2-2**). Settlements were created near a stable supply of water, such as a river or a natural spring. Ancient cities created cisterns to hold water against times of

FIGURE **2-1** **A lighthouse.**

drought (and especially while besieged by invaders). The city of Rome was founded on the banks of the Tiber River, but it gradually outgrew this water supply. The Romans constructed a vast aqueduct system to supply the city with fresh water from nearby mountains. By some estimates the population of Rome during this time exceeded one million. Many other Roman cities constructed aqueducts as well.

As precious as water is, national conflicts over water rights are relatively rare. It is not at all unusual to see low-intensity conflict between different claimants to the same water supply, and in westernized countries this often presents as legal challenges, but full-scale wars are rare. Perhaps this is because everyone understands the importance of fresh water and that the issue can quickly get out of control. For instance, the Israelis and the Palestinians must share water resources, and they have endured longstanding animosity. But their conflict over water remains far down on the list of grievances. In practice, nations adapt to water issues by promoting industries that correspond to realistic water availability and use trade to make up the water difference. This has proved to be a workable approach so far, but in the future water shortage may become even more acute. Rivers are good sources of water, especially if the water is moving swiftly. Egypt became one of the first great nations because of the Nile River and its supply of fresh water. The important Chinese cities of Wuhan, Nanjing, and Shanghai are all located along the Yangtze River. Paris is located along the Seine River; London along the Thames. In North America major

FIGURE 2-2 **Water is essential every day. It is used for (a) drinking, (b) cooking, (c) recreation, and (d) decorative fountains, among other uses.**



cities have grown up alongside rivers (**Figure 2-3**): Boston on the Charles River, Montreal at the juncture of the St. Lawrence and Ottawa rivers, Pittsburgh at the meeting point of three rivers (the Allegheny River, the Monongahela River, and the Ohio River).

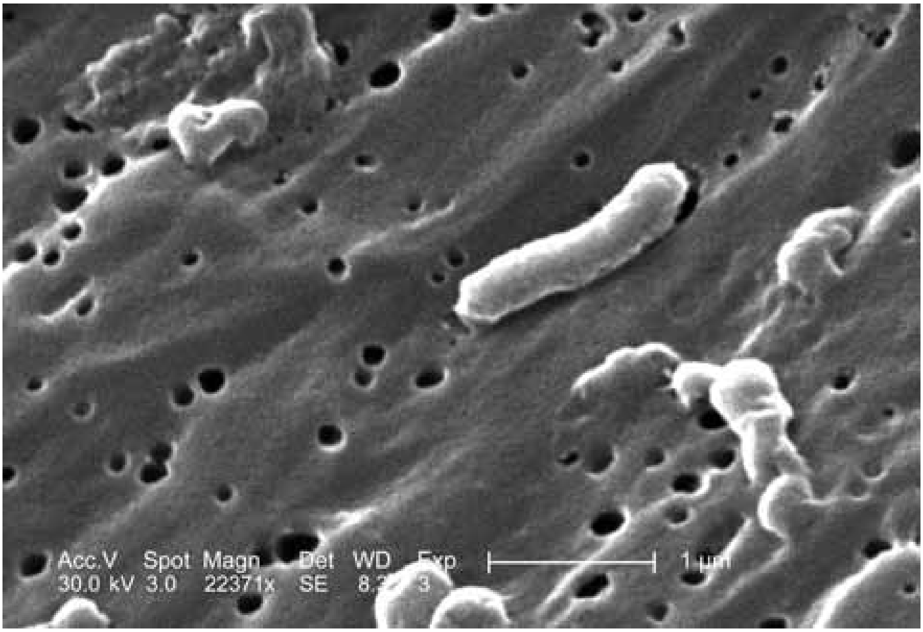
Quantity of water was obviously important, but quality of water was also a major concern. While the link between fresh water and health was not appreciated for many years, the idea of different levels of acceptable water based on taste and smell was quite obvious. Water from mountain streams was generally considered to be of high quality and cold as well. River water or well water (the ancients could dig shallow wells by hand) was also considered potable. Lake water was usually suitable only for cattle feeding, although various methods were proposed that would reduce the turbidity of the water and make it drinkable. For example, there is evidence that the Egyptians used alum to clarify water.

But water treatment is really a relatively modern invention, in common use only within the last 200 to 300 years. The use of sand filters for water purification appears to have started in the 1700s. By 1804, the city of Paisley, Scotland used sand filters to purify water for the entire town. Additional cities followed suit over the next half-century. Usually these developments were implemented to improve the aesthetic qualities of the water. In 1854 a substantial outbreak of cholera hit London, one of many such outbreaks over the years. Dr. John Snow analyzed the affected population and concluded that the water supply was to blame. He identified the public water pump at Broad Street as the likely source and stopped the outbreak by removing the handle of the pump. However, Snow based his conclusions on an analysis of illness (and thus became the father of epidemiology) rather than describing the cause of the illness. It was not until 1885 that Robert Koch identified *Vibrio cholerae* as the causative agent of cholera (**Figure 2-4**).

Although it seems obvious to us today, the idea of small living creatures causing disease is a modern concept. Two hundred years ago it was more common to believe that "bad air" or divine judgment was the cause of disease. One of the pioneers of microbiology, Robert Koch, probably did more than anyone else to prove the germ theory of disease—the idea that specific microorganisms caused specific illnesses. Koch's Postulates established the rules for assigning disease to microbes, and they

FIGURE **2-3** **The city of Milwaukee, Wisconsin, was founded at the confluence of three rivers, the Milwaukee, the Menomonee, and the Kinnickinnic.**

FIGURE 2-4 **An electron micrograph of *Vibrio cholerae*, causative agent of Cholera. For many years it was one of the most feared infectious diseases.**



SOURCE: Photo courtesy of the Centers for Disease Control and Prevention Public Health Image Library.

are still very much in use today. After the general acceptance of the germ theory of disease, many more researchers examined water as a vector for communicable disease, and public authorities began to address these threats with engineering techniques. During this time it was also discovered that the sand filters that had been used were also good at removing bacteria. Of course, killing the bacteria is just as good as removing them. In 1902 Belgium instituted chlorine addition specifically for the treatment of biological threats in the water supply. These techniques are still in use.

According to the U.S. Environmental Protection Agency (EPA), the average American family of four uses about 400 gallons of water per day, or about 146,000 gallons annually. Household uses of water include personal hygiene (e.g., brushing teeth, showering, and bathing), drinking, cooking, clothes washing, dishwashing, and outdoor activities such as lawn sprinkling, car washing, and water used in swimming pools (**Box 2-1**). However, household water use is a small fraction of the total fresh water that is needed. Nonhousehold uses include irrigation of farm fields (by far the largest use, requiring about 80% of freshwater use in the United States), industrial and commercial use, and livestock watering. Other uses of water include cooling water for thermoelectric generation of power, navigation, recreational use, and support of the fishing industry (**Figure 2-5**).

BOX 2-1 Water Quality

We demand high-quality household water, even though most of it does not need to be drinking-water quality. It is arguable whether water that is used for drinking and food preparation and water that is in close contact with the body should be potable. But water that is used in the toilets, for washing clothes, or for outdoor use does not need to be as clean. By some estimates toilets account for over 40% of indoor household water use, so toilet water represents a large use of water that does not need to be potable.

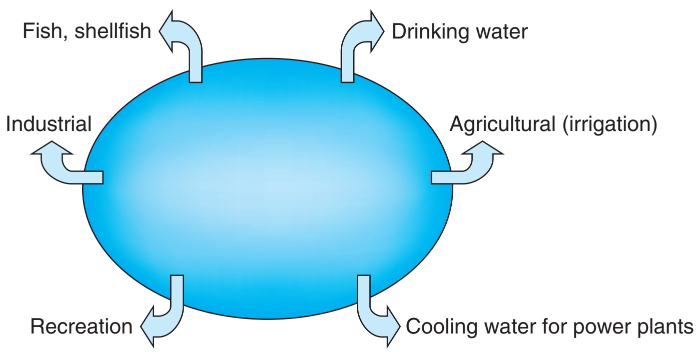
SOURCES OF WATER

Water is a renewable resource (**Box 2-2**). Water falls to the earth as precipitation (i.e., rain or snow), and then gravity guides it downhill where it seeks the lowest point and forms streams and rivers, eventually spilling into lakes and oceans. Sunlight warms the water and leads to water evaporation. When sufficient water vapor collects in the atmosphere, clouds form, and the rain falls once again (**Figure 2-6**).

Some water percolates into the soil, also due to gravity. Whether it enters the soil and how far it penetrates is dependent on soil porosity. Water that collects below the ground surface will pool at a low level called the **saturated zone**. In this zone the soil has acquired as much water as its porosity will permit. A conventional well bores into the ground in search of the saturated zone of water (**Figure 2-7**). The empty hole of the well then fills with water and can be pumped out. Many communities still rely on conventional wells; drilling costs are a significant cost of this resource, as is the cost of pumping the water out of the well.

Above the saturated zone, and proceeding to the ground surface is soil that is not saturated with water. This is the **unsaturated** or **vadose zone**. The soil in this layer has some moisture content, but it is usually unsuitable for wells. The line between the saturated and unsaturated zones is referred to as the **water table**. The water table changes constantly as water drains away or as more water percolates through the soil. In times of

FIGURE 2-5 Water is needed for every area of our lives.



BOX 2-2 All Rivers Run to the Sea . . .

"All the rivers run to the sea, yet the seas are not filled up. From the place where the water flows, there the waters return again."
Ecclesiastes 1:7

The above quotation was written long ago, perhaps 1000 BCE, and is usually attributed to King Solomon. In a simple statement the author accurately describes the hydrologic cycle. That is, the idea that water falls as rain, collects in streams that run downhill, finally emptying into a large body of water (in this case, the Mediterranean) and then, through the process we call evaporation, returns to the atmosphere and falls as rain again.

To the ancients, knowledge of water was absolutely critical. They had to know where to find drinkable (potable) water. Wells were good sources of water, and occasionally disputes over the ownership of a well or access to a well would lead to warfare. Rivers were also good sources of water, especially if the source of the river was a nearby mountain range. A mountain stream is typically a good place to get fresh, cold water.

drought the water table may drop below the bottom of the well, causing the well to run dry.

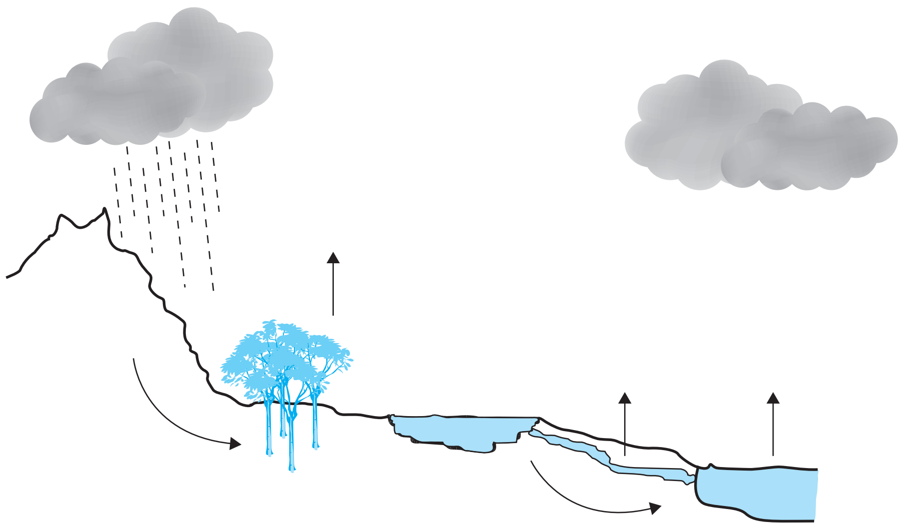
Water sources are typically divided into two types, depending on where they are located: groundwater and surface water (**Table 2-1**). This is a useful distinction because the two types of water have different rules associated with their use as drinking-water sources. **Groundwater** is defined as water that is not open to the atmosphere and is not subject to run-off. Water **run-off** occurs when rain falls or snow and ice melt and the water runs over the land surface. Some of it will eventually percolate through the soil, and some will follow the easiest downhill course until it meets a receiving water supply, such as a lake. The fact that groundwater is not typically affected by run-off is important because run-off can carry contaminants. Although some run-off eventually reaches the groundwater, the soil typically filters out the contaminants. Notably, groundwater contains a microbial community, but typically in low concentrations of bacteria and viruses. Rarely are pathogens found. Sources of groundwater include wells and aquifers (**Figure 2-8**). One example of groundwater is natural springs, in which the water emerges from the ground at a specific point.

The advantage of using groundwater as a water supply is that the water is often very clean. It will pick up mineral content as it percolates through rock, giving the water "hardness." Notably, however, water that is completely free of dissolved minerals (such as distilled water) is not particularly appealing, having a "flat" flavor. Many bottled waters, including expensive boutique varieties, are natural types of groundwater that impart a distinctive taste. One disadvantage of groundwater is its limited availability. Groundwater recharges as rain and snow seep into the land above and percolate through the soil to reach the water table. This is a slow process, and over-pumping of wells eventually drains the resource. Many aquifers in the United States are in danger of overuse (Alley et al., 1999). This source of water should be considered as nonrenewable for any meaningful time frame (**Figure 2-9**).

Below the saturated zone is a layer of nonporous rock, and for many years it was considered untenable to drill through this very hard rock. However, another source of groundwater is found here—aquifer water. This water has been trapped between confining layers of rock for a very long time, in many cases hundreds of thousands of years. The water is not found in the rock itself but within gravel, sand, or other unconsolidated materials. That is, a material with a significant porosity and free volume.

The advantage of aquifer water is that it is often under pressure, which means that it will be forced upward toward the surface when the aquifer is

FIGURE **2-6** **The hydrological cycle. Water falls in the form of rain and snow and then washes downhill by the force of gravity. As it collects, it makes small streams that eventually result in rivers. When the water encounters a flat area of land, a lake can form. Eventually the water will find its lowest point in an ocean. Water returns to the atmosphere through evaporation from land and water bodies and through transpiration of plants. Clouds form and precipitation starts the cycle again.**



tapped. This is then known as an **artesian well**. The disadvantage is that the water must be pumped a long distance if it is not under pressure and, more importantly, the water is typically recharged very, very slowly.

Surface waters are very visible and varied, ranging from fast-moving mountain streams to flowing rivers to quiet ponds, lakes, and reservoirs. Not surprisingly, the quality of the water and the dissolved and suspended material in it also vary. The area comprising the water source—the rivers which carry it and its final destination—are referred to as the watershed. Some watersheds have a vast geographic extent.

Flowing water is referred to as a **lotic** system, while still water is referred to as a **lentic** system. Different ecological factors, biotic and abiotic, predominate in each. **Surface water** is defined as water that is open to the atmosphere and subject to water run-off. As the water moves, it can pick up many kinds of contaminants, which makes this distinction for surface water very important. Run-off water that crosses agricultural fields may pick up pesticide residues and fecal material from animals.

FIGURE 2-7 **A well takes advantage of the saturated zone of soil, in which water fills up the available soil pore space. Above this is the vadose, or unsaturated zone of soil. The line between them is the water table. As water is pumped from the well a "cone of depression" is formed, in which the unsaturated zone is below the water table. If too much water is pumped from the well, or if the water table drops, the well will go dry.**

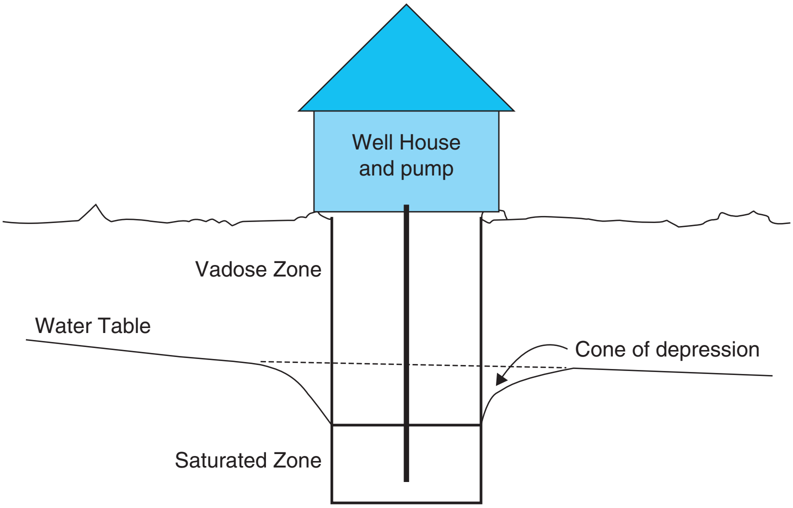
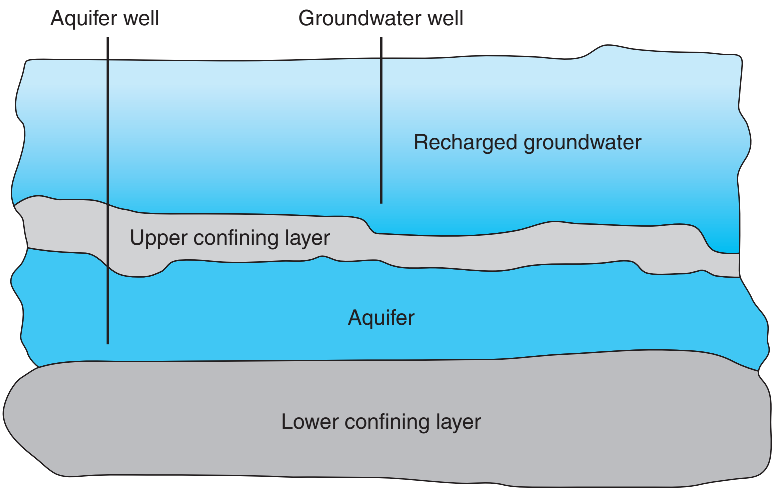


TABLE 2-1 **Characteristics of Surface Water and Groundwater**

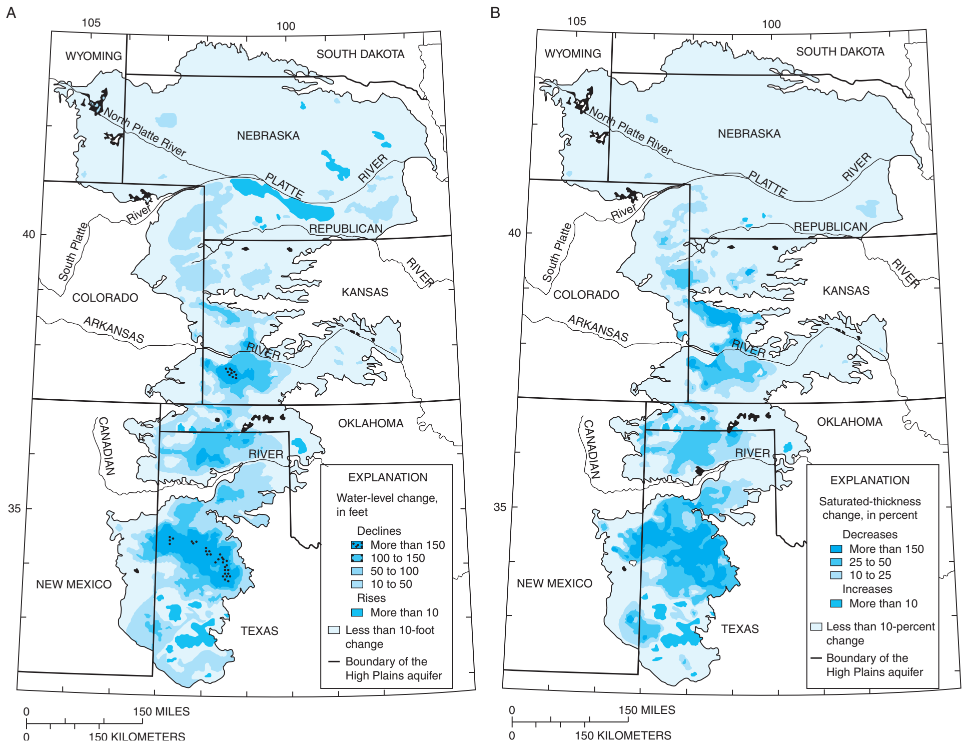
Surface Water	Groundwater
Open to the atmosphere	Not open to the atmosphere
Subject to run-off	Not subject to run-off
Easy to contaminate	Hard to contaminate
Easy to clean	Hard to clean

FIGURE **2-8** **Aquifers and wells. The aquifer resides between an upper and lower confining layer of impermeable rock. Shallow wells are drilled until the saturated zone of groundwater is found.**



Run-off in urban areas may pick up antifreeze, oils or other petroleum products, and litter. This is especially important in urban areas where asphalt and concrete cover much of the land, stopping rain and snowmelt from seeping into the ground. Run-off may travel for long distances before reaching another water source and may thereby pick up significant amounts of contaminants. The biota of surface water are typically very robust, and may include fish, crustaceans, amphibians, algae, protozoa, fungi and yeasts, and many, many species of bacteria and viruses. Other animal species (e.g., mammals, reptiles, and birds) may visit the surface water to drink and leave behind their waste products. Pathogens (e.g., bacteria, viruses, and parasites) are a risk in these water supplies. Determining flow of nutrients in such a complex web of life becomes difficult, and the picture changes with seasons and daily weather conditions in this dynamic environment. The water surface is the habitat for photosynthetic microorganisms (i.e., true algae and the cyanobacteria). The depth of this niche is dependent on the penetrating power of sunlight and, because different wavelengths of light penetrate to different depths, the photosynthetic communities vary with depth of the water column. Solid structures within the water are home to biofilms of bacteria, which are typically highly differentiated and home to a variety of microorganisms, and also support many types of stalked and appendaged bacteria (e.g., *Caulobacter* and *Hyphomicrobium*) that depend on the movement of water to bring nutrients to them. The sediments at the bottom of the water supply are also teeming with life due to the nutrients that settle here. Anaerobic zones in the sediment can support many different communities, such as the sulfate-reducing bacteria and, in swampy regions, the methanogens. Convection currents begin with the warming of the surface of the water by sunlight and lead to the mixing of surface and deep

FIGURE 2-9 **The Ogallala Aquifer is massive, part of 8 states west of the Mississippi River. It has been used for many years as a water resource in the nation's farmland, and is directly responsible for the high productivity of the area. However, it is a nonrenewable resource, and water levels within the aquifer have been declining. The two views in this figure show different aspects of the decline.**



SOURCE: From McGuire and Sharp, 1997. Figure courtesy of the U.S. Geological Survey, Department of the Interior.

waters and the nutrients in each. If the surface water is a river, then rapid mixing of the water and a high degree of oxygenation results as the water is transported downhill.

Another distinction between groundwater and surface water is that surface water is easy to contaminate but relatively easy to clean. The extensive biota and exposure to the environment provides the means for degradation of contaminants. The availability of oxygen and sunlight helps in the degradation process. Groundwater is difficult to contaminate, but once it is contaminated it is very difficult to decontaminate. Past practices of dumping toxic wastes led to infiltration of the groundwater supply. This created cubic miles of contaminated soil and contaminated the water held there. There is no practical way to dig up and treat so much soil. The best options employ a variety of techniques to treat the soil in place, often through bioremediation and the pretreatment of water that is pumped from the site. This can be expensive. Surface water often acquires contaminants through illegal dumping of waste materials or from run-off. This is particularly true in areas where the surface of the land is rendered impermeable to water by structures such as houses and roads.

About 60% of the water distributed through public water supplies comes from a surface water source, while the other 40% is groundwater. But groundwater and surface water are not always mutually exclusive; sometimes one affects the other. In practice groundwater can become contaminated with run-off, as occurs when local flooding infiltrates a wellhead. Because groundwater is typically cleaner than surface water, a special designation is reserved for groundwater that is (or can be) infiltrated by surface water: groundwater under the direct influence (GWUDI) of surface water. Such sources can sometimes be easily seen if the groundwater supply is contaminated by insects, algae, pathogens like *Giardia*, or if the physical characteristics of the water (e.g., pH, turbidity, temperature, or conductivity) change rapidly and in apparent correlation with changes in local surface-water sources.

Nearby surface-water supply might recharge the groundwater supply. If the bedrock is sufficiently fractured, or if the underlying material is coarse sand, gravel, or boulders, water has a greater opportunity to travel to the groundwater source. Rain and snow recharges groundwater by seeping through the soil, which acts as a filter for most contaminants. However, improper disposal of hazardous wastes has been known to contaminate the vast reservoir of groundwater, which can result in cubic miles of contaminated soil and water. Finally, if there is evidence that the aquifer is unconfined, or that the vadose zone is highly permeable, or if the well is poorly designed or maintained (cracks and holes in the well casing), there is the suspicion of water mixing.

WATER SYSTEMS

If you draw water from a well on your property or if you collect rainwater in a cistern, you have a private water system. Very few people are served by these systems, although in rural areas it is not uncommon to have a household well. The **public water system** supplies the water to most people. That is, a water source is tapped for a large number of people who pay a small fee for the treatment and distribution of the water by a water utility. Typically the system is linked to wastewater removal, and the two items are charged to the customer on the same bill.

Public water systems can be either community water systems or noncommunity water systems. A **community water** system provides water to a distinct population (at least 25 people) throughout the year. The typical city or suburban system is a community water system. The vast majority of Americans receive their drinking water from (often very large) community water systems.

A **noncommunity water system** is further divided into transient and nontransient systems. **Transient noncommunity water systems** typically involve businesses, such as campgrounds, gas stations, or restaurants that are not on a community water system and that serve individuals for a short time rather than on a continuous basis. They may be open year-round but serve different people during that time. A **nontransient noncommunity water system** supplies water to a specific population, but only for part of the year. Schools, which are typically open only 9 months per year, would be a typical example. The distinction with noncommunity water systems is that they either serve a variable group of people or are not available year-round.

QUESTIONS FOR DISCUSSION

1. If you wanted freshwater, where would you be likely to find it?
2. Define each of these terms:
    a. Groundwater
    b. Surface water
    c. Vadose zone
    d. Water table
    e. Saturated zone
    f. Aquifer
    g. Community water system
3. Why are wells dug so that the bottom is in the saturated zone? Why can these wells sometimes go dry?
4. Which contaminants would you expect to find in run-off from a city? From a farm?
5. What is GWUDI and how is it treated?
6. What is the source for the water in your own home?
7. Where are issues of water availability likely to emerge in the near future?

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