Sharing the Chattahoochee

FIGURE 10.1 *Rising in the mountains of northern Georgia, the Chattahoochee flows south through Atlanta before joining the Flint to form the Apalachicola River.*

Beginning from a small spring in northern Georgia's Blue Ridge Mountains, the Chattahoochee River provides drinking water, irrigation, hydropower, wildlife habitat, and recreation for millions of people. As it tumbles down from the mountains, the Chattahoochee is a clean, cool, swift-flowing stream, a popular destination for fishing, swimming, and boating. Far downstream, the Chattahoochee joins the Flint to form the Apalachicola River, which flows across the Florida Panhandle into Apalachicola Bay, in the Gulf of Mexico (fig. 10.1). Together, the Apalachicola, Chattahoochee, and Flint (ACF) watershed supports rich and diverse ecosystems, including valuable marine fisheries for oysters, shrimp, and finfish.

But between the mountains and the sea, the Chattahoochee River passes through Atlanta, where it undergoes dramatic changes. Atlanta is one of America's fastest-growing cities. Expanding suburbs and industries crowd the Chattahoochee's banks, producing runoff of silt, salts, and yard fertilizers that wash into the river. Growing households and industries withdraw water from the river, which becomes lower, slower, and warmer. Additional contaminants mix with remaining water—oils, metals, and dust from city streets and storm sewers, as well as chlorine and other contaminants from sewage treatment plants. The warm, shallow, turbid water holds less oxygen and supports fewer of the river's native plants and animals. The Environmental Protection Agency has named the 100 km of the Chattahoochee south of Atlanta one of the five most polluted river segments in the United States.

In an effort to force action, the EPA has levied millions of dollars in fines on Atlanta for polluting the river. Atlanta dilutes the contaminated waters by releasing more clean water from reservoirs upstream, but the city government says little can be done to prevent widespread runoff from the large and growing city. Meanwhile, Alabama and Florida complain that Georgia is taking too much water. They say the 2.3 billion liters (600 million gal) of water withdrawn each year in Georgia is needed downstream for homes, industries, and farms. Low river flows and contaminated water also threaten wildlife, shipping, and recreation. The Apalachicola Bay is particularly endangered. Pollution, reduced river flow, and increasing salinity in the estuary jeopardize the bay's multimillion-dollar-per-year fishing and tourism industries.

Atlanta recognized the looming problem of water supplies in the 1970s, and the city has been working with the Army Corps of Engineers to develop additional water supplies. In 2004 Georgia began working on a comprehensive state water plan, which is scheduled to be completed in 4 years. Ecologists worry that wildlife and biodiversity won't be adequately represented in this planning. Meanwhile, hydrologists point out that climate change could result in more erratic, less dependable rainfall in the future (see chapter 9). If river flows become more unpredictable as a result, water management could become an even more urgent and difficult concern.

In the United States, water shortages have long been a western problem, with growing cities in California and other western states struggling to acquire enough water without destroying river ecosystems. But like Atlanta, many growing metropolitan areas in other regions are increasingly competing with other users for water. Around the world, cities are experiencing water shortages, while pollution makes the water we do have less useful. The United Nations warns that water supplies are likely to become one of the most pressing environmental issues of the twenty-first century. By 2025 two-thirds of all humans could be living in countries where water resources are inadequate. In this chapter, we'll look at where our fresh water comes from, what we do with it, and how we can protect its quality and extend its usefulness.

WATER RESOURCES

Water is a marvelous substance—flowing, swirling, seeping, constantly moving from sea to land and back again. It shapes the earth's surface and moderates our climate. Water is essential for life. It is the medium in which all living processes occur (see chapter 2). Water dissolves nutrients and distributes them to cells, regulates body temperature, supports structures, and removes waste products. About 60 percent of your body is water. You could survive for weeks without food, but only a few days without water. Water also is needed for agriculture, industry, transportation, and a host of other human uses. In short, clean freshwater is one of our most vital natural resources.

FIGURE 10.17 *Typical household water use in the United States.*
Source: Data from U.S. Environmental Protection Agency, 2004.

this water use. Low-flow shower heads can reduce our second-largest household water use.

These steps are so important that a number of cities (including Los Angeles, Orlando, Austin, and Phoenix) ordered that water-saving toilets, showers, and faucets be installed in all new buildings. The motivation was two-fold: to relieve overburdened sewer systems and to conserve water.

Significant amounts of water also can be reclaimed and recycled (see the section "Sewage Treatment"). California uses more than 555 million m^3 (450,000 acre-feet) of recycled water annually. That's equivalent to about two-thirds of the water consumed by Los Angeles every year.

Signs of Progress

Growing recognition that water is a precious and finite resource has changed policies and encouraged conservation across the United States. Despite a growing population, the United States is now saving some 144 million l (38 million gal) per day—a tenth the volume of Lake Erie—compared with per capita consumption rates of 20 years ago. With 37 million more people in the United States now than in 1980, we get by with 10 percent less water. New requirements for water-efficient fixtures and low-flush toilets in many cities help conserve water on the home front. More efficient irrigation methods on farms also are a major reason for the downward trend. New sprinkler systems have small spray heads just a foot or so above the plant tops and apply water much more directly. Even better is drip irrigation, which applies water directly to plant roots (see fig. 10.10). California and Florida farmers currently water about 500,000 ha with this technique.

Charging a higher proportion of real costs to users of public water projects has helped encourage conservation, and so have water marketing policies that allow prospective users to bid on water rights. Both the United States and Australia have had effective water pricing and allocation policies that encourage the most socially beneficial uses and discourage wasteful water uses. It will be important, as water markets develop, to be sure that environmental, recreational, and wildlife values are not sacrificed to the lure of high-bidding industrial and domestic users.

Saving Water and Preventing Pollution

Each of us can conserve much of the water we use and avoid water pollution in many simple ways.

- Don't flush every time you use the toilet. Take shorter showers, and shower instead of taking baths.
- Don't let the faucet run while brushing your teeth or washing dishes. Draw a basin of water for washing and another for rinsing dishes. Don't run the dishwasher when it's half full.
- Use water-conserving appliances: low-flow showers, low-flush toilets, and aerated faucets.
- Fix leaking faucets, tubs, and toilets. A leaky toilet can waste 50 gal per day. To check your toilet, add a few drops of dark food coloring to the tank and wait 15 minutes. If the tank is leaking, the water in the bowl will change color.
- Put a brick or full water bottle in your toilet tank to reduce the volume of water in each flush.
- Dispose of used motor oil, household hazardous waste, batteries, and so on responsibly. Don't dump anything down a storm sewer that you wouldn't want to drink.
- Avoid using toxic or hazardous chemicals for simple cleaning or plumbing jobs. A plunger or plumber's snake will often unclog a drain just as well as caustic acids or lye. Hot water and soap can accomplish most cleaning tasks.
- If you have a lawn, or know someone who does, use water, fertilizer, and pesticides sparingly. Plant native, low-maintenance plants that have low water needs.
- Use recycled (gray) water for lawns, house plants, and car washing.

WATER POLLUTION

Any physical, biological, or chemical change in water quality that adversely affects living organisms or makes water unsuitable for desired uses can be considered pollution. There are natural sources of water contamination, such as poison springs, oil seeps, and sedimentation from erosion, but here we will focus primarily on human-caused changes that affect water quality or usability.

Point and Nonpoint Source Pollution

Pollution control standards and regulations usually distinguish between point and nonpoint pollution sources. Factories, power plants, sewage treatment plants, underground coal mines, and oil wells are classified as **point sources** because they discharge pollution from specific locations, such as drain pipes, ditches, or sewer outfalls (fig. 10.18). These sources are discrete and identifiable, so they are relatively easy to monitor and regulate. It is generally

FIGURE 10.18 *Sewer outfalls, industrial effluent pipes, acid draining out of abandoned mines, and other point sources of pollution are generally easy to recognize.*

possible to divert effluent from the waste streams of these sources and treat it before it enters the environment.

In contrast, **nonpoint sources** of water pollution are diffuse, having no specific location where they discharge into a particular body of water. They are much harder to monitor and regulate than point sources because their sources are hard to identify. Nonpoint sources include runoff from farm fields and feedlots, golf courses, lawns and gardens, construction sites, logging areas, roads, streets, and parking lots (fig. 10.19). While point sources may be fairly uniform and predictable throughout the year, nonpoint sources are often highly episodic. The first heavy rainfall after a dry period may flush high concentrations of gasoline, lead, oil, and rubber residues off city streets, for instance, while subsequent runoff may be much cleaner.

Perhaps the ultimate in diffuse, nonpoint pollution is atmospheric deposition of contaminants carried by air currents and precipitated into watersheds or directly onto surface waters as rain, snow, or dry particles. The Great Lakes, for example, have been

FIGURE 10.19 *This bucolic scene looks peaceful and idyllic, but allowing cows to trample stream banks is a major cause of bank erosion and water pollution. Nonpoint sources such as this have become the leading unresolved cause of stream and lake pollution in the United States.*

found to be accumulating industrial chemicals, such as PCBs (polychlorinated biphenyls) and dioxins, as well as agricultural toxins, such as the insecticide toxaphene, that cannot be accounted for by local sources alone. The nearest sources for many of these chemicals are sometimes thousands of kilometers away.

Biological Pollution

Although the types, sources, and effects of water pollutants are often interrelated, it is convenient to divide them into major categories for discussion (table 10.4). Here, we look at some of the important sources and effects of different pollutants.

TABLE 10.4 Major Categories of Water Pollutants

CATEGORY	EXAMPLES	SOURCES
CAUSE HEALTH PROBLEMS		
1. Infectious agents	Bacteria, viruses, parasites	Human and animal excreta
2. Organic chemicals	Pesticides, plastics, detergents, oil, gasoline	Industrial, household, and farm use
3. Inorganic chemicals	Acids, caustics, salts, metals	Industrial effluents, household cleansers, surface runoff
4. Radioactive materials	Uranium, thorium, cesium, iodine, radon	Mining and processing of ores, power plants, weapons production, natural sources
CAUSE ECOSYSTEM DISRUPTION		
1. Sediment	Soil, silt	Land erosion
2. Plant nutrients	Nitrates, phosphates, ammonium	Agricultural and urban fertilizers, sewage, manure
3. Oxygen-demanding wastes	Animal manure, plant residues	Sewage, agricultural runoff, paper mills, food processing
4. Thermal changes	Heat	Power plants, industrial cooling

Infectious Agents

The most serious water pollutants in terms of human health worldwide are pathogenic organisms (see chapter 8). Among the most important waterborne diseases are typhoid, cholera, bacterial and amoebic dysentery, enteritis, polio, infectious hepatitis, and schistosomiasis. Malaria, yellow fever, and filariasis are transmitted by insects that have aquatic larvae. Altogether, at least 25 million deaths each year are blamed on these water-related diseases. Nearly two-thirds of the mortalities of children under 5 years old are associated with waterborne diseases.

The main source of these pathogens is untreated or improperly treated human wastes. Animal wastes from feedlots or fields near waterways and food processing factories with inadequate waste treatment facilities also are sources of disease-causing organisms.

In developed countries, sewage treatment plants and other pollution-control techniques have reduced or eliminated most of the worst sources of pathogens in inland surface waters. Furthermore, drinking water is generally disinfected by chlorination, so epidemics of waterborne diseases are rare in these countries. The United Nations estimates that 90 percent of the people in developed countries have adequate (safe) sewage disposal, and 95 percent have clean drinking water.

The situation is quite different in less-developed countries, where billions of people lack adequate sanitation and access to clean drinking water. Conditions are especially bad in remote, rural areas, where sewage treatment is usually primitive or nonexistent and purified water is either unavailable or too expensive to obtain. The World Health Organization estimates that 80 percent of all sickness and disease in less-developed countries can be attributed to waterborne infectious agents and inadequate sanitation.

Fecal Coliform Bacteria and Oxygen Demand

Detecting specific pathogens in water is difficult, time-consuming, and costly, so water quality is usually described in terms of concentrations of **coliform bacteria**—any of the many types that live in the colon, or intestines, of humans and other animals. The most common of these is *Escherichia coli* (or *E. coli*), which lives symbiotically in many animals, but other bacteria, such as *Shigella, Salmonella,* or *Listeria,* can also cause fatal diseases. If any coliform bacteria are present in a water sample, infectious pathogens are usually assumed to be present also. Therefore, the Environmental Protection Agency (EPA) considers water with any coliform bacteria at all to be unsafe for drinking.

The amount of oxygen dissolved in water is a good indicator of water quality and of the kinds of life it will support. An oxygen content above 6 parts per million (ppm) will support game fish and other desirable forms of aquatic life. At oxygen levels below 2 ppm, water will support mainly worms, bacteria, fungi, and other detritus feeders and decomposers. Oxygen is added to water by diffusion from the air, especially when turbulence and mixing rates are high, and by photosynthesis of green plants, algae, and cyanobacteria. Therefore, turbulent, rapidly flowing water is constantly aerated, so it often recovers quickly from oxygen-depleting processes. Oxygen is removed from water by respiration and chemical processes that consume oxygen.

Adding organic materials, such as sewage or paper pulp, to water stimulates activity and oxygen consumption by decomposers. Consequently, **biochemical oxygen demand (BOD),** or the amount of dissolved oxygen consumed by aquatic microorganisms, is a standard measure of water contamination. Alternatively, chemical oxygen demand (COD) is a measure of all organic matter in water. In addition, **dissolved oxygen (DO) content** can be measured directly, with high DO levels indicating good-quality water.

Downstream from a point source, such as a municipal sewage plant discharge, a characteristic decline and restoration of water quality can be detected either by measuring DO content or by observing the types of flora and fauna that live in successive sections of the river. The oxygen decline downstream is called the **oxygen sag** (fig. 10.20). Upstream from the pollution source, oxygen levels support normal populations of clean-water organisms. Immediately below the source of pollution, oxygen levels begin to fall as decomposers metabolize waste materials. Trash fish, such as carp, bullheads, and gar, are able to survive in this oxygen-poor environment, where they eat both decomposer organisms and the waste itself.

Farther downstream, the water may become so oxygen depleted that only the most resistant microorganisms and invertebrates can survive. Eventually, most of the nutrients are used up, decomposer populations are smaller, and the water becomes oxygenated once again. Depending on the volumes and flow rates of the effluent plume and the river receiving it, normal communities may not appear for several miles downstream.

Plant Nutrients and Cultural Eutrophication

Water clarity (transparency) is affected by sediments, chemicals, and the abundance of plankton organisms; clarity is a useful measure of water quality and water pollution. Rivers and lakes that have clear water and low biological productivity are said to be **oligotrophic** (*oligo* = little + *trophic* = nutrition). By contrast, **eutrophic** (*eu* + *trophic* = well-nourished) waters are rich in organisms and organic materials. Eutrophication, an increase in nutrient levels and biological productivity, often accompanies successional changes (see chapter 5) in lakes. Tributary streams bring in sediments and nutrients that stimulate plant growth. Over time, ponds and lakes often fill in, becoming marshes or even terrestrial biomes. The rate of eutrophication depends on water chemistry and depth, volume of inflow, mineral content of the surrounding watershed, and biota of the lake itself.

Human activities can greatly accelerate eutrophication, an effect called **cultural eutrophication.** Cultural eutrophication is mainly caused by increased nutrient input into a water body. Increased productivity in an aquatic system sometimes can be beneficial. Fish and other desirable species may grow faster, providing a welcome food source. Often, however, eutrophication produces "blooms" of algae or thick growths of aquatic plants stimulated by elevated phosphorus or nitrogen levels (fig. 10.21). Bacterial populations then increase, fed by larger amounts of organic matter. The water often becomes cloudy, or turbid, and has unpleasant tastes and odors. Cultural eutrophication can accelerate the "aging" of a water body enormously over natural rates. Lakes

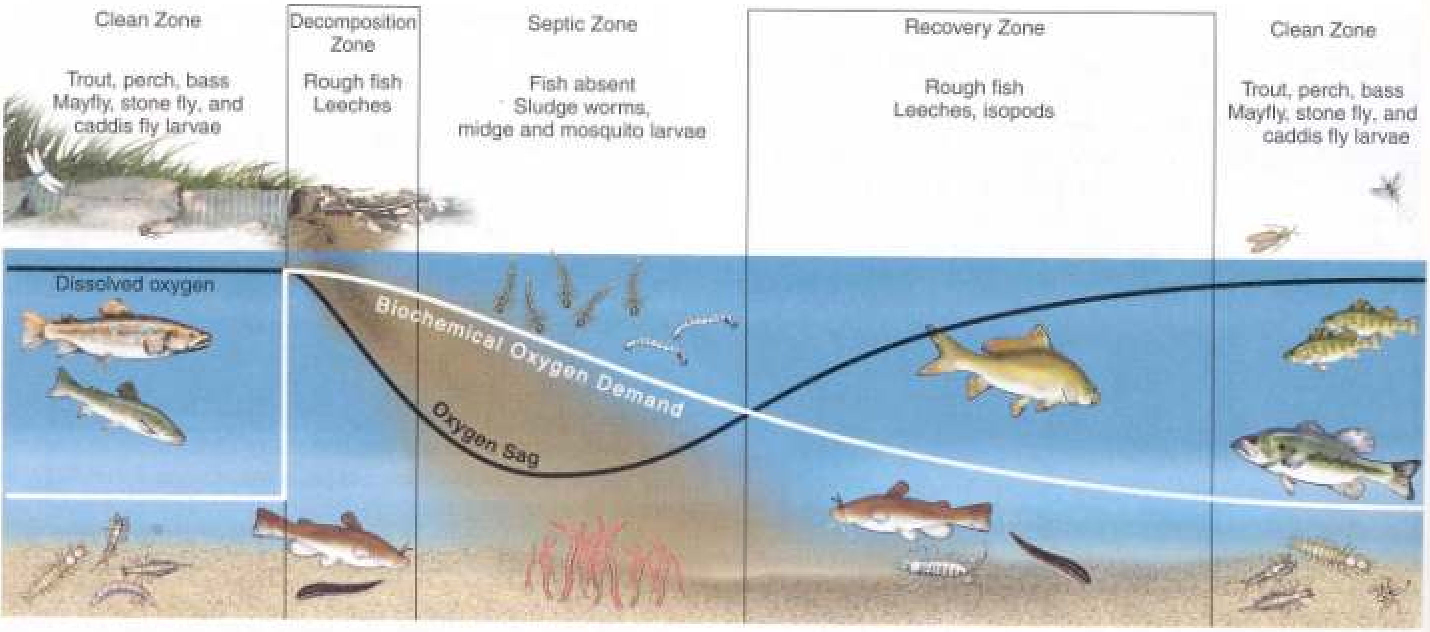

FIGURE 10.20 *Oxygen sag downstream of an organic source. A great deal of time and distance may be required for the stream and its inhabitants to recover.*

FIGURE 10.21 *Eutrophic lake. Nutrients from agriculture and domestic sources have stimulated growth of algae and aquatic plants. This reduces water quality, alters species composition, and lowers the lake's recreational and aesthetic values.*

and reservoirs that normally might exist for hundreds or thousands of years can be filled in a matter of decades.

Eutrophication also occurs in marine ecosystems, especially in nearshore waters and partially enclosed bays or estuaries. Partially enclosed seas, such as the Black, Baltic, and Mediterranean Seas, tend to be in especially critical condition. During the tourist season, the coastal population of the Mediterranean, for example, swells to 200 million people. Eighty-five percent of the effluents from large cities go untreated into the sea. Beach pollution, fish kills, and contaminated shellfish result. Extensive "dead zones" often form where rivers dump nutrients into estuaries and shallow seas. The largest in the world occurs during summer months in the Gulf of Mexico at the mouth of the Mississippi River. This hypoxic (oxygen-depleted) zone can cover 21,000 km^2, or about the area of New Hampshire. A federal study of the condition of U.S. coastal waters announced in 2004 that 28 percent of estuaries are impaired for aquatic life, and 80 percent of all coastal water is in fair to poor condition.

Toxic Tides

Excessive nutrients support blooms of deadly aquatic microorganisms in polluted nearshore waters. Red tides—and other colors, depending on the species involved—have become increasingly common where nutrients and wastes wash down rivers.

One of the most feared of these organisms is *Pfiesteria piscicida,* an extraordinarily poisonous dinoflagellate that only recently has been recognized as a killer of fish and shellfish in polluted rivers and estuaries. In North Carolina's Pamlico Sound, *Pfiesteria* kills hundreds of thousands to millions of fish annually. Dinoflagellates are peculiar organisms with complex life cycles and many different shapes. *Pfiesteria* can change into at least two dozen distinct forms and sizes, depending on water temperature, turbulence, and food supply. The right conditions can cause a population explosion. If fish blunder into this profuse swarm, *Pfiesteria* quickly turn into a toxic, swimming form that attacks with soluble poisons. These toxins produce skin lesions and paralyze fish, so they can't escape. The predatory *Pfiesteria* feed on both the flesh and the oozing sores.

Humans are harmed if they eat contaminated seafood or even if they breathe airborne *Pfiesteria* cells or secretions. Symptoms of *Pfiesteria* poisoning include headaches, blurred vision, aching joints, difficulty breathing, memory loss, and long-term damage to the brain, liver, and other organs. (See related story "A Flood of Pigs" at www.mhhe.com/cases.)

Inorganic Pollutants

Some toxic inorganic chemicals are naturally released into water from rocks by weathering processes (see chapter 11). Humans accelerate the transfer rates in these cycles thousands of times above natural background levels by mining, processing, using, and discarding minerals.

Among the chemicals of greatest concern are heavy metals, such as mercury, lead, tin, and cadmium. Supertoxic elements, such as selenium and arsenic, also have reached hazardous levels in some waters. Other inorganic materials, such as acids, salts, nitrates, and chlorine, that are nontoxic at low concentrations may become concentrated enough to lower water quality and adversely affect biological communities.

Metals

Many metals, such as mercury, lead, cadmium, and nickel, are highly toxic in minute concentrations. Because metals are highly persistent, they accumulate in food chains and have a cumulative effect in humans.

Currently the most widespread toxic metal contamination in North America is mercury released from incinerators and coal-burning power plants. Transported through the air, mercury precipitates in water supplies, where it bioconcentrates in food webs to reach dangerous levels in top predators. As a general rule, Americans are warned not to eat more than one meal of fish per week. Top marine predators, such as shark, swordfish, bluefin tuna, and king mackerel, tend to have especially high mercury content. Pregnant women and small children should avoid these species entirely. Public health officials estimate that 600,000 American children now have mercury levels in their bodies high enough to cause mental and developmental problems, while one woman in six in the United States has blood-mercury concentrations that would endanger a fetus.

Mine drainage and leaching of mining wastes are serious sources of metal pollution in water. A survey of water quality in eastern Tennessee found that 43 percent of all surface streams and lakes and more than half of all groundwater used for drinking supplies were contaminated by acids and metals from mine drainage. In some cases, metal levels were 200 times higher than what is considered safe for drinking water.

Nonmetallic Salts

Some soils contain high concentrations of soluble salts, including toxic selenium and arsenic (see Case Study, p. 246). You have probably heard of poison springs and seeps in the desert, where percolating groundwater brings these compounds to the surface. Irrigation and drainage of desert soils can mobilize these materials on a larger scale and result in serious pollution problems, as in Kesterson Marsh in California, where selenium poisoning killed thousands of migratory birds in the 1980s.

Salts, such as sodium chloride (table salt), that are nontoxic at low concentrations also can be mobilized by irrigation and concentrated by evaporation, reaching levels that are toxic for plants and animals. Salinity levels in the Colorado River and surrounding farm fields have become so high in recent years that millions of hectares of valuable croplands have had to be abandoned. In northern states, millions of tons of sodium chloride and calcium chloride are used to melt road ice in the winter. Leaching of road salts into surface waters has a devastating effect on some aquatic ecosystems.

Acids and Bases

Acids are released as by-products of industrial processes, such as leather tanning, metal smelting and plating, petroleum distillation, and organic chemical synthesis. Coal mining is an especially important source of acid water pollution. Sulfur compounds in coal react with oxygen and water to make sulfuric acid. Thousands of kilometers of streams in the United States have been acidified by acid mine drainage, some so severely that they are essentially lifeless.

Acid precipitation (see chapter 9) also acidifies surface-water systems. In addition to damaging living organisms directly, these acids leach aluminum and other elements from soil and rock, further destabilizing ecosystems.

Organic Chemicals

Thousands of different natural and synthetic organic chemicals are used in the chemical industry to make pesticides, plastics, pharmaceuticals, pigments, and other products that we use in everyday life. Many of these chemicals are highly toxic (see chapter 8). Exposure to very low concentrations (perhaps even parts per quadrillion, in the case of dioxins) can cause birth defects, genetic disorders, and cancer. Some can persist in the environment because they are resistant to degradation and toxic to organisms that ingest them.

The two principal sources of toxic organic chemicals in water are (1) improper disposal of industrial and household wastes and (2) pesticide runoff from farm fields, forests, roadsides, golf courses, and private lawns. The EPA estimates that about 500,000 metric tons of pesticides are used in the United States each year. Much of this material washes into the nearest waterway, where it passes through ecosystems and may accumulate in high levels in nontarget organisms. The bioaccumulation of DDT in aquatic ecosystems was one of the first of these pathways to be understood (see chapter 8). Dioxins and other chlorinated hydrocarbons (hydrocarbon molecules that contain chlorine atoms) have been shown to accumulate to dangerous levels in the fat of salmon, fish-eating birds, and humans and to cause health problems similar to those resulting from toxic metal compounds.

Hundreds of millions of tons of hazardous organic wastes are thought to be stored in dumps, landfills, lagoons, and underground

CASE STUDY

ARSENIC IN DRINKING WATER

When we think of water pollution, we usually visualize sewage or industrial effluents pouring out of a discharge pipe, but there are natural toxins that threaten us as well. One of these is arsenic, a common contaminate in drinking water that may be poisoning millions of people around the world. Arsenic has been known since the fourth century B.C. to be a potent poison. It has been used for centuries as a rodenticide, insecticide, and weed killer, as well as a way of assassinating enemies. Because it isn't metabolized or excreted from the body, arsenic accumulates in hair and fingernails, where it can be detected long after death. Napoleon Bonaparte was recently found to have high enough levels of arsenic in his body to suggest he was poisoned.

Perhaps the largest population to be threatened by naturally occurring groundwater contamination by arsenic is in West Bengal, India, and adjacent areas of Bangladesh. Arsenic occurs naturally in the sediments that make up the Ganges River delta (see map). Rapid population growth, industrialization, and intensification of agricultural irrigation, however, have put increasing stresses on the limited surface-water supplies. Most surface water is too contaminated to drink, so groundwater has all but replaced other water sources for most people in this region.

In the 1960s, thousands of deep tube wells were sunk throughout the region to improve water supplies. Much of this humanitarian effort was financed by loans from the World Bank. At first, villagers were suspicious of well water, regarding it as unnatural and possibly evil. But as surface-water supplies diminished and populations grew, Bengal and Bangladesh became more and more dependent on this new source of supposedly fresh, clean water. By the late 1980s, health workers had become aware of widespread signs of chronic arsenic poisoning among villagers. Symptoms include watery and inflamed eyes, gastrointestinal cramps, gradual loss of strength, scaly skin and skin tumors, anemia, confusion, and eventually death.

Why is arsenic poisoning appearing now? Part of the reason is increased dependence on well water, but some villages have had wells for centuries with no problem. One theory is that excessive withdrawals now lower the water table during the dry season, exposing arsenic-bearing minerals to air, which converts normally insoluble salts to soluble oxides. When aquifers are refilled during the next rainy season, dissolved arsenic can be pumped out. Health workers estimate that the total number of potential victims in India and Bangladesh may exceed 200 million people. But with no other source of easily accessible or affordable water, few of the poorest people have much choice.

There are worries that millions of Americans also are exposed to dangerously high levels of arsenic. In 1942 the U.S. government set the acceptable level of arsenic in drinking water at 50 ppb. A 1999 study by the National Academy of Sciences found a 1 in 100 risk for cancer from drinking water with that level of arsenic for a lifetime. This is 10,000 times the normally accepted risk level. Following years of heated debate, the U.S. limit was revised in 2002 to meet the World Health Organization standard of 10 ppb. Local officials and private water supply owners argued that it would cost too much to upgrade their systems.

In the end, public outrage over tainted water, combined with the enormous public health costs of chronic arsenic poisoning, convinced the federal government to enforce stricter standards.

West Bengal and adjoining areas of Bangladesh have hundreds of millions of people who may be exposed to dangerous arsenic levels in well water.

tanks in the United States (see chapter 13). Many, perhaps most, of these sites have leaked toxic chemicals into surface waters, groundwater, or both. The EPA estimates that about 26,000 hazardous waste sites will require cleanup because they pose an imminent threat to public health, mostly through water pollution.

Sediment and Thermal Pollution

Sediment is a natural and necessary part of river systems. Sediment fertilizes floodplains and creates fertile deltas. But human activities, chiefly farming and urbanization, greatly accelerate erosion and increase sediment loads in rivers. Silt and sediment are considered the largest source of water pollution in the United States, being responsible for 40 percent of the impaired river miles in EPA water quality surveys. Cropland erosion contributes about 25 billion metric tons of soil, sediment, and suspended solids to world surface waters each year. Forest disturbance, road building, urban construction sites, and other sources add at least 50 billion additional tons.

This sediment fills lakes and reservoirs, obstructs shipping channels, clogs hydroelectric turbines, and makes purification of drinking water more costly. Sediments smother gravel beds in which insects take refuge and fish lay their eggs. Sunlight is blocked, so that plants cannot carry out photosynthesis, and oxygen levels decline. Murky, cloudy water also is less attractive for swimming, boating, fishing, and other recreational uses (fig. 10.22). Sediment washed into the ocean clogs estuaries and coral reefs.

Thermal pollution, usually effluent from cooling systems of power plants or other industries, alters water temperature. Raising or lowering water temperatures from normal levels can adversely affect water quality and aquatic life. Water temperatures are usually much more stable than air temperatures, so aquatic organisms tend to be poorly adapted to rapid temperature changes. Lowering the temperature of tropical oceans by even 1° can be lethal to some corals and other reef species. Raising water temperatures can have similar devastating effects on sensitive organisms. Oxygen solubility in water decreases as temperatures increase, so species requiring high oxygen levels are adversely affected by warming water.

Humans also cause thermal pollution by altering vegetation cover and runoff patterns. Reducing water flow, clearing streamside trees, and adding sediment all make water warmer and alter the ecosystems in a lake or stream.

Warm-water plumes from power plants often attract fish and birds, which find food and refuge there, especially in cold weather. This artificial environment can be a fatal trap, however. Florida's manatees, an endangered mammal, are attracted to the abundant food supply and warm water in power plant thermal plumes. Often they are enticed into spending the winter much farther north than they normally would. On several occasions, a midwinter power plant breakdown has exposed a dozen or more of these rare animals to a sudden, deadly thermal shock.

FIGURE 10.22 *Sediment and industrial waste flow from this drainage canal into Lake Erie.*

WATER QUALITY TODAY

Surface-water pollution is often both highly visible and one of the most common threats to environmental quality. In more developed countries, reducing water pollution has been a high priority over the past few decades. Billions of dollars have been spent on control programs, and considerable progress has been made. Still, much remains to be done.

Surface Waters in the United States and Canada

Like most developed countries, the United States and Canada have made encouraging progress in protecting and restoring water quality in rivers and lakes over the past 40 years. In 1948 only about one-third of Americans were served by municipal sewage systems, and most of those systems discharged sewage without any treatment or with only primary treatment (the bigger lumps of waste are removed). Most people depended on cesspools and septic systems to dispose of domestic wastes.

Areas of Progress

The 1972 Clean Water Act established a National Pollution Discharge Elimination System (NPDES), which requires an easily revoked permit for any industry, municipality, or other entity dumping wastes in surface waters. The permit requires disclosure of what is being dumped and gives regulators valuable data and evidence for litigation. As a consequence, only about 10 percent of our water pollution now comes from industrial and municipal point sources. One of the biggest improvements has been in sewage treatment.

Since the Clean Water Act was passed in 1972, the United States has spent more than $180 billion in public funds and perhaps ten times as much in private investments on water pollution control. Most of that effort has been aimed at point sources, especially to build or upgrade thousands of municipal sewage treatment plants. As a result, nearly everyone in urban areas is now served by municipal sewage systems, and no major city discharges raw sewage into a river or lake except as overflow during heavy rainstorms.

This campaign has led to significant improvements in surface-water quality in many places. Fish and aquatic insects have returned to waters that formerly were depleted of life-giving oxygen. Swimming and other water-contact sports are again permitted people live in its catchment basin, and nearly 20 million get their drinking water from the river or its tributaries. By the 1970s, the Rhine had become so polluted that dozens of fish species disappeared and swimming was discouraged along most of its length.

Efforts to clean up this historic and economically important waterway began in the 1950s, but a disastrous fire at a chemical warehouse near Basel, Switzerland, in 1986 provided the impetus for major changes. Through a long and sometimes painful series of international conventions and compromises, land-use practices, waste disposal, urban runoff, and industrial dumping have been changed and water quality has significantly improved. Oxygen concentrations have gone up five-fold since 1970 (from less than 2 mg/l to nearly 10 mg/l, or about 90 percent of saturation) in long stretches of the river. Chemical oxygen demand has fallen five-fold during the same period, and organochlorine levels have decreased as much as ten-fold. Many species of fish and aquatic invertebrates have returned to the river. In 1992, for the first time in decades, mature salmon were caught in the Rhine.

The less-developed countries of South America, Africa, and Asia have even worse water quality than do the poorer countries of Europe. Sewage treatment is usually either totally lacking or woefully inadequate. In urban areas, 95 percent of all sewage is discharged untreated into rivers, lakes, or the ocean. Low technological capabilities and little money for pollution control are made even worse by burgeoning populations, rapid urbanization, and the shift of much heavy industry (especially the dirtier ones) from developed countries where pollution laws are strict to less-developed countries where regulations are more lenient.

Appalling environmental conditions often result from these combined factors (fig. 10.25). Two-thirds of India's surface waters are contaminated sufficiently to be considered dangerous to human health. The Yamuna River in New Delhi has 7,500 coliform bacteria per 100 ml (37 times the level considered safe for swimming in the United States) *before* entering the city. The coliform count increases to an incredible 24 *million* cells per 100 ml as the river leaves the city! At the same time, the river picks up some 20 million liters of industrial effluents every day from New Delhi. It's no wonder that disease rates are high and life expectancy is low in this area. Only 1 percent of India's towns and cities have any sewage treatment, and only eight cities have anything beyond primary treatment.

FIGURE 10.25 *Ditches in this Haitian slum serve as open sewers, into which all manner of refuse and waste are dumped. The health risks of living under these conditions are severe.*

In Malaysia, 42 of 50 major rivers are reported to be "ecological disasters." Residues from palm oil and rubber manufacturing, along with heavy erosion from logging of tropical rainforests, have destroyed all higher forms of life in most of these rivers. In the Philippines, domestic sewage makes up 60 to 70 percent of the total volume of Manila's Pasig River. Thousands of people use the river not only for bathing and washing clothes but also as their source of drinking and cooking water. China treats only 2 percent of its sewage. Of 78 monitored rivers in China, 54 are reported to be seriously polluted. Of 44 major cities in China, 41 use "contaminated" water supplies, and few do more than rudimentary treatment before it is delivered to the public.

Groundwater and Drinking-Water Supplies

About half the people in the United States, including 95 percent of those in rural areas, depend on underground aquifers for their drinking water. This vital resource is threatened in many areas by overuse and pollution and by a wide variety of industrial, agricultural, and domestic contaminants. For decades it was widely assumed that groundwater was impervious to pollution because soil would bind chemicals and cleanse water as it percolated through. Springwater or artesian well water was considered to be the definitive standard of water purity, but that is no longer true in many areas.

One of the serious sources of groundwater pollution throughout the United States is MTBE (methyl tertiary butyl ether), a suspected carcinogen added to gasoline to reduce carbon monoxide and ozone in urban air. Aquifers across the United States have been contaminated—mainly from leaking underground storage tanks at gas stations. In one U.S. Geological Survey (USGS) study, 27 percent of shallow urban wells tested contained MTBE. The additive is being phased out, but plumes of tainted water will continue to move through aquifers for decades to come. Liability for this contamination is a highly contentious issue.

The EPA estimates that every day some 4.5 trillion l (1.2 trillion gal) of contaminated water seep into the ground in the United States from septic tanks, cesspools, municipal and industrial landfills and waste disposal sites, surface impoundments, agricultural fields, forests, and wells (fig. 10.26). The most toxic of these are probably waste disposal sites. Agricultural chemicals and wastes are responsible for the largest total volume of pollutants and area affected. Because deep underground aquifers often have residence times of thousands of years, many contaminants are extremely stable once underground. It is possible, but expensive, to pump water out of aquifers, clean it, and then pump it back.

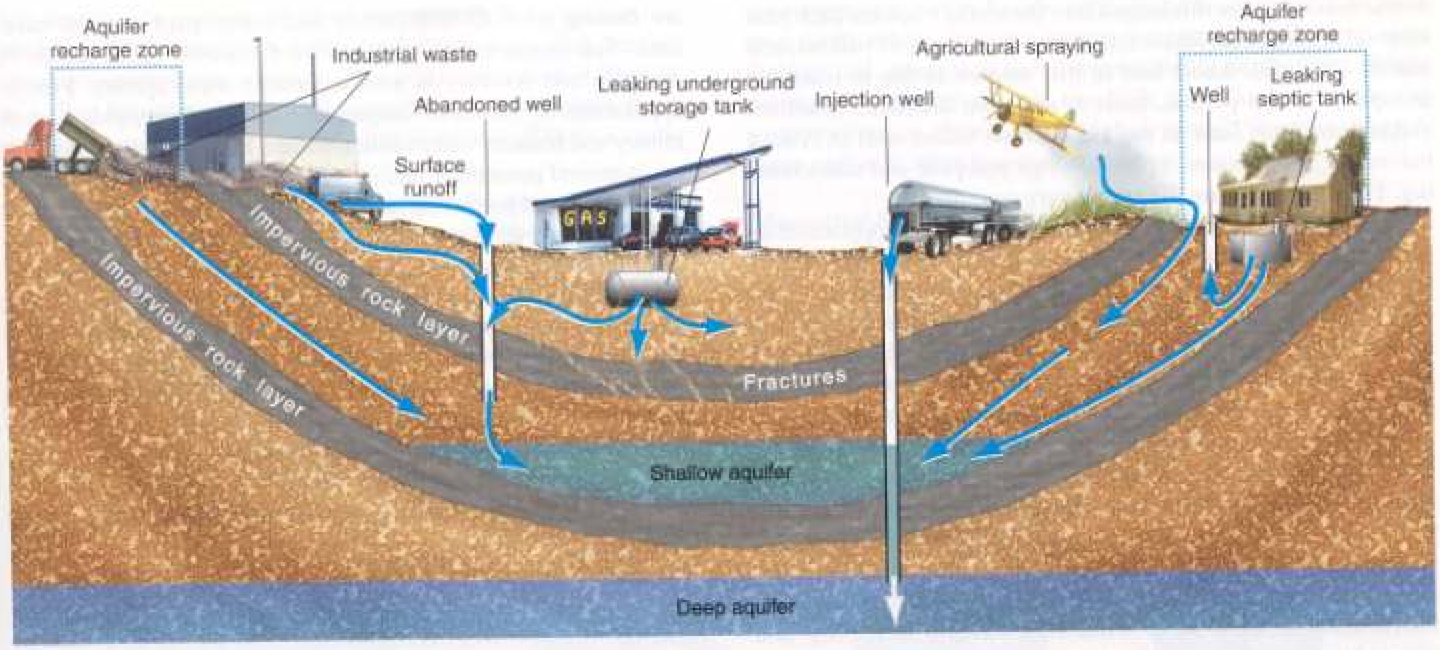

FIGURE 10.26 *Sources of groundwater pollution. Septic systems, landfills, and industrial activities on aquifer recharge zones leach contaminants into aquifers. Wells provide a direct route for injection of pollutants into aquifers.*

In farm country, especially in the Midwest's corn belt, fertilizers and pesticides commonly contaminate aquifers and wells. Herbicides such as atrazine and alachlor are widely used on corn and soybeans and show up in about half of all wells in Iowa, for example. Nitrates from fertilizers often exceed safety standards in rural drinking water. These high nitrate levels are dangerous to infants (nitrates combine with hemoglobin in the blood and result in "blue-baby" syndrome).

Every year, epidemiologists estimate that around 1.5 million Americans fall ill from infections caused by fecal contamination. In 1993, for instance, a pathogen called cryptosporidium got into the Milwaukee public water system, making 400,000 people sick and killing at least 100 people. The total costs of these diseases amount to billions of dollars per year. Preventative measures, such as protecting water sources and aquifer recharge zones and updating treatment and distribution systems, would cost far less.

Ocean Pollution

Although we don't use ocean waters directly, ocean pollution is serious and one of the fastest-growing water pollution problems. Coastal bays, estuaries, shoals, and reefs are often overwhelmed by pollution. Dead zones and poisonous algal blooms are increasingly widespread. Toxic chemicals, heavy metals, oil, sediment, and plastic refuse affect some of the most attractive and productive ocean regions. The potential losses caused by this pollution amount to billions of dollars each year. In terms of quality of life, the costs are incalculable.

Discarded plastic flotsam and jetsam are becoming a ubiquitous mark of human impact on the oceans. Since plastic is lightweight and nonbiodegradable, it is carried thousands of miles on ocean currents and lasts for years. Even the most remote beaches of distant islands are likely to have bits of polystyrene foam containers or polyethylene packing material that were discarded half a world away. It has been estimated that 6 million metric tons of plastic bottles, packaging material, and other litter are tossed from ships every year into the ocean, where they ensnare and choke seabirds, mammals, and even fish (fig. 10.27).

Oil pollution affects beaches and open seas around the world. Oceanographers estimate that between 3 million and 6 million

FIGURE 10.27 *A deadly necklace. Marine biologists estimate that cast-off nets, plastic beverage yokes, and other packing residue kill hundreds of thousands of birds, mammals, and fish each year.*

metric tons of oil are discharged into the world's oceans each year from oil tankers, fuel leaks, intentional discharges of fuel oil, and coastal industries. About half of this amount is due to maritime transport. Of this portion, most is not from dramatic, headline-making accidents such as the 1989 *Exxon Valdez* spill in Alaska but, rather, from routine, open-sea bilge pumping and tank cleaning. These activities are illegal but very common.

The transport of huge quantities of oil creates opportunities for major oil spills through a combination of human and natural hazards. Military conflict in the Middle East destabilizes shipping routes. More important, drilling and transport in stormy seas cause spills. Plans to drill for oil along the seismically active California and Alaska coasts have been controversial because of the damage that spills could cause to these biologically rich coastal ecosystems.

Fortunately, awareness of ocean pollution is growing. Oil spill cleanup technologies and response teams are improving, although most oil is eventually decomposed by natural bacteria. Efforts are growing to control waste plastic. Sixteen states now require that six-pack yokes be made of biodegradable or photodegradable plastic, limiting their longevity as potential killers. International concern about ocean ship waste is increasing, and some shipping companies have been prosecuted and fined for dumping fuel oil. Beach pollution—mainly plastic debris, but also sewage waste, oil, and chemical contaminants—is becoming more common, but it is also more frequently reported in the mainstream media. Volunteer efforts are helping to reduce beach pollution locally: in one day, volunteers in Texas gathered more than 300 tons of plastic refuse from Gulf Coast beaches.

POLLUTION CONTROL

The cheapest and most effective way to reduce pollution is to avoid producing it or releasing it in the first place. Eliminating lead from gasoline has resulted in a widespread and significant decrease in the amount of lead in U.S. surface waters. Studies have shown that as much as 90 percent less road deicing salt can be used in many areas without significantly affecting the safety of winter roads. Careful handling of oil and petroleum products can greatly reduce the amount of water pollution caused by these materials. Although we still have problems with persistent chlorinated hydrocarbons spread widely in the environment, the banning of DDT and PCBs in the 1970s has resulted in significant reductions in levels in wildlife.

Industry can reduce pollution by recycling or reclaiming materials that otherwise might be discarded in the waste stream. These approaches usually have economic as well as environmental benefits. Companies can extract valuable metals and chemicals and sell them, instead of releasing them as toxic contaminants into the water system. Both markets and reclamation technologies are improving as awareness of these opportunities grows. In addition, modifying land use is an important component of reducing pollution.

Nonpoint Sources and Land Management

Farmers have long contributed a huge share of water pollution, especially in the developed world. Increasingly, though, farmers are finding ways to save money and water quality at the same time. Soil conservation practices on farmlands (see chapter 7) maintain soil fertility, as well as protect water quality. Precise application of fertilizer, irrigation water, and pesticides saves money and reduces water contamination. Preserving wetlands that act as natural processing facilities for removing sediment and contaminants helps protect surface and groundwaters.

In urban areas, reducing waste that enters storm sewers is essential. It is getting easier for city residents to recycle waste oil and to properly dispose of paint and other household chemicals that they once dumped into storm sewers or the garbage. Urbanites can also minimize use of fertilizers and pesticides. Regular street sweeping greatly reduces nutrient loads (from decomposing leaves and debris) in rivers and lakes. Runoff can also be diverted away from streams and lakes. Many cities are separating storm sewers and municipal sewage lines to avoid overflow during storms.

A good example of the problems of watershed management is seen in Chesapeake Bay, America's largest estuary. Once fabled for its abundant oysters, crabs, shad, striped bass, and other valuable fisheries, the bay had deteriorated seriously by the early 1970s. Citizens' groups, local communities, state legislatures, and the federal government together established an innovative pollution-control program that made the bay the first estuary in America targeted for protection and restoration.

Among the principal objectives of this plan is reducing nutrient loading through land-use regulations in the bay's six watershed states to control agricultural and urban runoff. Pollution-prevention measures, such as banning phosphate detergents, also are important, as are upgrading wastewater treatment plants and improving compliance with discharge and filling permits. Efforts are underway to replant thousands of hectares of sea grasses and to restore wetlands that filter out pollutants. Since the 1980s, annual phosphorous discharges into Chesapeake Bay have dropped 40 percent. Nitrogen levels, however, have remained constant or have even risen in some tributaries. Although progress has been made, the goals of reducing both nitrogen and phosphate levels by 40 percent and restoring viable fish and shellfish populations are still decades away. Still, as EPA Administrator Carol Browner says, it demonstrates the "power of cooperation" in environmental protection. (See related story "Watershed Protection in the Catskills" at www.mhhe.com/cases.)

Sewage Treatment

As we have already seen, human and animal wastes usually create the most serious health-related water pollution problems. More than 500 types of disease-causing (pathogenic) bacteria, viruses, and parasites can travel from human or animal excrement through water.

Natural Processes

In the poorer countries of the world, most rural people simply go out into the fields and forests to relieve themselves, as they have always done. Where population densities are low, natural processes eliminate wastes quickly, making this an effective method of sanitation. The high population densities of cities, however, make this practice unworkable. Even major cities of many

Where Does Our Water Come From?

The water we use cycles endlessly through the environment. The total amount of water on our planet is immense—more than 1,404 million km^3 (370 billion billion gal) (table 10.1). This water evaporates from moist surfaces, falls as rain or snow, passes through living organisms, and returns to the ocean in a process known as the **hydrologic cycle** (see fig. 2.18). Every year, about 500,000 km^3, or a layer 1.4 m thick, evaporates from the oceans. More than 90 percent of that moisture falls back on the ocean. The 47,000 km^3 carried onshore joins some 72,000 km^3 that evaporate from lakes, rivers, soil, and plants to become our annual, renewable freshwater supply. Plants play a major role in the hydrologic cycle, absorbing groundwater and pumping it into the atmosphere by transpiration (transport plus evaporation). In tropical forests, as much as 75 percent of annual precipitation is returned to the atmosphere by plants.

Solar energy drives the hydrologic cycle by evaporating surface water, which becomes rain and snow. Because water and sunlight are unevenly distributed around the globe, water resources are very uneven. At Iquique in the Chilean desert, for instance, no rain has fallen in recorded history. At the other end of the scale, 22 m (72 ft) of rain was recorded in a single year at Cherrapunji in India. Figure 10.2 shows broad patterns of precipitation around the world. Most of the world's rainiest regions are tropical, where heavy rainy seasons occur, or in coastal mountain regions. Most of the driest areas are in the high-pressure bands of deserts (see chapter 9). Deserts occur on every continent just outside the tropics (the Sahara, the Namib, the Gobi, the Sonoran, and many others). Rainfall is also slight at very high latitudes, another high-pressure region.

Mountains also influence moisture distribution. The windward sides of mountain ranges, including the Pacific Northwest and the flanks of the Himalayas, are typically wet and have large rivers; on the leeward sides of mountains, in areas known as the rain shadow, dry conditions dominate, and water can be very scarce. The windward side of Mount Waialeale on the island of Kauai, for example, is one of the wettest places on earth, with an annual rainfall around 1,200 cm (460 in.). The leeward side, only a few kilometers away, has an average yearly rainfall of only 46 cm (18 in.).

TABLE 10.1 Units of Water Measurement

One cubic kilometer (km^3) equals 1 billion cubic meters (m^3), 1 trillion liters, or 264 billion gal.

One acre-foot is the amount of water required to cover an acre of ground 1 ft deep. This is equivalent to 325,851 gal, or 1.2 million liters, or 1,234 m^3, approximately the amount consumed annually by a family of four in the United States.

One cubic foot per second of river flow equals 28.3 liters per second, or 449 gal per minute.

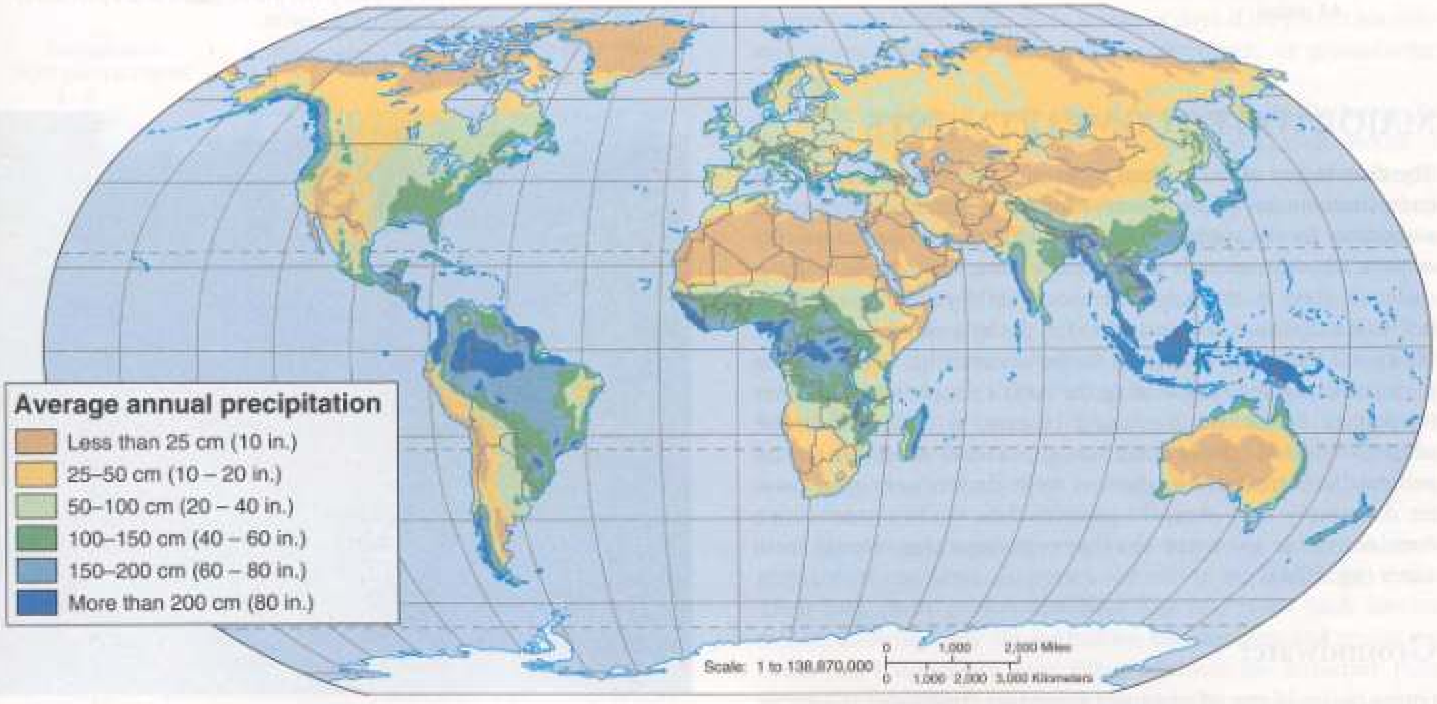

FIGURE 10.2 *Average annual precipitation. Note wet areas that support tropical rainforests occur along the equator, while the major world deserts occur in zones of dry, descending air between 20° and 40° north and south.*

TABLE 10.2 Earth's Water Compartments

COMPARTMENT	VOLUME (1,000 km^3)	PERCENT OF TOTAL WATER	AVERAGE RESIDENCE TIME
Total	1,386,000	100	2,800 years
Oceans	1,338,000	96.5	3,000 to 30,000 years*
Ice and snow	24,364	1.76	1 to 100,000 years*
Saline groundwater	12,870	0.93	Days to thousands of years*
Fresh groundwater	10,530	0.76	Days to thousands of years*
Fresh lakes	91	0.007	1 to 500 years*
Saline lakes	85	0.006	1 to 1,000 years*
Soil moisture	16.5	0.001	2 weeks to 1 year*
Atmosphere	12.9	0.001	1 week
Marshes, wetlands	11.5	0.001	Months to years
Rivers, streams	2.12	0.0002	1 week to 1 month
Living organisms	1.12	0.0001	1 week

Source: Data from UNEP, 2002.
*Depends on depth and other factors.

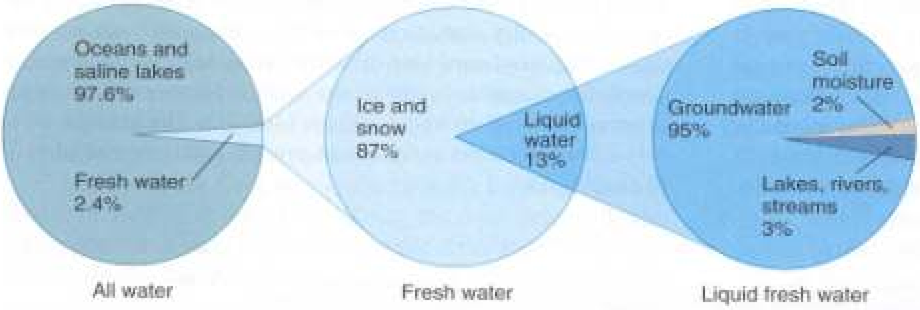

FIGURE 10.3 *The easily accessible water in lakes, rivers, and streams represents only 3 percent of all liquid fresh water, which is 13 percent of all fresh water, which is 2.4 percent of all water on the earth.*

MAJOR WATER COMPARTMENTS

The distribution of water often is described in terms of interacting compartments in which water resides, sometimes briefly and sometimes for eons (table 10.2). The length of time water typically stays in a compartment is its **residence time.** On average, a water molecule stays in the ocean for about 3,000 years, for example, before it evaporates and starts through the hydrologic cycle again. Nearly all the world's water is in the oceans (fig. 10.3). Oceans play a crucial role in moderating the earth's temperature, and over 90 percent of the world's living biomass is contained in the oceans. What we mainly need, though, is fresh water. Of the 2.4 percent that is fresh, most is locked up in glaciers or in groundwater. Amazingly, only about 0.1 percent of the world's water is in a form accessible to us and to other organisms that rely on fresh water (fig. 10.4).

FIGURE 10.4 *Water is essential for life, yet only about 0.1 percent of the world's supply is accessible, fresh, liquid water.*

Groundwater

Groundwater is one of our most important freshwater resources. Originating as precipitation that percolates into layers of soil and rock, groundwater makes up the largest compartment of liquid, fresh water. The groundwater within 1 km of the surface is more than 100 times the volume of all the freshwater lakes, rivers, and reservoirs combined.

Plants get moisture from a relatively shallow layer of soil containing both air and water, known as the *zone of aeration* (fig. 10.5). Depending on rainfall amount, soil type, and surface topography, the zone of aeration may be a few centimeters or many meters deep. Lower soil layers, where all soil pores are filled with water, make up the *zone of saturation*, the source of water in most wells; the top of this zone is the **water table.**

Geologic layers that contain water are known as **aquifers.** Aquifers may consist of porous layers of sand or gravel or of cracked or porous rock. Below an aquifer, relatively impermeable layers of rock or clay keep water from seeping out at the bottom. Instead, water seeps more or less horizontally through the porous layer. Depending on geology, it can take from a few hours to several years for water to move a few hundred meters through an aquifer. If impermeable layers lie above an aquifer, pressure can develop within the water-bearing layer. A well or conduit puncturing the aquifer flows freely at the surface and is called an *artesian well* or spring.

Areas where surface water filters into an aquifer are **recharge zones** (fig. 10.6). Most aquifers recharge extremely slowly, and road and house construction or water use at the surface can further slow recharge rates. Contaminants can also enter aquifers through recharge zones. Urban or agricultural runoff in recharge zones is often a serious problem. About 2 billion people—approximately one-third of the world's population—depend on groundwater for drinking and other uses. Every year 700 km^3 are withdrawn by humans, mostly from shallow, easily polluted aquifers.

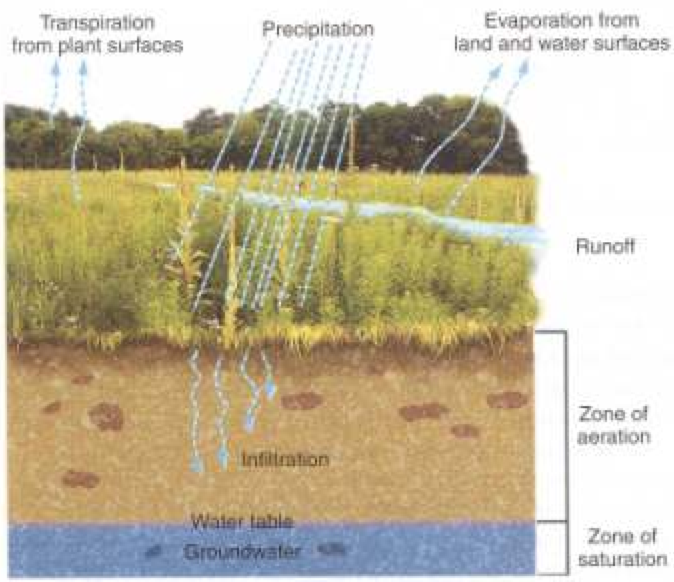

FIGURE 10.5 *Precipitation that does not evaporate or run off over the surface percolates through the soil in a process called infiltration. The upper layers of soil hold droplets of moisture between air-filled spaces. Lower layers, where all spaces are filled with water, make up the zone of saturation, or groundwater.*

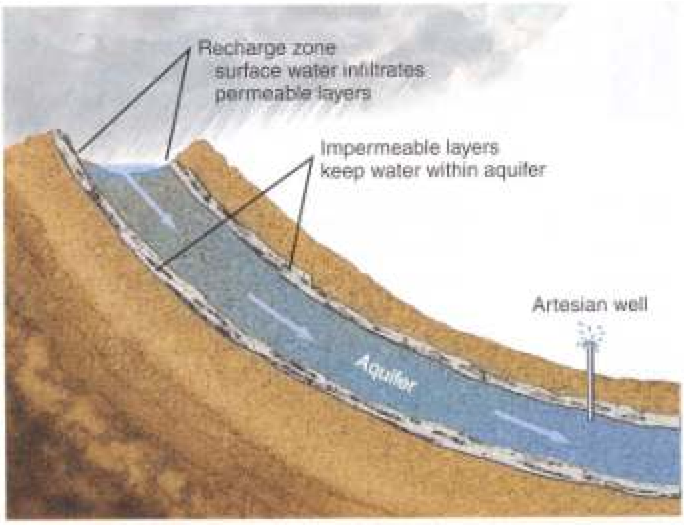

FIGURE 10.6 *An aquifer is a porous, water-bearing layer of sand, gravel, or rock. This aquifer is confined between layers of rock or clay and bent by geologic forces, creating hydrostatic pressure. A break in the overlying layer creates an artesian well or spring.*

Rivers, Lakes, and Wetlands

Fresh, flowing surface water is one of our most precious resources. Rivers contain a minute amount of water at any one time. Most rivers would begin to dry up in weeks or days if they were not constantly replenished by precipitation, snowmelt, or groundwater seepage.

The volume of water carried by a river is its **discharge,** or the amount of water that passes a fixed point in a given amount of time. This is usually expressed as liters or cubic feet of water per second. The 16 largest rivers in the world carry nearly half of all surface runoff on the earth, and a large fraction of that occurs in a single river, the Amazon, which carries 10 times as much water as the Mississippi (table 10.3).

Lakes contain nearly 100 times as much water as all rivers and streams combined, but much of this water is in a few of the world's largest lakes. Lake Baikal in Siberia, the Great Lakes of North America, the Great Rift Lakes of Africa, and a few other lakes contain vast amounts of water, not all of it fresh. Worldwide, lakes are almost as important as rivers in terms of water supplies, food, transportation, and settlement.

Wetlands—bogs, swamps, wet meadows, and marshes—play a vital and often unappreciated role in the hydrologic cycle. Their lush plant growth stabilizes soil and holds back surface runoff, allowing time for infiltration into aquifers and producing even, year-long stream flow. When wetlands are disturbed, their natural water-absorbing capacity is reduced, and surface waters run off quickly, resulting in floods and erosion during the rainy season and low stream flow the rest of the year.

TABLE 10.3 World's Ten Largest Rivers

RIVER	LOCATION	ANNUAL DISCHARGE (m^3/SECOND)*
Amazon	Brazil, Peru	175,000
Orinoco	Venezuela, Colombia	45,300
Congo	Congo	39,200
Yangtze	Tibet, China	28,000
Brahmaputra	South Asia	19,000
Mississippi	United States	18,400
Mekong	Southeast Asia	18,300
Paraná	Paraguay, Argentina	18,000
Yenisey	Russia	17,200
Lena	Russia	16,000

Source: Data from World Resource Institute.
*$1 m^3$ = 264 gal.

The Atmosphere

The atmosphere contains only 0.001 percent of the total water supply, but it is the most important mechanism for redistributing water around the world. An individual water molecule resides in the atmosphere for about ten days, on average. Some water evaporates and falls within hours. Water can also travel halfway around the world before it falls, replenishing streams and aquifers on land.

WATER AVAILABILITY AND USE

Clean, fresh water is essential for nearly every human endeavor (fig. 10.7). Collectively, we now appropriate more than half of all the freshwater in the world. Perhaps more than any other environmental factor, the availability of water determines the location and activities of humans on the earth. **Renewable water supplies** are resources that are replenished regularly—mainly surface water and shallow groundwater. Renewable water is most plentiful in the tropics, where rainfall is heavy, followed by midlatitudes, where rainfall is regular.

Water-Rich and Water-Poor Countries

Water availability is usually measured in terms of renewable water per capita, so population density, as well as total water volumes, dictate renewable supplies for human use. The highest per capita water supplies generally occur in countries with moist climates and low population densities. Iceland, for example, has about 160 million gal per person per year. In contrast, Kuwait, where temperatures are extremely high and rain almost never falls, has less than 3,000 gal per person per year from renewable natural sources. Almost all of Kuwait's water comes from imports and desalinized

FIGURE 10.7 *We depend on fresh water in many ways, but for billions of people, water shortages are a brutal fact of life.*

APPLICATION: Mapping the Water-Rich and Water-Poor Countries

The top ten water-rich countries, in terms of water availability per capita, and the ten most water-poor countries are listed below. Locate these countries on the political map (page 000). Describe the patterns. Where are the water-rich countries concentrated? (Hint: does latitude matter?) Where are the water-poor countries most concentrated?

Water-rich countries: Iceland, Surinam, Guyana, Papua New Guinea, Gabon, Solomon Islands, Canada, Norway, Panama, Brazil

Water-poor countries: Kuwait, Egypt, United Arab Emirates, Malta, Jordan, Saudi Arabia, Singapore, Moldavia, Israel, Oman

Answers: Water-rich countries (per capita) are either in the far north, where populations and evaporation are low, or in the tropics. Water-poor countries are in the desert belt at about 15° to 25° latitude or are densely populated island nations (e.g., Malta, Singapore).

seawater. In countries such as Libya and Israel, where water is one of the most crucial environmental resources, renewable supplies do not meet basic needs. These countries manage by "mining" groundwater, depleting sources that are probably unrenewable on a human time scale.

Much of the western United States has insufficient water to meet all the demands placed on this vital resource. The U.S. Department of the Interior warns that by 2025 many western states will face water crises (fig. 10.8). After five years of severe drought, flow in the Colorado River has decreased so much that Lake Powell has lost 60 percent of its volume and the lake surface has dropped more than 33 m (100 ft). Electric generation could cease in four years, if current conditions continue, and the reservoir may never refill. Serious suggestions have been made to remove the dam and let the river run free.

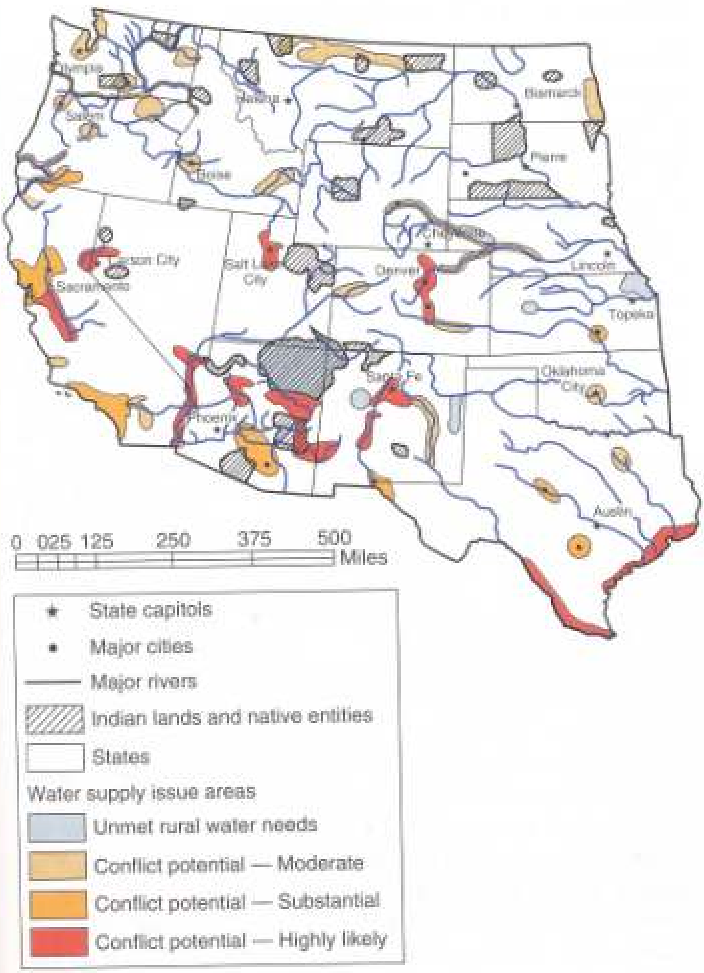

FIGURE 10.8 *Rapidly growing populations in arid regions are straining available water supplies. By 2025, the Department of the Interior warns, shortages could cause conflicts in many areas.*
Source: Data from U.S. Department of Interior.

As you can see, interannual variability in rainfall is an important issue in water availability. In the African Sahel region, like the American southwest, abundant rainfall occurs some years but not others. Usually natural ecosystems can survive these changes, but human societies, and ecosystems greatly altered by grazing, farming, or urban development, can be badly destabilized by rainfall fluctuations. Some of the world's earliest civilizations, such as the Sumerians and Babylonians of Mesopotamia, were based on communal efforts to divert floods during wet seasons or wet years and to store water in dry years. Many climatologists now worry that the greenhouse effect (see chapter 9) will bring about more serious or frequent droughts in dry parts of the world.

Water Use

In contrast to energy resources, which usually are consumed when used, water can be used over and over if it is not too badly contaminated. Water **withdrawal** is the total amount of water taken from a water body. Much of this water could be returned to circulation in a reusable form. Water **consumption,** on the other hand, is loss of water due to evaporation, absorption, or contamination.

The natural cleansing and renewing functions of the hydrologic cycle replace the water we need if natural systems are not overloaded or damaged. Water is a renewable resource, but renewal takes time. The rate at which many of us now use water may make it necessary to conscientiously protect, conserve, and replenish our water supply.

Quantities of Water Used

Water use has been increasing about twice as fast as population growth over the past century. Water withdrawals are expected to continue to grow as more land is irrigated to feed an expanding population (fig. 10.9). Conflicts increase as different countries, economic sectors, and other stakeholders compete for the same, limited water supply. Water wars may well be the major source of hostilities in the twenty-first century.

Worldwide, agriculture claims about 70 percent of total water withdrawal, ranging from 93 percent of all water used in India to only 4 percent in Kuwait, which cannot afford to spend its limited water on crops. In many developing countries and in parts of the United States, the most common type of irrigation is to simply flood the whole field or run water in rows between crops. As much as half the water can be lost through evaporation or seepage from unlined irrigation canals bringing water to fields. Sprinklers are more efficient in distributing water, but they are more costly and energy intensive (fig. 10.10). Water-efficient drip irrigation can save significant amounts of water but currently is used on only about 1 percent of the world's croplands (fig. 10.11).

Industry uses about one-fourth of water withdrawals worldwide. Some European countries use 70 percent of water for industry; less-industrialized countries use as little as 5 percent. Cooling water for power plants is by far the largest single industrial use of water, typically accounting for 50 to 75 percent of industrial withdrawal.

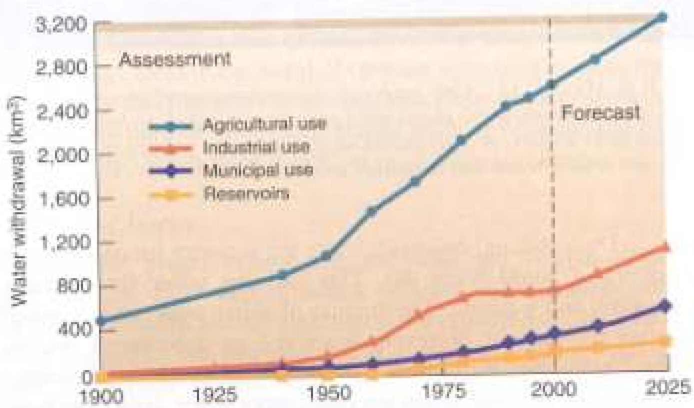

FIGURE 10.9 *Global water withdrawals have increased more than seven-fold over the past century and are expected to continue to rise in the future.*
Source: Data from UNESCO, 2001.

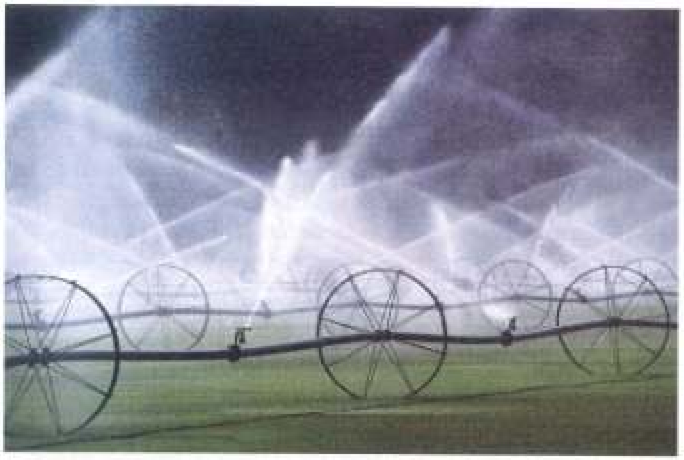

FIGURE 10.10 *Rolling sprinklers allow farmers to irrigate crops on uneven terrain. In some areas, irrigation consumes 90 percent of all available water.*

FIGURE 10.11 *Drip irrigation delivers measured amounts of water exactly where the plants need and can use it. This technique can save up to 90 percent of irrigation water usage and reduces salt buildup. It also is an efficient way to deliver soluble nutrients.*

Domestic, or household, water use accounts for only about 6 percent of world water use. This includes water for drinking, cooking, and washing. The amount of water used per household varies enormously, however, depending on a country's wealth. The United Nations reports that people in developed countries consume on average, about ten times more water daily than those in developing nations. Poorer counries can't afford the infrastructure to obtain and deliver water to citizens. Inadequate water supplies, on the other hand, prevent agriculture, industry, sanitation, and other devleopments that reduce poverty.

FRESHWATER SHORTAGES

Clean drinking water and basic sanitation are necessary to prevent communicable diseases and to maintain a healthy life. For many of the world's poorest people, one of the greatest environmental threats to health remains the continued use of polluted water. In 2004 the United Nations estimated that at least 1.5 billion people lacked access to safe drinking water and 3 billion didn't have adequate sanitation. These deficiencies result in hundreds of millions of cases of water-related illness and more than 5 million deaths every year. As populations grow, more people move into cities, and agriculture and industry compete for increasingly scarce water supplies, water shortages are expected to become even worse. By 2025 two-thirds of the world's people will be living in water-stressed countries—defined by the United Nations as consumption of more than 10 percent of renewable freshwater resources. One of the highest priorities announced at the UN World Summit in Johannesburg in 2002 was to reduce by one-half the proportion of people without reliable access to clean water and improved sanitation.

A Precious Resource

The World Health Organization considers an average of 1,000 m^3 (264,000 gal) per person per year to be a necessary amount of water for modern domestic, industrial, and agricultural uses. Some 45 countries, most of them in Africa or the Middle East, cannot meet the minimum essential water needs of all their citizens. In some countries, the problem is access to *clean* water. In Mali, for example, 88 percent of the population lacks clean water; in Ethiopia, it is 94 percent. Rural people often have less access to clean water than do city dwellers. Causes of water shortages include natural deficits, overconsumption by agriculture or industry, and inadequate funds for purifying and delivering good water.

More than two-thirds of the world's households have to fetch water from outside the home (fig. 10.12). This is heavy work, done mainly by women and children and sometimes taking several hours a day. Improved public systems bring many benefits to these poor families.

Availability does not always mean affordability. A typical poor family in Lima, Peru, for instance, uses one-sixth as much water as a middle-class American family but pays three times as much for it. If they followed government recommendations to boil all water to prevent cholera, up to one-third of the poor family's income could be used just in acquiring and purifying water.

Investments in rural development have brought significant improvements in recent years. Since 1990, nearly 800 million people—about 13 percent of the world's population—have gained access to clean water. The percentage of rural families with safe drinking water has risen from less than 10 percent to nearly 75 percent.

Depleting Groundwater

Groundwater provides nearly 40 percent of the fresh water for agricultural and domestic use in the United States. Nearly half of all Americans and about 95 percent of the rural population depend on groundwater for drinking and other domestic purposes. Overuse of these supplies dries up wells, natural springs, and even groundwater-fed wetlands, rivers, and lakes. Pollution of aquifers through dumping of contaminants on recharge zones, leaks through abandoned wells, or deliberate injection of toxic wastes can make this valuable resource unfit for use.

In many areas of the United States, groundwater is being withdrawn from aquifers faster than natural recharge can replace it. On a local level, this causes a cone of depression in the water table (fig. 10.13). On a broader scale, heavy pumping can deplete a whole aquifer. The Ogallala Aquifer underlies eight Great Plains states from Texas to North Dakota. This porous bed of sand, gravel, and sandstone once held more water than all the freshwater lakes, streams, and rivers on the earth. Excessive pumping for irrigation has removed so much water that wells have dried up in many places, and farms, ranches, even whole towns are being abandoned. Recharging many such aquifers will take thousands of years. Using "fossil" water like this is essentially water mining. For all practical purposes, these aquifers are nonrenewable resources.

Water withdrawal also allows aquifers to collapse. Subsidence, or sinking of the ground surface, follows. The San Joaquin Valley in California has sunk more than 10 m in the past 50 years because of excessive groundwater pumping. Where aquifers become compressed, recharge becomes impossible.

Another consequence of aquifer depletion is saltwater intrusion. Along coastlines and in areas where saltwater deposits are left from ancient oceans, overuse of freshwater reservoirs often allows saltwater to intrude into aquifers used for domestic and agricultural purposes.

FIGURE 10.12 *Village water supplies in Ghana.*

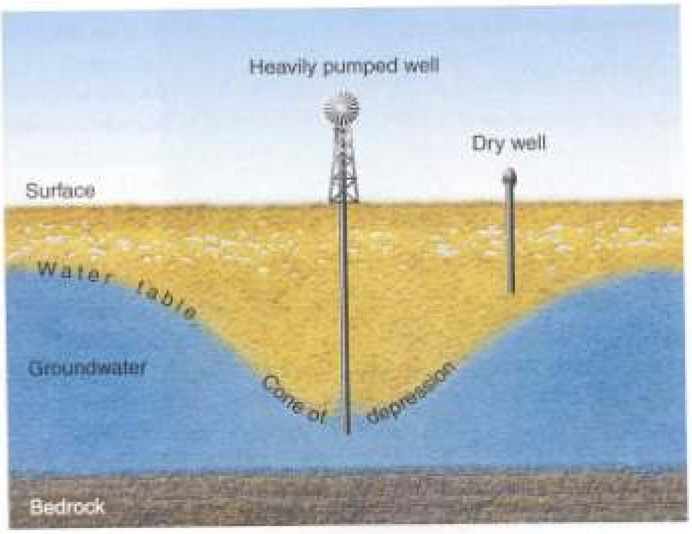

FIGURE 10.13 *A cone of depression forms in the water table under a heavily pumped well. This may dry up nearby shallow wells or make pumping so expensive that it becomes impractical.*

Can We Increase Water Supplies?

On a human time scale, the amount of water on the earth is fixed. Many efforts have been made to redistribute water resources, however. Towing icebergs from Antarctica has been proposed, and creating rain in dry regions has been accomplished, with mixed success, by cloud seeding—distributing condensation nuclei in humid air to help form raindrops. Desalination is locally important: in the arid Middle East, where energy and money are available but water is scarce, desalination is sometimes the principal source of water. Most efforts, however, have involved dams, canals, water diversions, and desalination. We will discuss some of the benefits and negative consequences of these projects next.

Dams, Reservoirs, and Canals

Dams and canals are a fundamental basis of civilization; they can also be a source of environmental disaster and injustice. Some of the great civilizations (Sumeria, Egypt, China, and the Incan culture of South America) were organized around the large-scale redistribution of water from rivers to irrigated farm fields. More than half the world's 227 largest rivers have been blocked by dams or diversion structures with adverse effects on freshwater ecosystems. Of the 50,000 large dams in the world, 90 percent were built in the twentieth century, and half of those are in China. Economically speaking, at least one-third of those dams should never have been built (see related story "South Water North" at www.mhhe.com/cases).

Dams and Justice

While many people benefit from the water and hydroelectricity provided by dams and diversion projects, other stakeholders, including wildlife and ecosystems, suffer. Towns and farms have been starved by the huge dams and diversions. Fishing enthusiasts, whitewater boaters, and others mourn the loss of rivers drowned in reservoirs or dried up by diversion projects. These projects also have been criticized for using public funds to increase the value of privately held farmland and for encouraging agricultural development and urban growth in arid lands, where other uses might be more appropriate (see Case Study, p. 238).

Worldwide, large dams often flood towns and farmlands, raising international outcry. In India, the Sardar Sarovar Dam on the sacred Narmada River has been the focus of decades of protest. Many of the 1 million villagers and tribal people being displaced by this project have engaged in mass resistance and civil disobedience, while police have tried to remove them forcibly. In Nepal, construction of the 240-m (850-ft)-high Tehri Dam on the Bhagirathi River has stirred fears that a strong earthquake in this active seismic region might cause the dam to collapse and cause a catastrophic flood downstream. This dam is only one of 17 high dams that Nepal and India plan for the Himalaya Mountains. Similar fears of earthquakes and floods of biblical proportions have plagued China's Three Gorges Dam on the Yangtze River (see related story "Three Gorges" at www.mhhe.com/cases).

Canada's James Bay project built by Hydro-Quebec has diverted three major rivers flowing west into Hudson Bay and has flooded more than 10,000 km^2 (4,000 mi^2) of forest and tundra to generate 26,000 megawatts of electrical power. In 1984 10,000 caribou drowned while trying to follow ancient migration routes across the newly flooded land. The loss of traditional hunting and fishing sites has been culturally devastating for native Cree people. In addition, mercury leeched out of rocks in newly submerged lands has entered the food chain, and many residents show signs of mercury poisoning.

Environmental Costs of Dams

Dams ensure a year-round water supply, but they also waste tremendous amounts of water from evaporation and through seepage into porous rock beds. Some dams built in the western United States lose more water than they make available. Evaporative losses from Lake Mead and Lake Powell on the Colorado River are about 1 km^3 (264 billion gal) per year (fig. 10.14). The salts left behind by evaporation and agricultural runoff nearly double the salinity of the river. Mexico had to sue the United States to force construction of a $350 million desalination plant at Yuma, Arizona, to make the water partially usable again.

Dams also collect silt, decreasing the effectiveness of reservoirs and starving streambeds and sandbars downstream. As the turbulent Colorado River slows in the reservoirs created by Glen Canyon and Boulder Dams, it drops its load of suspended material. More than 10 million metric tons of silt per year collect behind these dams. Imagine a line of 20,000 dump trucks backed up to Lake Mead and Lake Powell every day, dumping dirt into the water. Within as little as 100 years, these reservoirs could be full of silt and useless for either water storage or hydroelectric generation (fig. 10.15).

In Egypt, the Aswân High Dam was built to irrigate thousands of hectares of farmland, but the dam loses much of the Nile's river to evaporation. Without the annual floods that carried rich silt to farmlands for thousands of years, many farming areas are becoming infertile, and the famous Nile Delta—and its rich fisheries—are disappearing.

Dams and river channelization also drown or destroy free-flowing rivers. One of the first and most divisive battles over this loss was in the Hetch Hetchy Valley in Yosemite National Park. In the early 1900s, San Francisco wanted to dam the Tuolumne River to produce hydroelectric power and provide water for the city water system. This project was supported by many prominent San Francisco citizens because it represented an opportunity for both clean water and municipal power. John Muir, founder of the Sierra Club and protector of Yosemite Park, said, "These temple destroyers, devotees of ravaging commercialism, seem to have perfect contempt for Nature, and, instead of lifting their eyes to the God of the mountains, lift them to the Almighty Dollar. Dam Hetch Hetchy! As well dam for water-tanks the people's cathedrals and churches, for no holier temple has ever been consecrated by the heart of man." After a prolonged and bitter fight, the developers won, and the dam was built.

FIGURE 10.14 *Hoover Dam provides valuable electric power to Nevada and California but Lake Mead, behind the dam, loses about 1.3 billion m^3 of water per year to evaporation.*

FIGURE 10.15 *This dam is now useless because its reservoir has filled with silt and sediment.*

Price Mechanisms and Water Policy

Throughout most of U.S. history, water policies generally worked against conservation. In the well-watered eastern United States,