11 Water Pollution and Treatment

Hanauma Bay, Oahu, Hawaii. (*Edward A. Keller*)

Hanauma Bay Beach Park is located only a few kilometers west of the city of Honolulu on the island of Oahu, Hawaii. The bay, the result of collapse or marine erosion of a volcanic peak, is the site of a fringing coral reef that is now a marine sanctuary visited by tourists from around the world.

Hanauma Bay and its coral reef are in poor ecological condition, as are many coral reefs of the world's coastline as a result of a variety of human activities, including global warming of oceanic water, intensive coastal development, and pollution of nearshore waters. Coral reefs are particularly vulnerable to water pollution because they thrive best in clear coastal waters that are naturally relatively nutrient-poor. When raw sewage or even treated wastewater or agricultural runoff enters nearshore environments, nutrient levels may rise, causing problems for coral reefs as other organisms that prey on coral experience a population explosion in response to the increased nutrient load. Coastal development and agriculture may also greatly increase the amount of sediment entering coastal waters that may partially cover coral reefs, blocking sunlight and weakening the coral so that they become vulnerable to disease. It is estimated that 60 percent of the world's coral reefs are today being threatened by human activities.

We once thought that the oceans of the world could never be polluted because they are so vast. Today we are learning that this is far from the case. Beaches in southern California are sometimes closed as a result of pollutants entering the coastal environment from streams and other sources. Raw sewage and chemicals from cities around the world, particularly in developing countries, are being indiscriminately dumped into rivers that enter our lakes and oceans in growing quantities as human population increases. In southern California, beach closures are blamed on everything from seagulls to dogs on beaches to seals, when we ought to be looking more closely at processes of urban runoff and waste disposal into streams and rivers that make their way to the coastal environment.

LEARNING OBJECTIVES

One of the most serious environmental problems for billions of people on earth is the continuous or sporadic lack of a pollution- and disease-free water supply for personal consumption. With this in mind, learning objectives for the chapter are:

- *To be able to define water pollution and discuss some of the common water pollutants.*
- *To gain an appreciation for selected water pollution problems, including cultural eutrophication and acid mine drainage.*
- *To know the difference between point and nonpoint sources of water pollution.*
- *To understand processes by which groundwater may become polluted and how polluted water may be treated.*
- *To become familiar with some of the important issues related to water quality standards.*
- *To understand the principles of wastewater treatment associated with septic-tank sewage disposal and wastewater treatment plants.*
- *To gain an appreciation for processes related to wastewater renovation and wastewater treatment involving resource recovery.*
- *To become familiar with the basic doctrine of law associated with surface water and groundwater as well as some of the major federal water legislation important in protecting water resources.*

Web Resources

Visit the "Environmental Geology" Web site at www.prenhall.com/keller to find additional resources for this chapter, including:

- Web Destinations
- On-line Quizzes
- On-line "Web Essay" Questions
- Search Engines
- Regional Updates

11.1 An Overview of Water Pollution

Water pollution refers to degradation of water quality as measured by biological, chemical, or physical criteria. This degradation is judged according to the intended use of the water, departure from the norm, and public health or ecological impacts. From a public health or ecological point of view, a pollutant is any substance in which an identifiable excess is known to be harmful to desirable living organisms. Thus, excessive amounts of heavy metals, certain radioactive isotopes, phosphorus, nitrogen, sodium, and other useful (even necessary) elements, as well as certain pathogenic bacteria and viruses, are all pollutants. In some instances, a material may be considered a pollutant to a particular segment of the population although not harmful to other segments. For example, excessive sodium as a salt is not generally harmful, but it is to some people on diets restricting intake of salt for medical purposes. Table 11.1 lists some common sources of groundwater pollution.

Problems related to water pollution are extremely variable. Of particular significance are the residence times and reservoir sizes of water in the various parts of the hydraulic cycle, because these factors are related to pollution potential. For example, water in rivers has a short average residence time of about 2 weeks. Therefore, a one-time pollution event (one that does not involve the pollutant's attaching itself to sediment on the riverbed, which would result in a much longer residence time) will be relatively short-lived because the water will soon leave the river environment. On the other hand, the same pollutant may enter a lake or an ocean, where residence times are longer and pollutants more difficult to deal with. Many circumstances, such as sewage spills or pollutant-carrying truck or train crashes, can produce one-time pollution events. News of such events is frequent these days. However, pollution is more likely to result from chronic processes that discharge pollutants directly into rivers (Figure 11.1). Groundwaters, unlike river waters, have long res-

Table 11.1 Common sources of groundwater pollution and/or contamination

Leaks from storage tanks and pipes
Leaks from waste disposal sites such as landfills
Seepage from septic systems and cesspools
Accidental spills and seepage (train or truck accidents, for example)
Seepage from agricultural activities such as feedlots
Intrusion of salt water into coastal aquifers
Leaching and seepage from mine spoil piles and tailings
Seepage from spray irrigation
Improper operation of injection wells
Seepage of acid water from mines
Seepage of irrigation return flow
Infiltration of urban, industrial, and agricultural runoff

▲ **FIGURE 11.1** An example of severe water pollution producing a health hazard: This ditch carries sewage and toxic waste to the Rio Grande in Mexico. *(Jim Richardson/Richardson Photography)*

idence times (from hundreds to thousands of years). Therefore, natural removal of pollutants from groundwater is a very slow process, and correction is very costly and difficult.

11.2 Selected Water Pollutants

Many different materials may pollute surface water or groundwater. Our discussion here will focus on oxygen-demanding waste; pathogenic organisms; nutrients; oil; hazardous chemicals; heavy metals; radioactive materials; and sediment.

Oxygen-Demanding Waste

Dead organic matter in streams decays; that is, it is consumed by bacteria, which require oxygen. If there is enough bacterial activity, the oxygen in the water can be reduced to levels so low that fish and other organisms die. A stream without oxygen is a dead stream for fish and many organisms we value. The amount of oxygen used for bacterial decomposition is the **biochemical oxygen demand (BOD),** a commonly used measure in water quality management. The BOD is measured as milligrams per liter of oxygen consumed over 5 days at 20°C. A high BOD indicates a high level of decaying organic matter in the water.

Dead organic matter in streams and rivers comes from natural sources (for example, dead leaves from a forest) as well as from agriculture and urban sewage. Approximately 33 percent of all BOD in streams results from agricultural activities, but urban areas, particularly those with sewer systems that combine sewage and storm-water runoff, may add considerable BOD to streams during floods, when sewers entering treatment plants can be overloaded and overflow into streams, producing pollution events.

The Council on Environmental Quality defines the threshold for water pollution as a dissolved oxygen content of less than 5 mg per liter (mg/l) of water. The diagram in Figure 11.2 illustrates the effect of BOD on dissolved oxygen content in a stream when raw sewage is introduced as a result of an accidental spill. Three zones are recognized. The *pollution zone* has a high BOD and a reduced dissolved oxygen content as initial decomposition of the waste begins. In the *active decomposition zone*, the dissolved oxygen content is at a minimum owing to biochemical decomposition as the organic waste is transported downstream. In the *recovery zone*, the dissolved oxygen increases and the BOD is reduced because most oxygen-demanding organic waste from the input of sewage has decomposed, and natural stream processes replenish the water with dissolved oxygen. All streams have some capability to degrade organic waste after it enters the stream. Problems result when the stream is overloaded with biochemical oxygen-demanding waste, overpowering the stream's natural cleansing function.

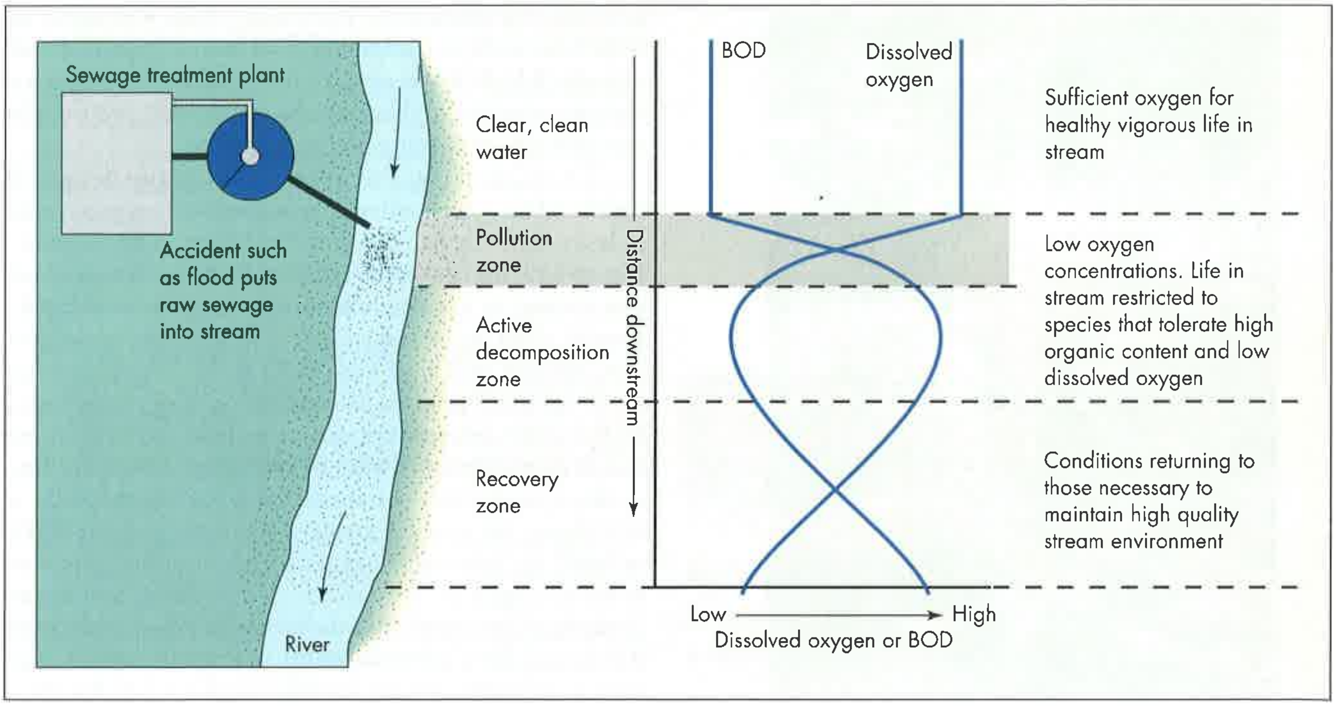
Pathogenic Organisms

Pathogenic (disease-causing) microorganisms are important biological pollutants. Among the major waterborne human diseases are cholera, typhoid infections, hepatitis, and dysentery. Because it is often difficult to monitor the pathogens directly, we use the count of human **fecal coliform bacteria** as a common measure of biological pollution and a standard measure of microbial pollution. These common and usually harmless bacteria are normal constituents of human intestines and are found in all human waste.

All forms of fecal coliform bacteria are not harmless! *E. coli*, a type of fecal coliform bacteria, has been responsible for human illness and deaths in the 1990s. Outbreaks of disease, apparently caused by *E. coli*, occurred from people eating contaminated meat at a popular fast-food restaurant in 1993, and in 1998 *E. coli* apparently contaminated the water in a Georgia water park and a town's water supply in Wyoming, causing illness and one death.

In the past, epidemics of waterborne diseases have killed thousands of people in U.S. cities. Such epidemics have been largely eliminated by separating sewage water and drinking water and treating drinking water prior to consumption. Unfortunately, this is not the case worldwide, and every year several billion people (particularly in poor countries) are exposed to waterborne diseases. For example, as recently as the early 1990s epidemics of cholera occurred in South America. Outbreaks of waterborne diseases are always a threat, even in developed countries.

Perhaps the largest known outbreak of a waterborne disease in the United States took place in 1993. In that year, approximately 400,000 cases of cryptosporidiosis occurred in Milwaukee, Wisconsin. The disease, which causes flu-like



▲ **FIGURE 11.2** Relationship between dissolved oxygen and biochemical oxygen demand (BOD) for a stream following the input of sewage.

symptoms, is carried by a microorganism (a parasite) and can be fatal to people with a depressed immune system, such as AIDS or cancer patients. The parasite is resistant to chlorination, and people in Milwaukee were advised to boil their water during the epidemic. The outbreak was a wake-up call concerning water quality and disease, because many other cities utilizing surface water supplies are just as vulnerable as Milwaukee (1).

The threat of an outbreak of a waterborne disease is accentuated following disasters such as earthquakes, floods, and hurricanes, because these events may damage sewer lines or cause them to overflow, resulting in contamination of water supplies. Following the 1994 Northridge earthquake, people in the San Fernando Valley of the Los Angeles Basin were advised to purify municipal water by boiling.

Nutrients

Nutrients released by human activity may lead to water pollution. Two important nutrients that can cause problems are phosphorus and nitrogen, both of which are released from a variety of materials including fertilizers, detergents, and the products of sewage treatment plants. The concentration of phosphorus and nitrogen in streams is related to land use, as shown in Figure 11.3. Forested land has the lowest concentrations, whereas the highest concentrations are found in agricultural areas—sites of such sources as fertilized farm fields and feedlots (2). Urban areas can also add a lot of phosphorus and nitrogen to local waters, particularly where wastewater treatment plants discharge treated waters into rivers, lakes, or the ocean. These plants are effective in reducing organic pollutants and pathogens, but without advanced treatment nutrients pass through the system.

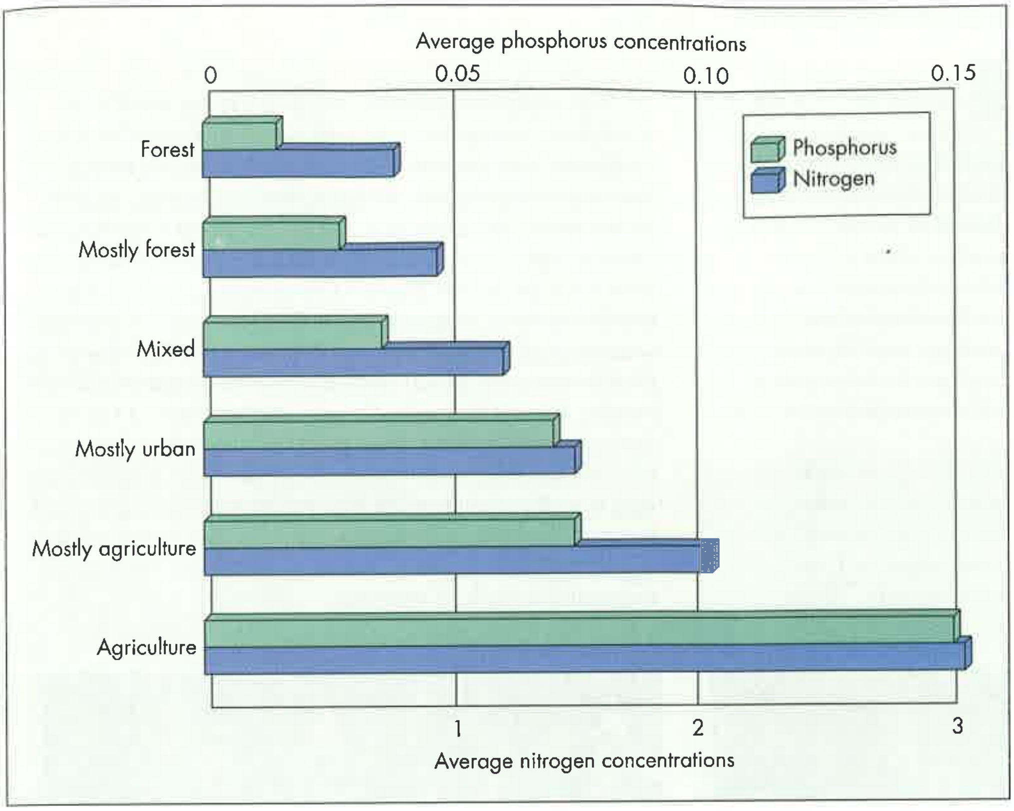
High concentrations of nitrogen and phosphorus in water often result in the process known as **cultural eutrophication.** Eutrophication (from the Greek for "well-fed") is characterized by rapid increase in the abundance of plant life, particularly algae. In freshwater ponds and lakes, blooms of algae form thick mats that sometimes nearly cover the surface of the water, blocking sunlight to plants below, which eventually die. In addition, as the algae decompose, the oxygen content of the water decreases, and fish and aquatic animals may die.

In the marine environment, nutrients in nearshore waters may cause blooms of seaweed (marine algae) that can become a nuisance when the seaweed is torn loose and piles up on beaches. Algae may also damage or kill coral in tropical areas. For example, the island of Maui in the Hawaiian Islands has a cultural eutrophication problem resulting from nutrients entering the nearshore environment from waste disposal practices and agricultural runoff. The inhabitants of the island may be killing the goose that lays the golden egg. Beaches in some areas become fouled with algae that washes up on the shore, where it rots, smells bad, and provides a home for irritating insects, eventually driving away tourists (Figure 11.4). In the water, algae that covers coral may damage or kill it.

Oil

Oil discharged into surface water, usually the ocean, has caused major pollution problems. The largest oil discharges have usually involved oil-tanker accidents at sea (see *Case History: Exxon Valdez*).

Military activity has become another source of pollution of the marine environment by oil. The huge oil spill in the Persian Gulf during the 1991 war released an unknown



◀ **FIGURE 11.3** Relationship between land use and average nitrogen and phosphorus concentration in streams (in milligrams per liter). (*From Council on Environmental Quality*, 1978)

(a)

◀ **FIGURE 11.4** Oceanfront condominium on the island of Maui, Hawaii. Note brown line along edge of beach, which is an accumulation of marine algae (locally called *seaweed*) (a). On the beach itself, the algae piles up sometimes to a depth of about 0.5 m and is avoided by people using the beach (b). Condominium complexes often have small wastewater treatment plants, such as the one shown here, that provide primary and secondary treatment. Following this treatment, the water is injected underground at a relatively shallow depth. The treatment does not remove nutrients such as phosphorus and nitrogen that apparently encourage the accelerated growth of marine algae in the nearshore environment (c). (*Edward A. Keller*)

(b)

(c)

CASE HISTORY Exxon Valdez

Just after midnight on March 24, 1989, the oil tanker *Exxon Valdez* ran aground on Bligh Reef, 40 km south of Valdez, Alaska, in Prince William Sound. Crude oil delivered to Valdez via the Trans-Alaskan Pipeline poured out of the ruptured tanks of the vessel at a rate of approximately 20,000 barrels per hour (Figure 11.A). The *Exxon Valdez* was loaded with 1.2 million barrels of North Slope crude, and of this, more than 250,000 barrels (11 million gallons) gushed from the hold of the 300-m tanker. The oil remaining in the *Exxon Valdez* was loaded into another tanker (3).

Any hope of containment of the oil slick was lost as winds began blowing a few days after the accident, spreading the oil. Of the 11 million gallons of spilled oil, 50 percent was deposited on the shoreline, 20 percent evaporated, and only 14 percent was collected by waste recovery (4).

The oil spilled into what is considered one of the most pristine and ecologically rich marine environments of the world (3, 5), and the accident is now known as the worst oil spill in the history of the United States. Following the spill, the oil spread over a very large area. Figure 11.B, left side, shows the extent of oil sheens, tar balls, and mousse that was suspected to have come from the *Exxon Valdez* as of August 10, 1989. Mousse is a thick, weathered patch of oil with the consistency of a soft pudding that often washes up on beaches. Figure 11.B, right side, compares the area of the spill as of August 10 to the eastern seaboard of the United States. Notice that it would extend from Massachusetts to North Carolina! Many species of fish, birds, and marine mammals are present in Prince William Sound, and the long-term impact of the oil spill on the environment is difficult to ascertain.

(a)

(b)

▲ **FIGURE 11.A** Oil spill from the *Exxon Valdez* in Alaska, 1989. (a) Aerial view of oil being offloaded from the leaking tanker *Exxon Valdez* on the left to the smaller *Exxon Baton Rouge* on the right. Floating oil is clearly visible on the water (*Michelle Barns/Liaison Agency, Inc.*); (b) attempting to clean oil from the coastal environment by scrubbing and spraying with hot water. (*I. L. Atlan/Sygma*)

volume of oil into a fragile environment. It may be the world's largest spill, and it is certainly the largest deliberate spill.

Oil spills on land can also lead to serious environmental problems if pipelines rupture, as happened in the fall of 1994 in northern Russia. That event allowed an unknown but very large volume (estimates range from 4 million to 80 million gallons) of crude oil to pollute land and water resources. This brings up an important point: Pipelines 25 to 30 years old are more vulnerable to fatigue and corrosion than are new pipelines. Periodic monitoring of aging systems and repair or replacement of worn-out pipelines should be a priority in minimizing the occurrence of leaks.

Toxic Substances

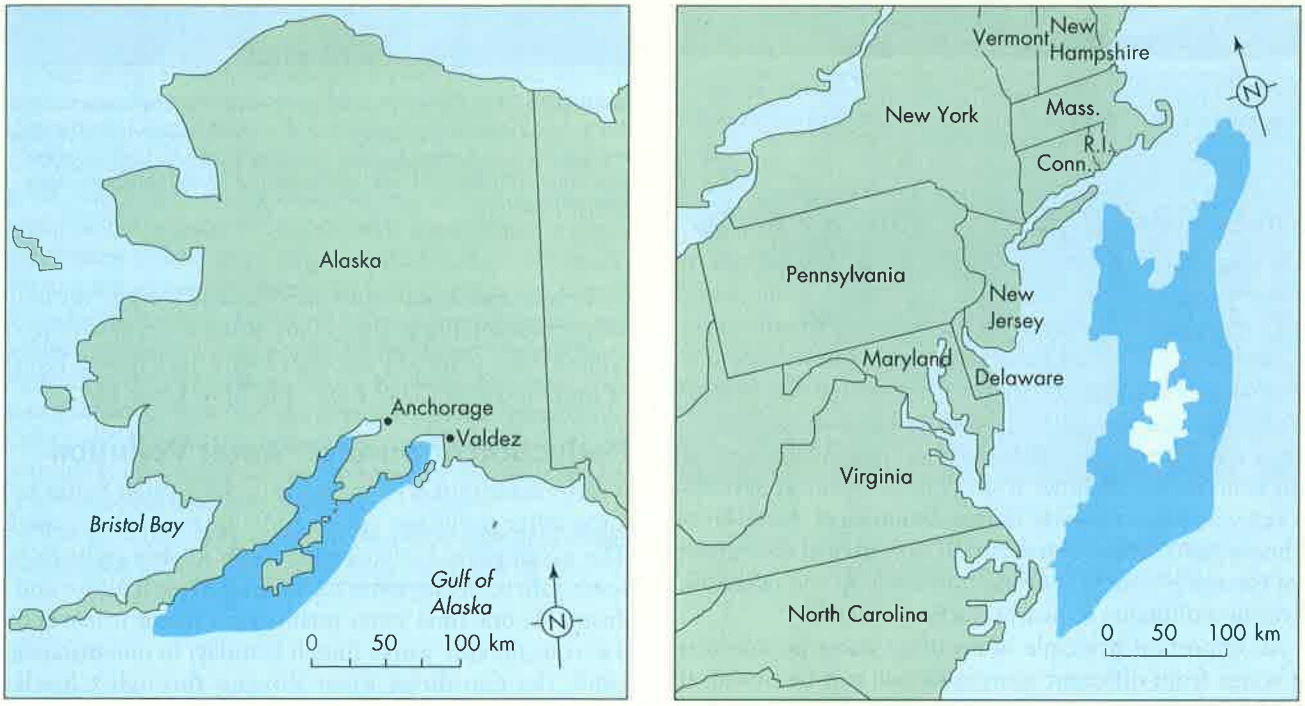
Many substances that enter surface- and groundwater are toxic to organisms. We will mention three general categories of toxic substances here and discuss them in detail in Chapters 12 and 13:

Hazardous chemicals are synthetic organic and inorganic compounds that are toxic to humans and other living things. When these materials are accidentally introduced into surface or subsurface waters, serious pollution may result. The complex problem of hazardous chemicals and their management is discussed in Chapter 12 ("Waste Management").

Heavy metals such as lead, mercury, zinc, and cadmium are dangerous pollutants and are often deposited with natural sediment in the bottoms of stream channels. If these metals are deposited on floodplains, they may become incorporated into plants, including food crops, and animals. If they are dissolved and the water is withdrawn for agriculture or human use, heavy-metal poisoning can result. Heavy metals are discussed in detail in Chapter 13 ("The Geologic Aspects of Environmental Health").

Radioactive materials in water may be dangerous pollutants. Of particular concern are possible effects to people, other animals, and plants of long-term exposure to low

Soon after the accident, the governor of Alaska declared Prince William Sound a disaster area and applied for federal assistance. Cleanup work on the coastline posed enormous problems to workers attempting the project. Photographs and videotapes of the work suggest an almost futile attempt to clean individual pebbles on beaches. The spill completely disrupted the lives of those who work in the vicinity of Prince William Sound, and only after the passage of time will its impacts be fully understood. Certainly the short-term effects were very significant indeed. These included the death of 100,000–645,000 seabirds, 28 percent of the sea otters, and 13 percent of the harbor seals in the Sound (4,5), as well as disruption of the commercial fisheries, sport fisheries, and tourism. Interruption of the flow of North Slope crude resulted in an almost immediate increase in the price of oil to the lower 48 states. Lessons learned from the *Exxon Valdez* spill have resulted in better management strategies for both the shipment of crude oil and the emergency plans to minimize environmental degradation.



▲ **FIGURE 11.B** (left) Extent of Alaskan oil spill of 1989. (right) Area of 1989 Alaskan oil spill compared to the eastern coast of the United States. (*From* Alaska Fish and Game, *July–August* 1989)

doses of radioactivity. Chapters 12 and 13 discuss radiation in terms of waste disposal and environmental effects.

Sediments

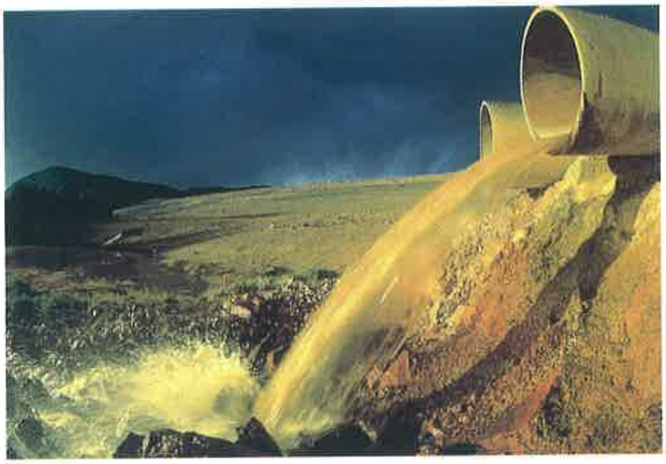
Sediment consists of rock and mineral fragments ranging in size from sand particles less than 2 mm in diameter to silt, clay, and even finer colloidal particles. Our greatest water pollutant by volume, sediment, is a resource out of place. It depletes a land resource (soil), reduces the quality of the water resource it enters, and may deposit sterile materials on productive croplands or other useful land. Sediment pollution is discussed in detail in Chapter 3.

Thermal Pollution

Thermal pollution is the artificial heating of waters, primarily by hot-water emission from industrial operations and power plants. Heated water causes several problems. Even water only a few degrees warmer than the surrounding water holds less oxygen. Warmer water favors different species than does cooler water and may increase growth rates of undesirable organisms, including certain water plants and fish. On the other hand, the warm water may attract and allow better survival of certain desirable fish species, particularly during the winter.

11.3 Surface-Water Pollution and Treatment

Pollution of surface waters occurs when too much of an undesirable or harmful substance flows into a body of water, exceeding the natural ability of that ecosystem to utilize or remove the pollutant or convert it to a harmless form. Water pollutants are emitted from point (localized) sources or nonpoint (diffuse) sources.



▲ **FIGURE 11.5** Pipe discharging partially treated effluent from the Climax Molybdenum Mine in Colorado. (*Jim Richardson/Richardson Photography*)

▲ **FIGURE 11.6** Sediment is being removed here by heavy equipment (background) following the 1995 flood in Goleta, California. The sediment came from a nearby stream that overflowed its bank and deposited all this sediment at a new car dealership. (*Rafael Maldonado/Santa Barbara News-Press*)

Point Sources of Surface-Water Pollution

Point sources are discrete and confined, such as pipes that empty into streams or rivers from industrial or municipal sites (Figure 11.5). In general, point-source pollutants from industries are controlled through on-site treatment or disposal and are regulated by permit. Municipal point sources are also regulated by permit. In older cities in the northeastern and Great Lakes areas of the United States, most point sources are outflows from combined sewer systems that carry both storm-water flow and municipal waste. During heavy rains, urban storm runoff may exceed the capacity of the sewer system, causing it to back up and overflow, delivering pollutants to nearby surface waters.

An important principle of avoiding water pollution is that water from different sources should not be mixed; it should remain separated according to the intended use. For example, agricultural runoff containing pollutants such as nitrates and pesticides should be kept from entering water intended for urban consumption. This is a primary problem for large water delivery systems (as, for example, in California) that supply several different users requiring different water quality.

Nonpoint Sources of Surface-Water Pollution

Nonpoint sources are diffused and intermittent; they are influenced by such factors as land use, climate, hydrology, topography, native vegetation, and geology. Pollution from nonpoint sources, or *polluted runoff,* is difficult to control. Common urban nonpoint sources include urban runoff from streets or fields containing all sorts of pollutants, including heavy metals, chemicals, and sediment (Figure 11.6). When you wash your car in your driveway and the detergent and oil on the surface run down a storm drain that enters a stream, you are contributing to polluted runoff. Polluted runoff is also produced when rainwater washes insecticides from the plants in your garden, then runs off into a stream or infiltrates the surface to contaminate groundwater. Similarly, rain and runoff from factories and storage yards are a source of nonpoint pollution (6). Rural sources of nonpoint pollution are generally associated with agriculture, forestry, or mining (see *A Closer Look: Acid Mine Drainage*).

Reduction of Surface-Water Pollution

A serious attempt is being made in the United States to reduce water pollution and thereby increase water quality. The assumption is that people have a basic right to have water safe to drink, swim in, and use in agriculture and industry. At one time water quality near major urban centers was considerably worse than it is today; in one instance, in 1969, the Cuyahoga River flowing through Cleveland, Ohio, was inadvertently set on fire. The fire was an environmental shock to the city and state, which responded by passing laws to reduce discharge of pollutants into the river. Today the river is much cleaner and is being used for recreational purposes (7).

In recent years the number of success stories, including the Cuyahoga, has been very encouraging. Perhaps the best-known case is the Detroit River. In the 1950s and the early 1960s the Detroit River was considered dead, having been an open dump for sewage, chemicals, garbage, and urban trash. Tons of phosphorus were discharged daily into the river, and a film of oil up to 0.5 cm thick was often present. Aquatic life was damaged considerably, and thousands of ducks and fish were killed. Although today the Detroit River is not a pristine stream, considerable improvement has resulted from industrial and municipal pollution control. Oil and grease emissions were reduced by 82 percent, and phosphorus and sewage discharges have also been greatly diminished. Fish once again are found in the Detroit River, and the shoreline is usually clean. Other success stories include New York's Hudson River (see *Case History: Cleaning Up the Hudson*), New Hampshire's Pemigewasset River, North Carolina's French Broad River, and the Sa-

A CLOSER LOOK Acid Mine Drainage

Acid mine drainage does not refer to an acid mine, but to acidic water that drains from mines. Specifically, **acid mine drainage** is water with a high concentration of sulfuric acid (H_2SO_4) that drains from some mining areas to pollute surface-water resources. The acid is produced by a simple weathering reaction: When sulfide minerals associated with coal or a metal (zinc, lead, or copper) come into contact with oxygen-rich water near the surface, the sulfide mineral oxidizes. For example, pyrite (FeS_2) is a common sulfide often associated with coal, and when pyrite oxidizes in the presence of water, sulfuric acid is formed. The sources for the water may be surface water that infiltrates into mines or shallow groundwater that moves through mines. Similarly, surface and shallow groundwaters that come into contact with mining waste (tailings) also may react with sulfide minerals found there to form acid-rich waters.

When waters with a high concentration of sulfuric acid migrate away from a mining area, they may pollute surface and groundwater resources. If the acid-rich water runs into a natural stream or lake, significant ecological damage can result, because the acid water is extremely toxic to plants and animals in aquatic ecosystems. Acid mine drainage is a significant water pollution problem in many areas of the United States, including parts of Wyoming, Illinois, Indiana, Kentucky, Tennessee, Missouri, Kansas, Oklahoma, West Virginia, Maryland, Pennsylvania, Ohio, and Colorado. The total impact associated with acid mine drainage is very significant because thousands of kilometers of streams have been polluted (Figure 11.C).

The Tar Creek area of Oklahoma was at one time designated as the nation's worst hazardous waste site by the U.S. Environmental Protection Agency (EPA). The creeks in the area were severely polluted by acid-rich water from abandoned mines of the Tri-State Mining District of Arkansas, Oklahoma, and Missouri. Sulfide deposits containing both lead and zinc were first mined in the late nineteenth century, and mining ended in some areas in the 1960s. During operation of the mines, subsurface areas were kept dry by pumping out groundwater that was constantly seeping in. After mining ceased, the groundwater table naturally rose again, and some mines flooded and overflowed into nearby streams, polluting them.

▲ **FIGURE 11.C** Water seeping from this Colorado mine is an example of acid mine drainage. The water is also contaminated by heavy metals. *(Tim Haske/Profiles West/Index Stock Imagery, Inc.)*

vannah River in the southeastern United States. These examples are evidence that water pollution abatement has positive results (8).

An innovative system that uses naturally occurring earth materials to purify water for public consumption is reported from a Michigan community on the Lake Michigan shore. The city of Ludington, with a summer population exceeding 10,000, uses sands and gravels below the lake bottom to prefilter and thus treat the lake water for municipal use. A system of lateral intakes is buried in sand and gravel 4 to 5 m below the lake bottom, where the water depth is at least 5 m. The water is pumped out for municipal use, and in some cases the only additional treatment is chlorination. We will say more about the ability of rock and soil to filter out impurities in the discussion of groundwater pollution.

11.4 Groundwater Pollution and Treatment

Approximately one-half of all people in the United States today depend on groundwater as their source of drinking water. We are therefore concerned about the introduction into aquifers of chemical elements, compounds, and microorganisms that do not occur there naturally. The hazard presented by a particular groundwater pollutant depends upon several factors, including the volume of pollutant discharged, the concentration or toxicity of the pollutant in the environment, and the degree of exposure to people or other organisms (12).

Most of us have long believed that groundwater is pure and safe to drink, so many of us find it alarming to learn that it may be easily polluted by any one of several sources (see Table 11.1). In addition, the pollutants, even the very toxic ones, may be difficult to recognize. One of the best-known examples of groundwater pollution is the Love Canal near Niagara Falls, New York, where burial of chemical waste has caused serious water pollution and health problems, which we will discuss in Chapter 12.

Unfortunately, Love Canal is not an isolated case. Hazardous chemicals have been found or are suspected to be in groundwater supplies in nearly all parts of the world, developed and developing nations alike. Developed industrial countries produce thousands of chemicals; many of these, particularly pesticides, are exported to developing countries, where they protect crops that eventually are imported by the same industrial countries, completing a circle.

CASE HISTORY Cleaning Up the Hudson

The Hudson River assessment and cleanup of PCBs (polychlorinated biphenyls) is a good example of people's determination to clean up our rivers. The PCBs, which have a chemical structure similar to DDT and dioxin, were used mainly in electrical capacitors and transformers; discharge of the chemicals from two outfalls on the Hudson River started about 1950 and terminated in 1977. Approximately 295,000 kg of PCBs are believed to be present in Hudson River sediments. Concentrations in the sediment are as high as 1500 parts per million (ppm) near the outfalls, compared to *less* than 10 ppm several hundred kilometers downstream at New York City (9, 10). An important source of PCBs in the New York metropolitan area has been sewage effluent and urban runoff. These have delivered up to about half of the PCB load to the Hudson–New York harbor in recent years (11). The U.S. Food and Drug Administration (FDA) permits less than 2.5 ppm PCBs in dairy products, whereas the New York State limit for drinking water is 0.1 part per billion (ppb).

It is known that PCBs are carcinogenic and can cause disturbances of the liver, nervous system, blood, and immune response system in humans. Furthermore, PCBs are nearly indestructible in the natural environment and become concentrated in the higher rungs of the food chain—thus the concern! Water samples in the 240-km tidal reach of the Hudson River have yielded average PCB concentrations ranging from 0.1 to 0.4 ppb, but PCBs are concentrated to much higher levels in some fish. As a result, fishermen on the lower Hudson have suffered a significant economic impact from the contamination because nearly all commercial fishing was banned, and sport fishing was greatly reduced (9,10).

Cleanup of the Hudson River has considered two alternatives (10,11).

- Dredging "hot spots" where concentrations of PCBs are greater than 50 ppm. It is anticipated that dreging would reduce the time necessary for the river to clean itself up by natural processes, such as sediment transport to the ocean; burial of the most contaminated sediments by river processes; and biogeochemical dechlorination by organisms in the sediment of the river bed.
- No action. This alternative would allow natural processes to clean up the PCBs. This assumes that sources of input of the chemicals have been greatly reduced.

The no-action alternative, perhaps by default because there has been continued postponement of removal by dredging in the upper Hudson River, is what is happening. Natural cleansing is occurring and the concentrations of PCBs on sediment particles transported downstream in the river were several times lower in the mid-1980s compared to the mid-1970s. Half-life response times in the Hudson River system (that is, the time for the concentration of PCB on the sediment to be reduced by one-half) is about 3.5 years. Inputs of PCBs have been greatly reduced due to EPA restrictions on manufacture of the chemicals (11).

For example, Costa Rica imports several pesticides, including DDT, aldrin, endrin, and chlordane, that are banned or heavily restricted in the United States. Thus, these chemicals are polluting the surface and groundwater of Costa Rica and other places where they are still being used, and residual concentrations of some of them are returned to us on crops we import (13).

In the United States today, the problem of groundwater pollution is becoming more apparent as testing of water becomes more common. For example, Atlantic City, New Jersey, and Miami, Florida, are two eastern cities threatened by polluted groundwater that is slowly migrating toward municipal wells. It is estimated that 75 percent of the 175,000 known waste disposal sites in the country may be producing **plumes** (body of earth material above and/or below the water table contaminated by a water pollutant) of hazardous chemicals that are migrating into and polluting groundwater resources. Because many of the chemicals are toxic or suspected carcinogens, it appears we have been conducting a large-scale experiment on the effects of chronic low-level exposure of people to potentially harmful chemicals. Unfortunately, the final results of the experiment will not be known for many years (14). Preliminary results suggest we had better act now before a hidden time bomb of health problems explodes.

Comparison of Groundwater and Surface-Water Pollution

Differences in the physical, geologic, and biologic environments make the problems associated with groundwater pollution significantly different from those of surface-water pollution. In the case of surface-water pollution, the rapidity of the flow results in rapid dilution and dispersion of pollutants, and the availability of oxygen and sunlight contributes to their rapid degradation. The situation is markedly different for groundwater, where the opportunity for dilution and dispersion of pollutants is limited and opportunity for bacterial degradation of pollutants is generally confined to the soil a few meters or so below the surface. The channels through which groundwater moves are often very small and variable, so the rate of movement is quite slow, except in some large solution channels within limestones. Furthermore, the lack of oxygen in groundwater kills the aerobic (oxygen-requiring) microorganisms that help degrade pollutants but may provide a happy home for anaerobic varieties that live in oxygen-deficient environments.

The often long residence time for groundwaters (hundreds to thousands of years) reflects the deep, insulated type of storage that aquifers provide. Not all groundwater takes hundreds of years to rejoin the other, more rapidly moving parts of the hydrologic cycle, but most of it is well below the influence of transpiration by plants and evaporation into the atmosphere. Where it is not that deep, it is most susceptible to evapotranspiration, discharge to streams, and use or abuse by humans. The latter is of increasing concern because of the potential long-term damage to this resource, the high cost of cleaning up polluted groundwater, and the increasing need to use it as per capita water use increases.

Exchanges Between Groundwater and Its Surroundings

The soil, sediment, and rocks through which groundwater passes may act as natural filters. The water may actually exchange materials with the soil and rock. Under the right conditions, this filtering system cleanses the water, trapping and biodegrading disease-causing microorganisms and particulates that contain toxic compounds. However, if the soil or rock surface is already highly contaminated or contains naturally occurring toxic elements such as arsenic, the natural exchange processes may make the water toxic.

An interesting example with serious environmental implications comes from the western San Joaquin Valley in California, where selenium, a very toxic heavy metal present in the soil, is released by application of irrigation waters. Subsurface drainage of the selenium-rich water from fields has entered the surface waters and has caused birth defects in waterfowl. The extent of the general problem related to agriculture drainage water is only now being learned. Selenium is also toxic to people. Like many trace metals, selenium has a dual character: It is necessary for life processes at trace concentrations, but it is toxic at some higher concentrations. The environmental impact of the selenium problem is discussed in Chapter 18.

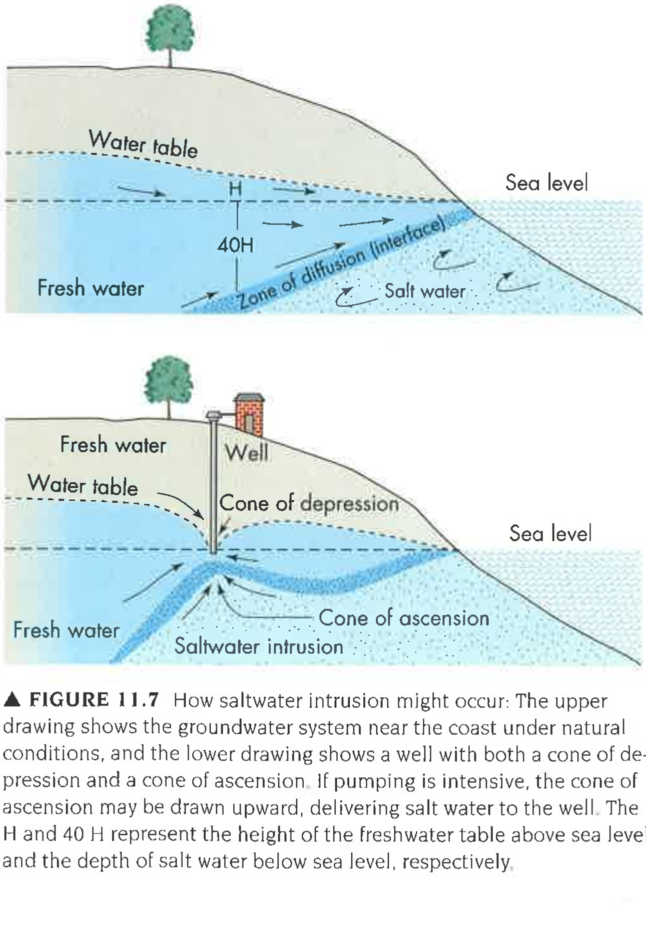
Groundwaters moving through rock and soil dissolve a mixture of minerals and some gases that can be nuisances to some human uses. Some examples are iron as ferrous hydroxide, which colors the water brown and leaves a brown discoloration on laundry and plumbing fixtures; calcium, which creates in part the so-called hardness of water; and hydrogen sulfide, which produces a "rotten egg" odor.

The ability of most soils and rocks to filter out solids, including pollution solids, by physical means is well recognized. This ability varies with different sizes, shapes, and arrangements of filtering particles, as evidenced in the use of selected sands and other materials in water filtration plants. Also known, but perhaps not so generally, is the ability of clays and other selected minerals to capture and exchange some elements and compounds when they are dissociated in solutions as positively or negatively charged elements or compounds. Such exchanges, along with sorption and precipitation processes, are important in the capture of pollutants. These processes, however, have definable units of capacity and are reversible. They also can be overlooked easily in designing facilities to correct pollution problems by relying on soils and rocks of the geologic environment for treatment. This oversight, which can result in possible groundwater pollution, is especially significant in land application of wastewaters.

Salt Water Intrusion

Aquifer pollution is not solely the result of disposal of wastes on the land surface or in the ground. Overpumping or mining of groundwater so that inferior waters migrate from adjacent aquifers or the sea can also cause contamination problems. Hence, human use of public or private water supplies can accidentally result in aquifer pollution. Intrusion of salt water into freshwater supplies has caused problems in coastal areas of New York, Florida, and California, among other areas (including many islands) (see *Case History: The Threatened Groundwater of Long Island*).

Figure 11.7 illustrates the general principle of saltwater intrusion. The groundwater table generally is inclined toward the ocean, while a wedge of salt water is inclined toward the land. Thus, with no confining layers, salt water near the coast may be encountered at depth. Because fresh water is slightly less dense than salt water (1.000 compared to 1.025 g/cm^3), a column of fresh water 41 cm high is needed to balance 40 cm of salt water. A more general relationship is that the depth to salt water below sea level is 40 times the height (H in Figure 11.7) of the water table above sea level. When wells are drilled, a cone of depression develops in the freshwater table, which may allow intrusion of salt water as the interface between fresh and salt water rises (forming a core of ascension) in response to the loss of freshwater mass.



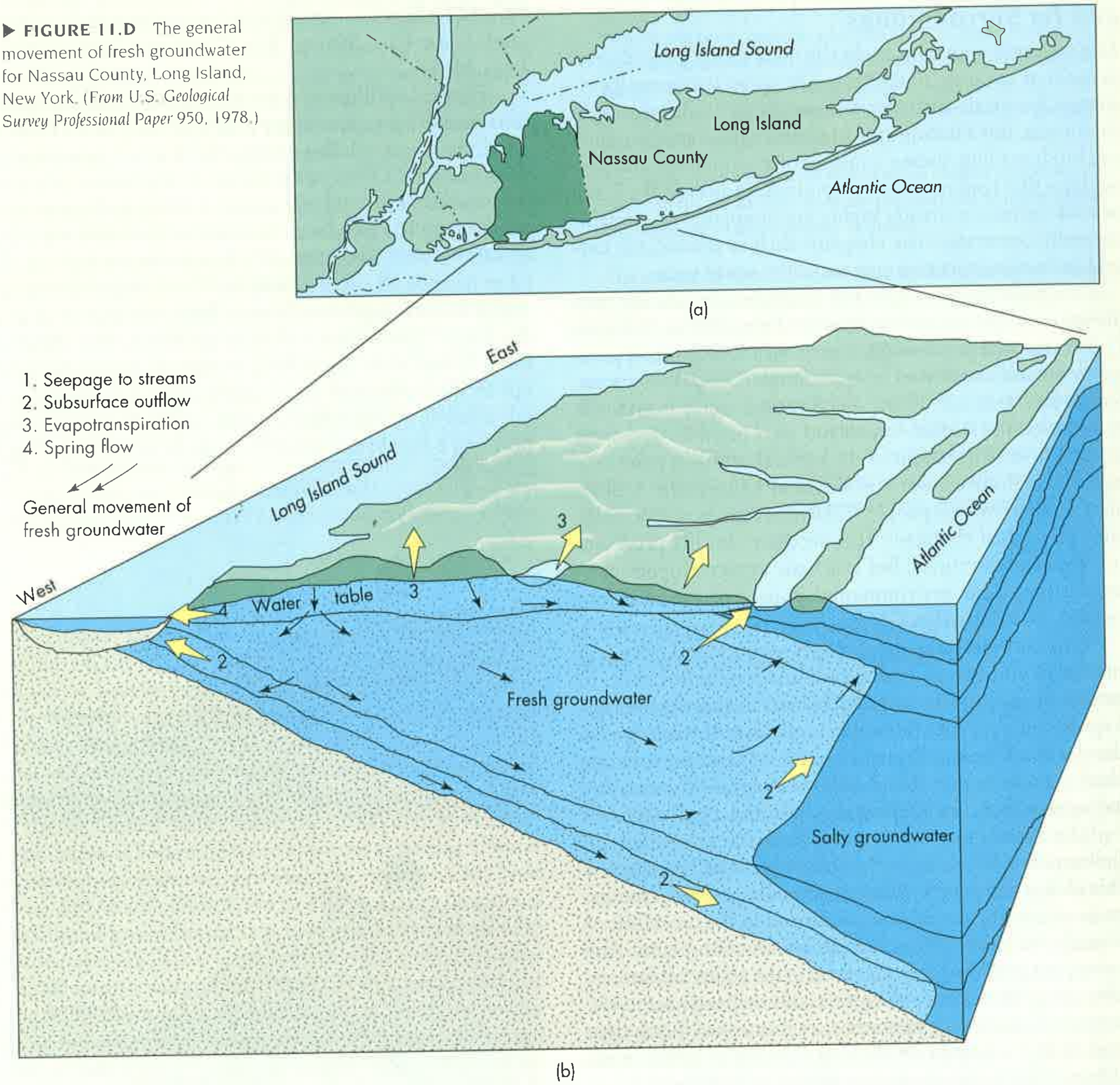
▲ **FIGURE 11.7** How saltwater intrusion might occur: The upper drawing shows the groundwater system near the coast under natural conditions, and the lower drawing shows a well with both a cone of depression and a cone of ascension. If pumping is intensive, the cone of ascension may be drawn upward, delivering salt water to the well. The H and 40 H represent the height of the freshwater table above sea level and the depth of salt water below sea level, respectively.

CASE HISTORY The Threatened Groundwater of Long Island

Long Island, New York, provides a good example of an area with groundwater problems. Two counties on the island, Nassau and Suffolk, with a population of several million people, are entirely dependent on groundwater for their water supply. In terms of the total volume of water and number of people who use it, the groundwater resource for Long Island is one of the world's largest, but it is threatened by two major problems, intrusion of salt water and shallow-aquifer contamination, particularly in Nassau County (15).

Figure 11.D shows the general movement of groundwater under natural conditions for Nassau County. Salty groundwater is restricted from inland migration by the large wedge of

▶ **FIGURE 11.D** The general movement of fresh groundwater for Nassau County, Long Island, New York. (From U.S. *Geological Survey Professional Paper* 950, 1978.)



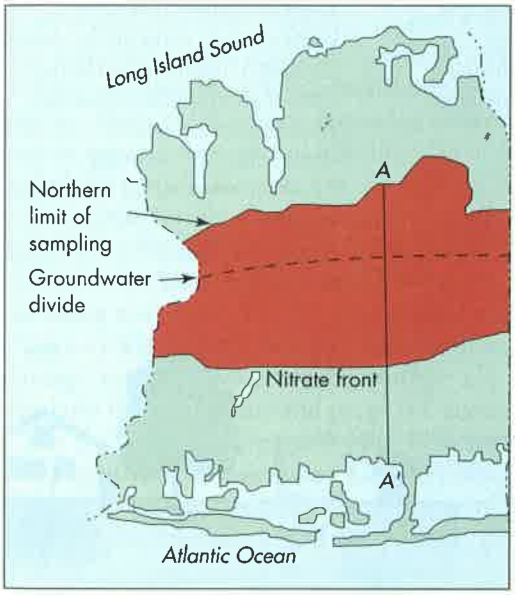
Groundwater Treatment

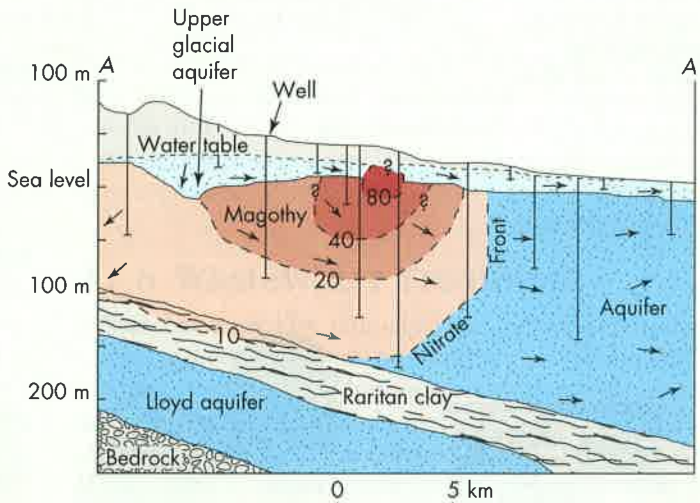
In view of the difficulty of detecting groundwater pollution, the long-term residency of groundwater, the degradation of the polluted aquifer, and the difficulty and expense of aquifer recovery, a strong argument can be made that no wastes or possible pollutants should be allowed to enter any part of the groundwater system. This is an impossible dream. Rather, the response to groundwater pollution must be to learn more about how natural processes treat wastes, so that when soil and rocks cannot treat, store, or recycle wastes, we can develop processes to make the pollutants treatable, storable, or recyclable.

Correction of aquifer and vadose zone contamination is not impossible, though it may be a complex and expensive fresh water moving beneath the island. Groundwater resources of Nassau County are in two main aquifers, as shown in Figures 11.D and 11.E. The upper aquifer is composed of young glacial deposits that yield large amounts of water at depths of less than 30 m. Below the glacial deposits are older marine sedimentary rocks consisting of interbedded sands, clays, and silts (the Magothy Aquifer). Most of the fresh water in Nassau County is pumped from this lower aquifer, from sandy beds at depths below 30 m. Most of the water-bearing sands are confined by overlying clay and silt beds of low permeability. That is, the aquifer is composed of alternating and discontinuous layers of sand and finer-grained silt and clay. Because of the confining layers in the aquifer the water is under artesian pressure, which causes it to rise to within 15 m of the surface in wells.

Despite the huge quantities of water in Nassau County's groundwater system, intensive pumping in recent years has caused water levels to decline as much as 15 m in some areas. As groundwater is removed near coastal areas, the subsurface outflow to the ocean decreases, allowing salt water to migrate inland. Saltwater intrusion in the deep aquifer has occurred in Nassau County. The mechanism of salt intrusion is more complex than the idealized mechanism shown in Figure 11.7. As fresh water from sandy beds in the deep aquifer is intensely pumped, salt water is drawn inland as a series of narrow wedges. Although the problem of saltwater intrusion is not yet widespread, the saltwater front is being carefully monitored as part of a comprehensive management program.

The most serious groundwater problem on Long Island is shallow-aquifer pollution associated with urbanization. Sources of pollution in Nassau County include urban runoff, household sewage from cesspools and septic tanks, salt used to deice highways, and industrial and solid waste. These pollutants enter surface waters and then migrate downward, especially in areas of intensive pumping and declining groundwater levels. Figure 11.E shows the extent of high concentration of dissolved nitrate in deep groundwater zones. The greatest concentrations are located beneath densely populated urban zones, where water levels have dramatically declined and where nitrates from such sources as cesspools, septic tanks, and fertilizers are routinely introduced into the hydrologic environment (15). Landfills, sites where urban waste are buried, have been of particular concern because urban waste (garbage) often contains many pollutants. When landfills are located on sandy (permeable) soil over a shallow aquifer, groundwater pollution is inevitable. As a result, most landfills on Long Island have been closed.





▲ **FIGURE 11.E** Extent of high concentration of dissolved nitrate in groundwater zone, Nassau County, Long Island, New York. The greatest concentrations are located beneath densely populated urban zones, where water levels have dramatically declined and nitrates are more abundant because of urban waste disposal and horticulture practices. Contours shown in milligrams per liter of dissolved nitrate. (From U.S. *Geological Survey Professional Paper* 950, 1978)

problem requiring careful evaluation and treatment. Important steps involved in correcting a groundwater pollution problem are:

- **Characterizing the geology.** This is particularly important because features such as more permeable buried channels, soil macropores, and geologic structures such as fractured, folded, and faulted rocks may be the dominant factors controlling the direction of groundwater flow.
- **Characterizing the hydrology.** Factors such as depth to groundwater, direction of flow, and rate of flow must be determined. Characterizing the hydrology

also involves identifying relationships between surface water and groundwater processes affecting the site.

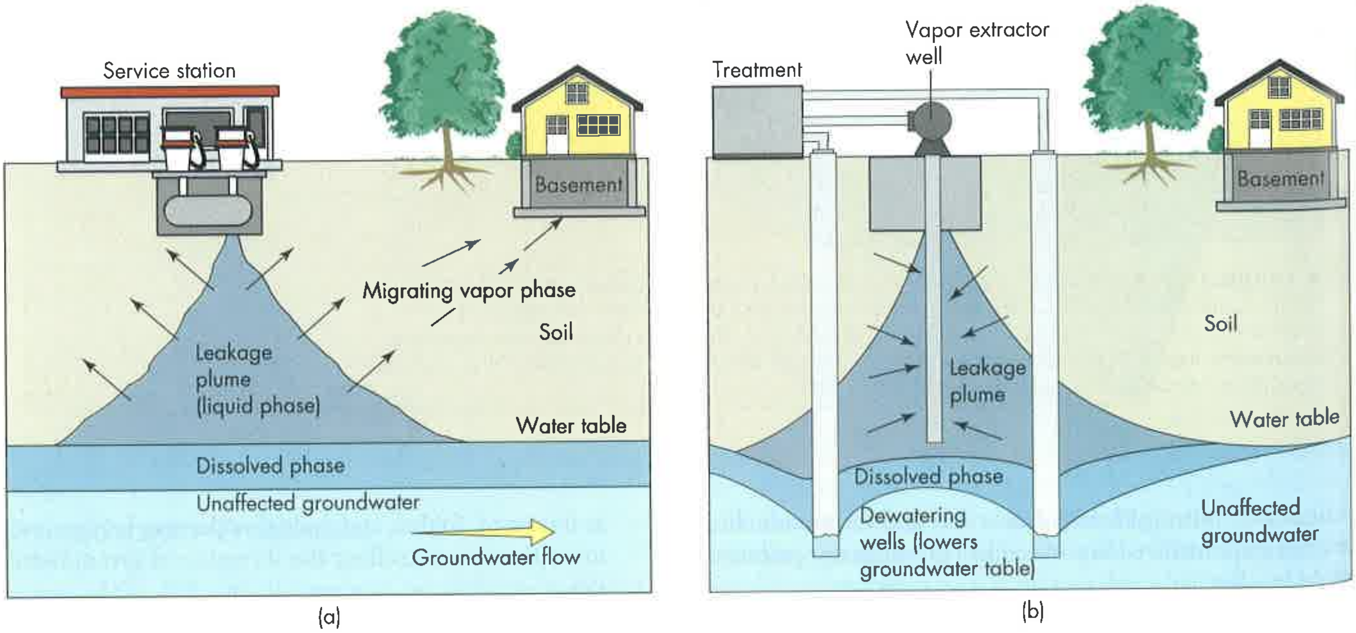
- **Identifying the contaminants and their transport processes.** Contaminants are identified through careful site evaluation and gathering of samples. Some contaminants, such as gasoline, are floaters; that is, most of the gasoline will be found on top of the water table because it is lighter than water. However, some components in gasoline are soluble in water, so there will also be a dissolved phase below the water table. On the other hand, contaminants such as trichloroethylene (TCE), which is a dry-cleaning solvent that is heavier than water, will sink rather than float. Other pollutants, such as some salts, are very soluble in water and will move with the general flow of the groundwater environment.
- **Initiating the treatment process.** Table 11.2 briefly outlines some of the methods for treating groundwater and vadose zone water. The specific treatment selected depends upon variables such as type of contaminant, method of transport, and characteristics of the local environment, such as depth to water table and geologic characteristics.

As an example of groundwater treatment, consider Figure 11.8. Figure 11.8a shows a site with a service station and underground-gasoline tank that is leaking. Most of the contaminant is floating on top of the water table, but some is also dissolved and moves with the groundwater. The direction of the migrating vapor phase is away from the leakage plume. Figure 11.8b shows the same location after a system consisting of dewatering wells and a vapor extractor well has been installed. The dewatering wells lower the groundwater table locally, and the vapor extraction well, which uses a vacuum pump, collects the contaminant in a vapor phase, where it may be treated.

Underground gasoline tanks that leak are a very common phenomena in today's urban environment. In recent years regulation of underground tanks has been tightened. It

Table 11.2 Methods of treating groundwater and vadose zone water

Extraction Wells	Vapor Extraction	Bioremediation	Permeable Treatment Bed
Pump out contaminated water and treat it by filtration, oxidation, or air stripping (volatilization of contaminant in an air column), or by biological processes.	Uses vapor extraction well and then treatment.	Injection of nutrients and oxygen to encourage growth of organisms that degrade the contaminant in the groundwater.	Provides contact treatment as contaminated water plume moves through a treatment bed in the path of groundwater movement. Encourages neutralization of the contaminant by chemical, physical, or biological processes.



▲ **FIGURE 11.8** Idealized diagram of a leaking buried tank (a) and possible remediation method (b). See text for explanation. (*Courtesy of University of California–Santa Barbara Vadose Zone Laboratory and David Springer.*)

is not uncommon to see drill rigs testing gasoline station sites and to notice later that the tanks have been excavated and treatment for leaking gasoline has begun. In a particular pollution case it may be difficult to show where a contaminant such as gasoline has come from. At many intersections there may be two or more gasoline stations that have had a series of buried tanks over a long period of time. Litigation over responsibilities concerning groundwater pollution from leaking underground tanks may be difficult to resolve.

11.5 Water Quality Standards

A question people commonly ask is: How safe is our water supply? Americans are used to believing that their drinking water is of high quality, some of the best in the world. For the most part this is true, but in recent years we have gained an ability to detect specific contaminants in parts per billion (ppb) of water, or in some cases even parts per trillion (ppt). The question that then arises is: How dangerous might some of these chemicals be? You may think that such small amounts of contaminants cannot possibly be dangerous, but as the U.S. Environmental Protection Agency (EPA) reminds us, a single microscopic virus can cause a disease. Physicians are able to delineate fairly clearly what diseases are caused by particular "bugs," but we are less sure about the effects of long-term exposure to very small amounts of chemicals.

In response to this concern, Congress has mandated the EPA to establish minimum national drinking water standards for a variety of chemicals and other materials. In 1986 Congress expanded the Safe Drinking Water Act of 1974 to include 83 contaminants, for 26 of which the EPA had already set **Maximum Contaminant Levels (MCLs).** Among other regulations, the new legislation banned the use of lead in the installation or repair of water systems used for drinking water. Health effects associated with lead toxicity are very well known. At high concentrations, lead causes damage to the nervous system and the kidneys and is particularly toxic to infants and pregnant women (16).

The EPA was also required by the 1986 amendment to issue **Maximum Contaminant Level Goals (MCLGs)** along with an MCL. The MCLGs, which were recognized as an unenforceable health goal, were set at the maximum level at which a particular contaminant was not expected to cause adverse health effects over a lifetime of exposure. By law MCLs must be set as close to the MCLG as economics and technology allow (16).

The EPA has set standards for a number of contaminants that might possibly be found in our drinking water. However, only two substances for which these standards have been set are thought to pose an immediate health threat when standards are exceeded. These are (16):

- **Coliform bacteria**—because they may indicate that the water is contaminated by harmful disease-causing organisms.
- **Nitrate**—because contamination above the standard is an immediate threat to young children. In youngsters under a year old, high levels of nitrate may react with their blood to produce an anemic condition known as "blue baby."

Table 11.3 is an abbreviated list enumerating some of the contaminants covered by the National Primary Drinking Water Standards. A complete list can be obtained from the U.S. Environmental Protection Agency. The purpose of the standards and regulations concerning drinking water are (16):

- To ensure that our water supply is treated to remove harmful contaminants.
- To regularly test and monitor the quality of our water supply.
- To provide information to citizens so that they are better informed concerning the quality and testing of their water supply.

How are we doing in the effort to reduce water pollution and improve water quality in the United States? Regulation of toxic chemicals in our water supply has only been going on for a few decades, but there has been progress. Figure 11.9 shows trends in water quality from 1970 to 1989, based on data collected from the U.S. Fish and Wildlife Service monitoring stations. These data suggest that concentrations of selected toxic metals and toxic organic compounds (in fish tissue) have been significantly reduced. Organic compounds such as DDT and PCBs that have been regulated the longest show the greatest decrease. On the other hand, new organic chemicals found in herbicides are present in some areas in concentrations that exceed established health limits (1).

11.6 Wastewater Treatment

Water that is used for municipal and industrial purposes is often degraded during use by a variety of contaminants, including oxygen-demanding materials, bacteria, nutrients, salts, suspended solids, and a variety of other chemicals. In the United States our laws dictate that these contaminated waters must be treated before they are released back into the environment. The annual cost for such treatment is approximately \$20 billion, and will increase during the next decade. Because so much money is involved, wastewater treatment is big business. In rural areas the conventional method of treatment is by way of septic-tank disposal systems. In larger communities, wastewaters are generally collected and centralized in water-treatment plants that collect the wastewater from a sewer system.

In many parts of the country, water resources are being stressed, and as a result innovative systems are being developed to reclaim wastewaters so that they can be used for such purposes as irrigating fields, parks, or golf courses, rather than being discharged into the nearest body of water. New technologies are also being developed for treating wastewaters not as a waste but as a resource to be used. Those developing the new technologies say that sewage

Table 11.3 National Primary Drinking Water Standards: Some examples

Contaminant	Maximum Contaminant Level (mg/l)	Comments/Problems
Inorganics		
Arsenic	0.05	Highly toxic
Cadmium	0.01	Kidney
Lead	0.015[a]	Highly toxic
Mercury	0.002	Kidney, nervous system
Selenium	0.01	Nervous system
Asbestos	7 MFL[b]	Benign tumors
Fluoride	4	Skeletal damage
Organic chemicals		
Pesticides		
Endrin	0.0002	Nervous system, kidney
Lindane	0.004	Nervous system, kidney, liver
Methoxychlor	0.1	Nervous system, kidney, liver
Herbicides		
2,4D	0.07	Liver, kidney, nervous system
Silvex	0.05	Nervous system, liver, kidney
Volatile organic chemicals		
Benzene	0.005	Cancer
Carbon tetrachloride	0.005	Possible cancer
Trichloroethylene	0.005	Probable cancer
Vinyl chloride	0.002	Cancer risk
Microbiological organisms		
Fecal coliform bacteria	1 cell/100 ml	Indicator—disease-causing organisms

[a]The action level for lead related to treatment of water to reduce lead to the safe level. There is no MCL for lead.
[b]Million fibers per liter with fiber length >10 microns.
Source: U.S. Environmental Protection Agency.

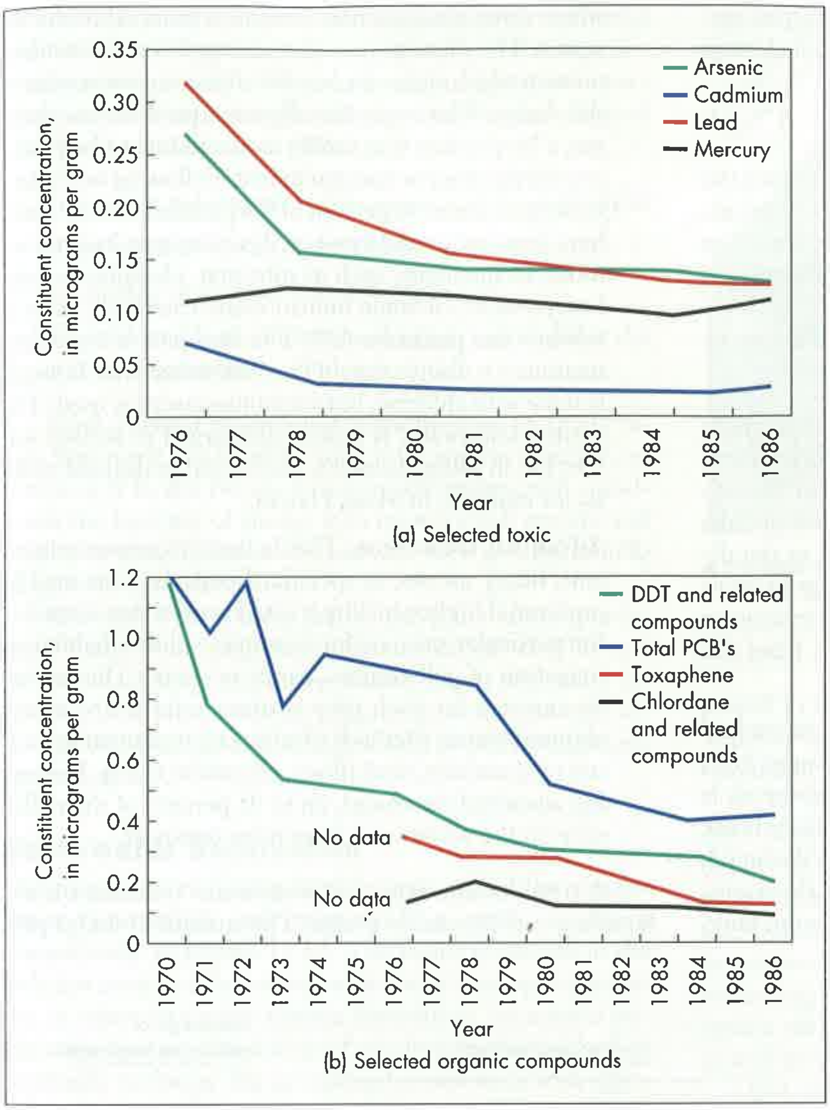
treatment sites should not have to be hidden from the public. Rather, we should come to expect sewage to be reclaimed at small cost while producing flowers and shrubs in a park-like setting (17).

Septic-Tank Sewage Disposal

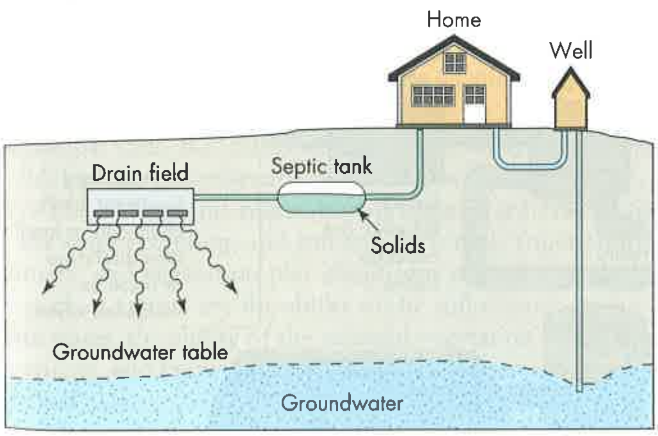
Population movement in the United States continues to be from rural to urban, or urbanizing, areas. Although the most satisfactory method of sewage disposal is through municipal sewers and sewage-treatment facilities, construction of an adequate sewage system often has not kept pace with growth. As a result, the individual **septic-tank** disposal system continues to be an important method of sewage disposal. There are more than 22 million systems in operation, and about a half-million new systems are added each year. As a result, septic systems are used by about 30 percent of the people in the United States (18). Not all land, however, is suitable for installation of a septic-tank disposal system, so evaluation of individual sites is necessary and often required by law before a permit can be issued.

The basic parts of a septic-tank disposal system are shown in Figure 11.10. The sewer line from the house or small business leads to an underground septic tank in the yard. Solid organic matter settles to the bottom of the tank where it is digested and liquefied by bacterial action. The clarified liquid discharges into the drain field, a system of piping through which it seeps into the surrounding soil. As the water moves through the soil, it is further treated and purified by natural processes of filtering and oxidation.

Geologic factors affecting the suitability of a septic-tank disposal system include type of soil, depth to the water table, depth to bedrock, and topography. These variables are generally listed, with soil descriptions associated with a soil survey of a county or other area. Soil surveys are published by the Soil Conservation Service and are extremely valuable in interpreting possible land use, such as suitability for a septic system. However, the reliability of a soils map for predicting limitations of soils is limited to an area larger than a few thousand square meters, and soil types can change within a few meters, so it is often necessary to have an on



◀ **FIGURE 11.9** Trends from 1970 to 1989 in the concentration of selected toxic metals (a) and toxic organic chemicals (b) in fish tissue, measured at monitoring stations by U.S. Fish and Wildlife Service. (*Source:* R. A. Smith, 1994. *Water quality and health.* Geotimes 39(1):14–21.)



▲ **FIGURE 11.10** Idealized diagram showing septic-tank sewage disposal system.

site evaluation by a soil scientist or soils engineer. To calculate the size of the absorption field needed, it is necessary to know the rate at which water moves through the soil, which is best determined by a percolation test.

Sewage absorption fields may fail for several reasons. The most common cause is poor soil drainage, which allows the effluent to rise to the surface in wet weather. Poor drainage can be expected in areas with clay or compacted soils with low hydraulic conductivity, and in areas that have a high water table, rock with low hydraulic conductivity near the surface, or frequent flooding.

When septic systems fail, waste materials often surface above the drainage field, producing a potential health hazard. This sort of failure is easy to see. Unfortunately, what is happening beneath the ground is not so easy to see, and if extensive leaching of waste occurs, then groundwater resources may be polluted. Of particular concern are septic systems that serve small commercial and industrial activities. These tend to cause more severe problems of groundwater pollution than do septic systems for homes because of the potentially hazardous nature of waste disposed by these activities. Possible contaminants include nutrients such as nitrates; heavy metals such as zinc, copper, and lead; and synthetic organic chemicals such as benzene, carbon tetrachloride, and vinyl chloride. In recent years the EPA has identified a number of commercial and industrial septic systems that have caused sufficient water pollution that cleanup has been necessary (18).

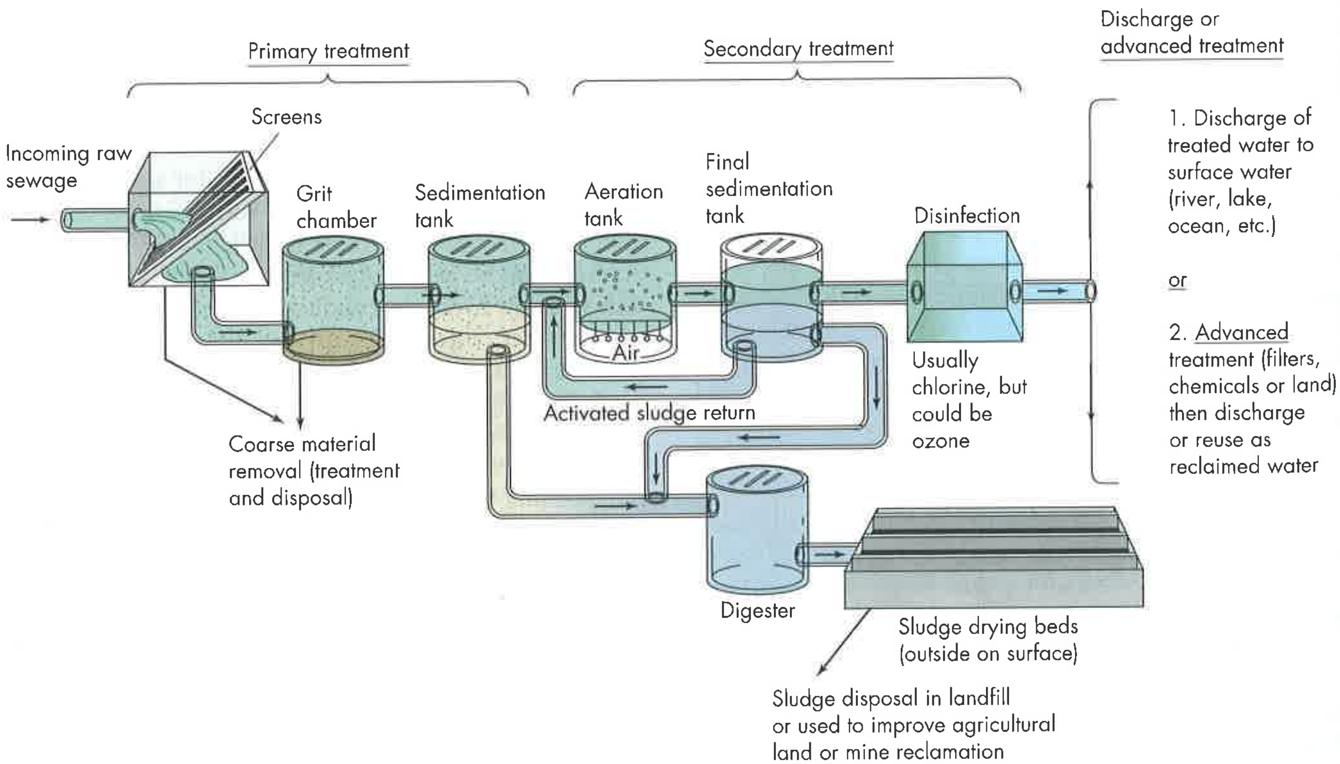
Wastewater Treatment Plants

The main purpose of wastewater treatment is to reduce the amount of suspended solids, bacteria, and oxygen-demanding materials in wastewater. In addition, new techniques are being developed to remove nutrients and harmful dissolved inorganic materials that may be present.

Existing wastewater treatment generally has two or three stages (Figure 11.11):

- **Primary treatment.** This includes screening, which removes the grit (sand, stones, and other large particles); and sedimentation, in which much of the remaining particulate matter settles out to form a mudlike sediment called *sludge*. The sludge is piped to the digester, and the partially clarified wastewater goes on to the secondary stage of treatment. Primary treatment removes 30 to 40 percent of the pollutants from the wastewater (19).
- **Secondary treatment.** The most common secondary treatment is known as *activated sludge*. Wastewater from primary treatment enters the aeration tank, where air is pumped in and aerobic (oxygen-requiring) bacteria break down much of the organic matter remaining in the liquid. This process takes several hours, after which the wastewater is then pumped to the final sedimentation tank, where more sludge settles out and is pumped to the digester. The digester provides an oxygen-poor environment in which anaerobic bacteria digest organic matter in the sludge. This anaerobic digestion produces methane gas, a by-product that can be used as a fuel to help heat or cool the plant or run equipment. Following secondary treatment, about 90 percent of the pollutants in the waste have been removed. However, this treatment does not remove all nutrients, such as nitrogen, phosphorus, and heavy metals, or some human-made chemicals, such as solvents and pesticides (19). The final part of secondary treatment is disinfection of the wastewater. This is usually done with chlorine, but sometimes ozone is used. The treated wastewater is usually discharged to surface waters, but in some places it is discharged to disposal wells, as, for example, in Maui, Hawaii.
- **Advanced treatment.** This is done to remove nutrients, heavy metals, or specific chemicals. This may be required if higher-quality treated wastewater is needed for particular uses as, for example, wildlife habitat or irrigation of golf courses, parks, or crops. The treated wastewater for such uses is often referred to as **reclaimed water.** Methods of advanced treatment include use of chemicals, sand filters, or carbon filters. Following advanced treatment, up to 95 percent of the pollutants in the wastewater have been removed.

A troublesome aspect of wastewater treatment is the handling and disposal of sludge. The amount of sludge pro-



▲ **FIGURE 11.11** Idealized diagram showing activated sludge sewage treatment with (or without) advanced treatment.

duced in the treatment process is conservatively estimated at about 54 to 112 grams per person per day, and sludge disposal accounts for 25 to 50 percent of the capital and operating cost of a treatment plant. Sludge handling and disposal have four main objectives (20):

- To convert the organic matter to a relatively stable form
- To reduce the volume of sludge by removing liquid
- To destroy or control harmful organisms
- To produce by-products whose use or sale reduces the cost of processing the sludge

Final disposal of sludge is accomplished by incineration, burying it in a landfill, using it for soil reclamation, or dumping it in the ocean. From an environmental standpoint, the best use of sludge is to improve soil texture and fertility in areas disturbed by activity, such as strip mining and poor soil conservation.

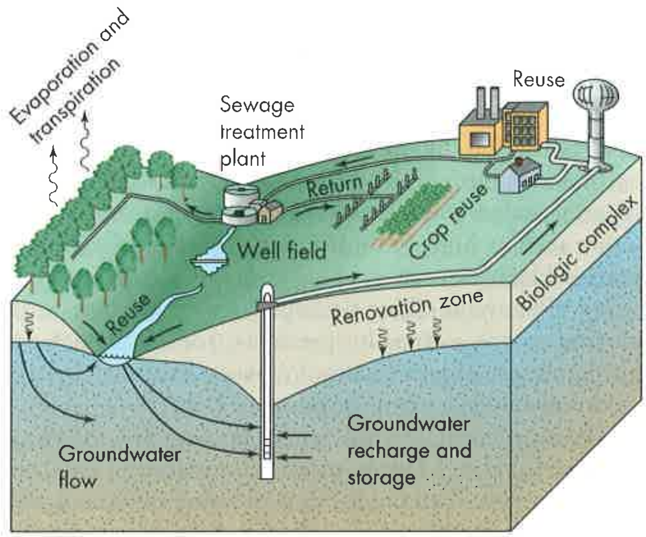
Although it is unlikely that all the tremendous quantities of sludge from large metropolitan areas can ever be used for beneficial purposes, many smaller towns and many industries, institutions, and agricultural activities can take advantage of municipal and animal wastes by converting them into resources.

Wastewater Renovation

The process of recycling liquid waste, called the **wastewater renovation and conservation cycle,** is shown schematically in Figure 11.12. The major processes in the cycle are return of the treated wastewater to crops by sprinkler or other irrigation system; renovation, or natural purification by slow percolation of wastewater through soil to eventually recharge the groundwater resource with clean water; and reuse (conservation) of the water by pumping it out of the ground for municipal, industrial, institutional, or agricultural purposes (21). Of course, not all aspects of the cycle are equally applicable to a particular wastewater problem. Wastewater renovation from cattle feedlots differs considerably from renovation of water from industrial or municipal sites. But the general principle of renovation is valid, and the processes are similar in theory.

The return and renovation processes are crucial to wastewater recycling, and soil and rock type, topography, climate, and vegetation play significant roles. Particularly important factors are the ability of the soil to safely assimilate waste, the ability of the selected vegetation to use the nutrients, and knowledge of how much wastewater can be applied (21).

Wastewater is recycled on a large scale near Muskegon and Whitehall, Michigan. Raw sewage from homes and industries is transported by sewers to the treatment plant, where it receives primary and secondary treatment. The wastewaters are then chlorinated and pumped into a piping network that transports the effluent to a series of spray irrigation rigs. After the wastewater trickles down through the soil, it is collected in a network of tile drains and transported to the Muskegon River for final disposal. This last step is an indirect advanced treatment, using the natural environment as a filter.



▲ **FIGURE 11.12** The wastewater renovation and conservation cycle. (*From* R. R. *Pasizek and* E. A. *Myers*. 1968. *American Resources Administration.*)

The Michigan project is controversial because of concern for possible pollution of surface water and groundwater, as well as problems associated with an elevated groundwater table. However, it provides a possible alternative to direct (at a treatment plant) advanced treatment, and experience gained from this project has been valuable in evaluating other possible sites for recycling wastewater. The system effectively removes most of the potential pollutants, as well as heavy metals and viruses.

In Clayton County, Georgia, just south of Atlanta, a large water renovation and conservation cycle project was recently initiated. The project handles up to 760,000 m^3 (20 million gallons) of wastewater per day, which is applied to a 972-ha (2400-acre) pine forest. Trees will be harvested on a 20-year rotation. The forest is part of the watershed that supplies water to the area; therefore, wastewater is recycled to become part of the drinking-water supply (22).

Wastewater Treatment as Resource Recovery

At the beginning of this section, we said that we hoped people would some day look at raw sewage as a resource and that treatment plants could be constructed in a parklike setting. Pioneering work in this area has been done in Arcata, California, located on Humboldt Bay. For secondary and advanced treatment of wastewater, this community has constructed oxidation ponds that form part of a large wetland system in the bay. Water drawn from the oxidation ponds has also been used to rear Pacific salmon fingerlings. Thus, the wastewater treatment scheme utilizes wetlands as part of the treatment and can produce a resource—in this case Pacific salmon—that are released into the ocean.

The United States has developed a tremendous capacity for treating wastewater. The treatment is primarily in large plants such as that shown in Figure 11.11. This sort of treatment is certainly effective and has a relatively good track record. On the other hand, it is a very expensive endeavor and failures of the system are certainly not unheard of, particularly when the systems are stressed from external factors such as high rates of input of raw sewage during floods. Chlorination in the final stages of secondary treatment is effective in killing pathogens, but it produces toxic chlorine compounds as by-products, some of which are known to cause cancer. Finally, following treatment, a large amount of sludge must be disposed of (17).

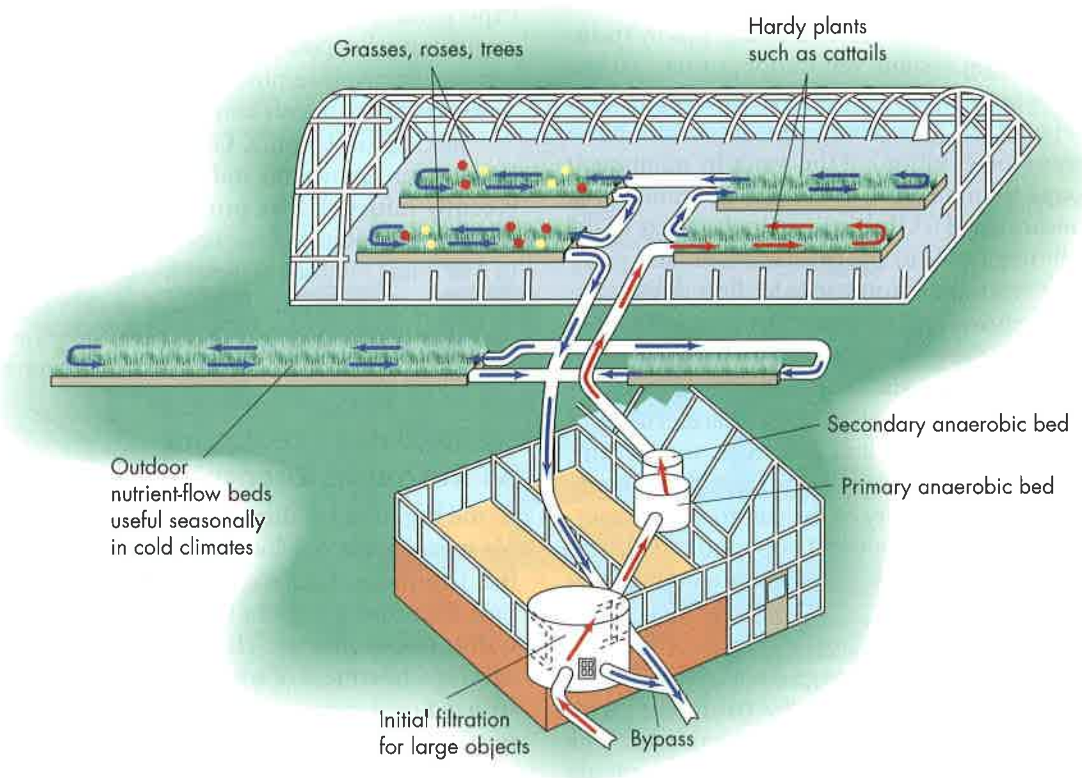
We must constantly ask our technology the following question: Is there a better, more economic, and environmentally preferred method? For wastewater treatment, that question cannot yet be answered. However, experiments are being conducted to test the hypothesis that a more environmentally preferable resource recovery system of wastewater treatment might be possible. By *resource recovery* we mean that the process of treatment would produce resources such as methane gas (which can be used as a fuel) and production of ornamental plants or other plants that have commercial value. Figure 11.13 is an idealized diagram of a pilot plant that illustrates treatment starting with screening and filtration. The next and often final steps are anaerobic treatment followed by a process known as *nutrient-film treatment* (either outdoors or in a greenhouse). In nutrient-film treatment, nutrient-rich wastewater flows in a thin film over the inclined surfaces of plant beds. This constitutes the secondary treatment. Additional advanced treatment can be obtained by further biological purification utilizing other plants. The anaerobic bacteria that perform the primary wastewater treatment also produce methane gas.

Results of pilot studies suggest resource-recovery plants produce a relatively small amount of sludge and that the treated wastewater is of high quality (meets secondary treatment standards). Some of the problems that this new technology face in being more widely used are (17):

- We have a tremendous investment in more traditional wastewater treatment plants and are familiar with them.
- There is a general lack of economic incentives to provide for new technologies.
- There is a general lack of personnel capable of designing, building, and operating these systems. However, as more universities are developing true environmental engineering programs, this problem may be rectified.

11.7 Water Law and Federal Legislation

Water is absolutely necessary to life and to all aspects of human use of the land. As a result, water resources are probably the most legislated and discussed commodity in the area of envi-



▲ **FIGURE 11.13** Idealized diagram illustrating process of resource-recovery wastewater treatment. The recovery is of two types: methane (energy) from the anaerobic beds; and ornamental plants, flowers, etc. (*After* W. J. Jewell. 1994. *Resource-recovery wastewater treatment.* American Scientist 82(4):366–75.)

ronmental law. In the United States today, an elaborate framework of state water laws surrounds the use of surface waters and groundwaters. In addition, the federal government has attempted to regulate water quality by means of legislation.

Surface-Water Law

American states generally fall into one of two camps with respect to surface-water rights: those that apply the **Riparian Doctrine,** and those that apply the **Prior Appropriation Doctrine** (23).

The **Riparian Doctrine** was the prevailing water law in most states prior to 1850 and is still used in most of the eastern half of the United States. Riparian rights to water are restricted for the most part to owners of the land adjoining a stream or body of standing water. It is important to keep in mind that a water right is not a legal title to the water—it is simply the legal right to use water in a manner dictated by law (23). Therefore, under the Riparian Doctrine, the right to use water is considered real property, but the water itself does not belong to the property owner. Riparian water rights are considered property that enters into the value of the land and may be transferred, sold, or granted to other people (24). Under riparian rights, landowners have the right to make reasonable use of water on their land, provided the water is returned to its natural stream before it leaves the property. A property owner also has the right to receive the full flow of the stream undiminished in quantity and quality but is not entitled to make withdrawals of water that infringe upon the rights of other riparian owners (25).

The **Prior Appropriation Doctrine** in water law holds that prior usage is a significant factor. That is, the first person to divert and use water from a surface water supply has the primary water right and this may be passed to successive owners. Furthermore, the right to use water is separate from other property rights (23). Appropriation water law is common in the western part of the United States, and generally states with the least abundant water supply must manage their water most closely. For example, the state of Arizona, with an average precipitation of less than 38 cm/yr, must manage water very closely indeed. As a result, the Arizona state constitution states that riparian water rights are not authorized and declares all water subject to appropriation. Preferred uses are domestic, municipal, and irrigation (24).

Comparison of the two doctrines suggest that management of water resources is considerably more effective when the principles of appropriation are applied. Because riparian law requires judicial decision, it is therefore subject to possible variations and interpretations in different courts. As a result, property owners are never sure of their position. The riparian system also tends to encourage nonuse of water and thus is counterproductive in times of shortage. On the other hand, states with appropriation systems have the power to make and enforce regulations based on sound hydrologic principles that are more likely to lead to effective management of water resources (24).

Court decisions concerning water use and the environment have also been involved with the government's obligation to protect our common heritage, including ecosystems. This is known as the *Public Trust Doctrine* (see *Case History: Mono Lake and the Public Trust Doctrine*).

Groundwater Law

In the United States, laws governing groundwater use go back to the right of absolute ownership of the water beneath a particular person's land. This doctrine is known as the **English Rule,** or the **Absolute Ownership Doctrine.** Under this doctrine landowners could pump at will and take as much water as they wished, even though that water was shared in a common groundwater aquifer with adjacent landowners. This sort of arrangement works pretty well in a region with a wet, humid climate, such as England or the eastern United States, where there is usually plenty of water. Even in the eastern United States, however, problems may arise during drought conditions.

In the western United States, where water is a much more scarce resource, it became apparent early on that absolute ownership led to major problems, and legal modifications were made that limited property owners' rights to groundwater. Under one such modification, known as the **American Rule,** or the **Reasonable Use Doctrine,** the amount of groundwater withdrawn is based upon the reasonable and beneficial purposes the water is used for on the land above the aquifer. Establishing what is reasonable use may be difficult, however. Problems also arise from the fact that the doctrine is applied through a system of laws regulating the issuing of pumping permits (23,26). California has developed what is known as the **Correlative Rights Doctrine** as a reasonable alternative to the idea of absolute ownership of the groundwater. This doctrine recognizes a landowner's right to use water beneath the land, but it limits these rights by making provisions for other landowners whose property overlies a common groundwater source. All of the landowners have equal or correlative rights to a reasonable amount of groundwater when that water is applied to beneficial use of the land over the groundwater basin (aquifer) (26).

Establishing correlative rights is not an easy endeavor. It requires determination of the availability of water on an annual basis to determine the **safe yield** of the aquifer. If the total withdrawal of water by pumping is less than the average annual recharge of the aquifer, then the excess water can be apportioned to users. On the other hand, if an overdraft exists (groundwater withdrawal exceeds recharge), then the water rights are apportioned among all users, with the total withdrawals set at the average annual recharge for the aquifer (23).

Most of the states in the western United States have also adopted the Prior Appropriation Doctrine, cited earlier with respect to surface water. As noted previously, this doctrine states that the first user of groundwater has a right to continue that use, provided the water is put to a beneficial use without waste. These rights are then superior to rights of people who at a later time appropriate water. In those states that utilize the Prior Appropriation

CASE HISTORY Mono Lake and the Public Trust Doctrine

Mono Lake, located in the Mono basin at the foot of the Sierra Nevada east of Yosemite National Park in California (Figure 11.F), is the focus of a recent controversy centering around the very existence of the lake. From the lake's watershed, approximately 100,000 acre-feet of water per year are diverted south to the city of Los Angeles. The water is diverted from streams before entering the lake. Mono Lake measures approximately 21 by 13 km, with an average depth of about 17 m, making it the largest lake by volume contained entirely within the state of California. It is fed by a number of streams from the Sierra Nevada and some groundwater flow as well. During the last million years, geologic events associated with uplift of the Sierra Nevada, volcanic activity, and glaciation have left the lake with no natural outlet. Mono Lake is therefore salty, having a salinity approximately three times that of seawater.

Mark Twain visited Mono Lake in the 1860s and had little good to say about it except that the alkaline waters made laundry work easy. In *Roughing It,* Twain wrote, "Half a dozen little mountain brooks flow into Mono Lake but not a stream of any kind flows out of it. What it does with its surplus water is a dark and bloody mystery" (27). What happens to the water, of course, is that it evaporates. In fact, approximately 22 cm/yr of water evaporates from the surface of Mono Lake. Under natural conditions this loss is matched from streams that feed the lake system (27).

Mono Lake and its basin have a long and interesting history dating back at least to 1853, when Native Americans living in Yosemite were pursued by the military to the shores of the lake. About that time, gold was discovered in the area, initiating a small gold rush that lasted until approximately 1889. In 1913 the city of Los Angeles considered importing water into the growing urban area, and by 1930 funds had been approved for the construction of dams, reservoirs, and a tunnel to divert water from the eastern Sierra and Mono Lake area. In 1941 diversion of water from Mono basin streams began in earnest, and by 1981 the lake level had dropped (by evaporation) approximately 15 m. This decreased the volume of the lake by approximately one-half, which increased the salinity by 100 percent.

Brine shrimp grow in great abundance in the lake and provide the major food source for migrating birds. If the salinity were to become too high, the brine shrimp would die and the birds would have no food during a crucial stage in their migration. More significantly, lowering of the lake formed a land bridge to several volcanic islands in the lake that are major breeding grounds for California gulls. In 1979, after the land bridge had formed, coyotes entered the nesting area and chased off all 34,000 nesting birds. In addition, the lowering of the lake level exposed nearly 9000 ha of highly alkaline lake bed. During windy periods, alkali dust may rise into the atmosphere several hundred meters and be transported both around and out of the basin, causing air pollution (27). Extremely wet years in 1983 and 1984 caused the lake level to rise a bit, but it was still much lower than the 1941 level. Figure 11.F shows the 1980 situation with inflow and diversion of waters (27).

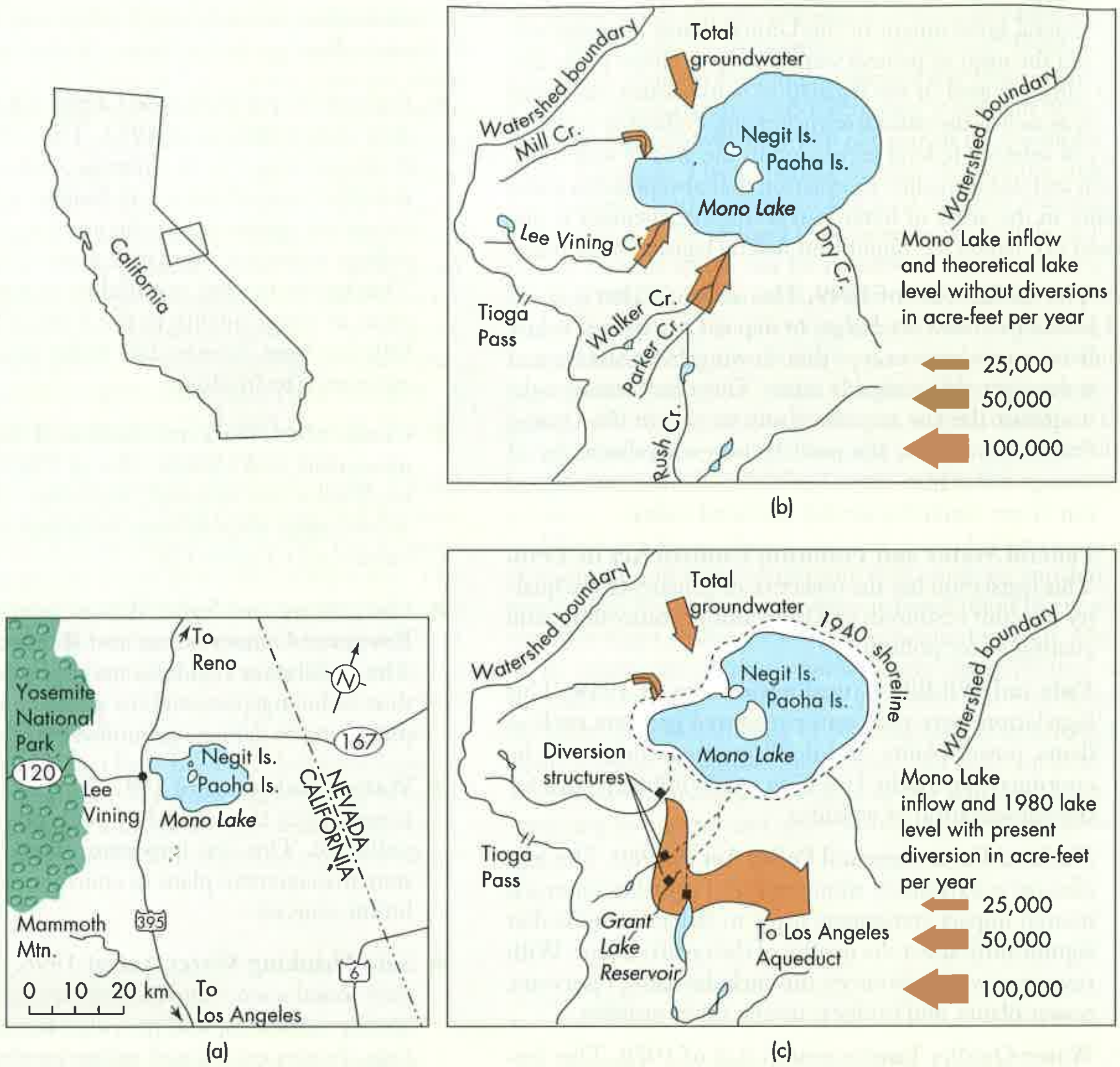
People interested in the preservation of Mono Lake and its ecosystem would like to see the lake level stabilized approximately 3 m above that necessary to support the healthy ecosystem. They advocate a wet year/dry year plan that would limit diversion to the dry years when the city of Los Angeles really needs the water. They further advocate a statewide program to conserve urban and agricultural water.

No one disagrees with the advocacy of water conservation. The city of Los Angeles, however, which receives approximately 17 percent of its water supply from the Mono basin, would like to see diversions continue at a rate greater than that advocated by those who want to see the lake preserved. The people in favor of continued diversion point out that the project produces a good deal of energy (approximately 300 million kilowatt hours per year, which saves approximately half a million barrels of oil annually). They would like to see the diversions continued and the lake level eventually stabilized at about 15 m below the 1981 level. One of their arguments is that the city of Los Angeles has invested more than $100 million in the area since the 1930s and really needs the water.

The Mono Lake story is an important one in environmental law because in 1983 the California Supreme Court reaffirmed the public interest in protecting natural resources through what is known as the Public Trust Doctrine. The 1983 decision states that it is the duty of the state to protect the people's common heritage, including streams, lakes, marshlands, and tidelands. In essence, the court decided that public trust obligates the state of California to protect lakes such as Mono as much as possible, even if this means reexamining past water allocations (27). In effect, the city of Los Angeles is forced to reduce diversion of water to such an extent that the Mono Lake ecosystem remains healthy.

Doctrine, the water rights are generally managed through a permit procedure supervised by a state government official (26).

In sum, a variety of doctrines and laws govern use of groundwater. One issue that constantly comes forward is what constitutes "beneficial use." To some people, beneficial use might be ensuring sufficient water for a river system to support a healthy ecosystem and aesthetic values. To others, beneficial uses may be limited to activities such as agriculture or public water supply. In still other cases, people might argue that recreational use of water is a beneficial use. These arguments come up because when groundwater is withdrawn from an area, it often affects the surface water supplies as well. When pumping lowers the water table below the bed of a perennial stream, the flow may cease and the riparian vegetation die, damaging the ecosystem. Downstream users of the surface water supply would also be denied their water. Because surface and groundwaters are so interrelated, the laws governing water use are complex and sometimes difficult to apply to specific situations.



▲ **FIGURE 11.F** (a) Location of Mono Lake. (b) Situation without water diversion. (c) With water diversion. (d) Aerial view of Mono Lake in California showing the white ring or shoreline exposed from the lake's being at a lower level. (*Peter Essick/Aurora & Quanta Productions*)

Federal Water Legislation

The federal government of the United States has long recognized the need to protect water resources from pollution. The ultimate goal of the legislation is to protect our water supply as well as the natural environment. Following is a summary of selected federal legislation in the area of water pollution and water quality. Legislation that also protects water quality in the areas of hazardous waste management is discussed in Chapter 12. Significant federal legislation includes:

- **The Refuse Act of 1899.** This act states that it is unlawful to throw, discharge, or deposit any type of refuse from any source except that flowing from streets and sewers into any navigable water. The intent was to make it against the law to pollute any stream in the United States. Of course, the part dealing with discharge of sewage water into rivers has had to change, or many of our rivers would be terribly polluted today.
- **Federal Water and Pollution Control Act of 1956.** This legislation has the objective of enhancing the quality of water resources and preventing, controlling, and abating water pollution.
- **Fish and Wildlife Coordination Act of 1958.** This legislation state that water resource projects such as dams, power plants, and flood-control works must be coordinated with the U.S. Fish and Wildlife Service for the conservation of wildlife.
- **National Environmental Policy Act of 1969.** This legislation is extremely significant in requiring environmental impact statements prior to federal actions that significantly affect the quality of the environment. With respect to water resources, this includes dams, reservoirs, power plants, and bridges, among other projects.
- **Water Quality Improvement Act of 1970.** This legislation expanded the power of the 1956 act through control of oil pollution and hazardous pollutants. It also established research and development to eliminate acid mine drainage and pollution in the Great Lakes.
- **Federal Water Pollution Control Act (Clean Water Act) Amendments of 1972.** The primary purpose of this legislation is to clean up the nation's waters. It provided billions of dollars in federal grants for sewage treatment plants while encouraging innovative technology, including alternative water treatment methods. This legislation has resulted in tremendous improvement of water quality in the United States, although little has been done to date in the area of encouraging innovative technology.
- **Comprehensive Environmental Response, Compensation, and Liability Act of 1980.** This legislation establishes the so-called Superfund to clean up hazardous waste disposal sites, reducing groundwater pollution (see Chapter 12).
- **Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act of 1984.** This legislation regulates underground storage tanks, thus reducing potential for gasoline and other liquid pollutants to damage groundwater resources.
- **Water Quality Act of 1987.** This act establishes as national policy the control of nonpoint sources of water pollution. This was important in the development of state management plans to control nonpoint water pollution sources.
- **Safe Drinking Water Act of 1996.** This act emphasizes sound science and development of risk-based water quality standards, and provided for consumer awareness of water quality and assistance obtaining improvement in the water system infrastructure.

SUMMARY

Water pollution is the degradation of water quality as measured by physical, chemical, or biological criteria. These criteria take into consideration the intended use for the water, departure from the norm, effects on public health, and ecological impacts.

The major water pollutants are oxygen-demanding waste, measured by biochemical oxygen demand (BOD); pathogens, measured by the fecal coliform bacteria count; nutrients that lead to eutrophication, in which overgrowth of algae deprives water of oxygen and sunlight; oil; toxic substances, including synthetic organic and inorganic compounds, heavy metals, and radioactive materials; heat; and sediment.

Surface-water pollutants have either point or nonpoint sources. Point sources include pipes that empty industrial and municipal wastes into streams, and combined sewer systems that carry both waste and storm-water flow in older cities. Nonpoint sources, or polluted runoff, are more difficult to control than point sources. Nonpoint sources include urban, agricultural, forestry, and mining runoff carrying a wide variety of pollutants. *Acid mine drainage* refers to water with a high concentration of sulfuric acid that drains from some coal or metal-mining areas, causing surface-water and groundwater pollution in many parts of the United States.

Since the 1960s there has been a serious attempt to reduce surface-water pollution and improve water quality in the United States. Although the program has been quite successful, water quality is still substandard in some areas.

In the case of surface water, pollution processes are slowed by dilution and dispersion of pollutants and degradation of pollutants in the presence of sunlight and oxygen. In the case of groundwater, the depth, slow flow, and long residency time of the water limit the opportunities for these natural controls to operate. On the other hand, many soils and rocks act as filters, exchanging certain elements and compounds with groundwater. In moving through an aquifer, groundwater may improve in quality, but it may also be rendered unsuitable for human use by natural or artificial contaminants. Pollution of an aquifer can result from disposal of wastes on the land surface or in the ground. It can also result from overpumping of groundwater in coastal areas, leading to intrusion of salt water into freshwater aquifers. Because we cannot prevent all pollutants from entering groundwater, and reversal of aquifer and vadose zone contamination is complex and expensive, we must find ways to assist the natural processes that limit groundwater pollution.

Development of water quality standards in the United States has been mandated by federal legislation and involves setting of Maximum Contaminant Levels (MCLs) for contaminants that might be found in our drinking water. The major purposes of the standards are to ensure that our water supply is treated to remove harmful contaminants and that water quality is regularly tested and monitored. Monitoring of toxic metals and organic compounds in fish indicates that the levels of toxins in water have been significantly reduced, particularly for toxins that have been regulated the longest.

Wastewater treatment facilities include septic-tank sewage disposal systems and wastewater treatment plants. Septic-tank systems, utilized by homes and small commercial and industrial activities, are very common in the United States today. Failure of these systems may cause significant pollution to groundwater resources. Wastewater treatment plants collect and process water from municipal sewage systems. Primary and secondary treatment by wastewater plants removes up to 90 percent of the pollutants in the wastewater. These include oxygen-demanding materials, bacteria, and suspended solids. Advanced wastewater treatment may be utilized to remove heavy metals and nutrients so that water can be reclaimed for other uses, including wildlife habitat or application to farm fields, parks, and golf courses. The use of reclaimed water is growing fast in the United States, particularly in areas where water shortages are most likely to occur. Considerable research is ongoing to develop methods of wastewater treatment that involve resource recovery. Typically, such treatment involves use of the biologic environment as part of the treatment process.

Water law for surface water and groundwater resources is complex and varies from one U.S. state to another. In some cases the right to use water is based upon living adjacent to a water resource or over a groundwater basin, whereas in other cases water resources are appropriated and regulated by regional and state agencies. The federal government has a long history of enacting laws in an attempt to control water pollution. As a result, we have some of the highest water quality standards in the world and are attempting to control and abate water pollution problems.

REFERENCES

1. **Smith, R. A.** 1994. Water quality and health. *Geotimes* 39(1):19–21.
2. **Water Resources Council.** 1978. *The nation's water resources, 1975–2000*, vol. 1. Washington, DC: U.S. Government Printing Office.
3. **Special oil spill issue.** 1989. *Alaska Fish and Game* 21, July–August.
4. **Rice, S. D., ed.** 1996. *Proceedings of the Exxon Valdez Oil Spill Symposium.* Anchorage, AK: American Fisheries Society.
5. **Hollway, M.** 1991. Soiled shores. *Scientific American* 265:102–106.
6. **Parfit, M.** 1993. Troubled waters run deep. *National Geographic* 184(5A):78–89.
7. **Miller, G. Tyler, Jr.** 1994. *Living in the environment.* Belmont, CA: Wadsworth.
8. **Council on Environmental Quality.** 1979. *Environmental quality.* Washington, DC: U.S. Government Printing Office.
9. **Anonymous.** 1982. U.S. Geological Survey activities, fiscal year 1982. *U.S. Geological Survey Circular* 875:90–3.
10. **Geiser, K., and Waneck, G.** 1983. PCBs and Warren County. *Science for the People.*
11. **Bopp, R. F., and Simpson, H. J.** 1989. *Contamination of the Hudson River: The sediment record in contaminated marine sediments—assessment and remediation.* Washington, DC: National Academy Press.
12. **Pye, U. I., and Patrick, R.** 1983. Ground water contamination in the United States. *Science* 221:713–18.
13. **Weir, D., and Schapico, M.** 1980. The circle of poison. *The Nation*, November 15.
14. **Carey, J.** 1984. Is it safe to drink? *National Wildlife*, February–March:19–21.
15. **Foxworthy, G. L.** 1978. Nassau County, Long Island, New York—Water problems in humid country. In *Nature to be commanded*, eds. G. D. Robinson and A. M. Spieker, pp. 55–68. U.S. Geological Survey Professional Paper 950.
16. **Environmental Protection Agency.** 1991. *Is your drinking water safe?* EPA 570-9-91-0005.
17. **Jewell, W. J.** 1994. Resource-recovery wastewater treatment. *American Scientist* 82(4):366–75.
18. **Bedient, P. B., Rifai, H. S., and Newell, C. J.** 1994. *Groundwater contamination.* Englewood Cliffs, NJ: Prentice Hall.
19. **Leeden, F., Troise, F. L., and Todd, D. K.** 1990. *The water encyclopedia*, 2nd ed. Chelsea, MI: Lewis Publishers.
20. **American Chemical Society.** 1969. *Clean our environment: The chemical basis for action.* Washington, DC: U.S. Government Printing Office.

21. **Parizek, R. R., and Myers, E. A.** 1968. Recharge of ground water from renovated sewage effluent by spray irrigation. *Proceedings of the Fourth American Water Resources Conference*, pp. 425–43.
22. **Bastian, R. K., and Benforado, J.** 1983. Waste treatment: Doing what comes naturally. *Technology Review*, February–March:59–66.
23. **Fetter, C. W.** 1994. *Applied hydrogeology*. New York: Macmillan.
24. **Legal Approach to Water Rights.** 1972. In *Water quality in a stressed environment*, ed. W. A. Pettyjohn, pp. 255–76. Minneapolis: Burgess.
25. **Research and Documentation Corp.** 1970. Private remedies for water pollution. *Environmental Law:* 47–49.
26. **Smith, Z. A.** 1989. *Groundwater in the West*. New York: Academic Press.
27. **Mono Lake Committee.** 1985. *Mono Lake: Endangered oasis*. Lee Vining, CA: author.

KEY TERMS

water pollution (p. 292)
biochemical oxygen demand (BOD) (p. 293)
fecal coliform bacteria (p. 293)
cultural eutrophication (p. 294)
point sources (p. 298)
nonpoint sources (p. 298)
acid mine drainage (p. 299)
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septic tank (p. 306)
primary treatment (p. 308)
secondary treatment (p. 308)
advanced treatment (p. 308)
reclaimed water (p. 308)
wastewater renovation and conservation cycle (p. 309)

SOME QUESTIONS TO THINK ABOUT

1. The island of Maui, one of the Hawaiian Islands, has a strong tourist industry. Near some of the urban areas, the beaches are occasionally spoiled by accumulation of decaying algae (seaweed) that may smell so bad that it drives people from the beaches. The algae evidently increase (bloom) in the shallow waters offshore in response to input of nutrients from urban wastewater and/or agricultural runoff. Urban wastewaters are treated to secondary standards in a series of small units for a particular development and, in some cases, for larger communities. These waters are injected into the ground near the ocean. How could you develop a research plan to try to determine if the eutrophication that is taking place is the result of the injection of urban wastewater or agricultural runoff? How might each of these pollution sources be controlled to preserve the water quality in the nearshore marine environment and eliminate the algae blooms?
2. For your community, develop an inventory of point and nonpoint sources of water pollution. Carefully consider how each of these might be eliminated or minimized as part of a pollution abatement strategy.
3. Visit a wastewater treatment plant. What are the processes utilized at the plant, and could the concept of resource-recovery or wastewater renovation cycle be utilized? What would be the advantages and disadvantages of using a biologic system, such as plants, as part of the wastewater treatment procedures?
4. How safe do you think your water supply is? If you drink bottled water, how safe is it? Upon what are you basing your answers? What do you need to know to give informed answers?