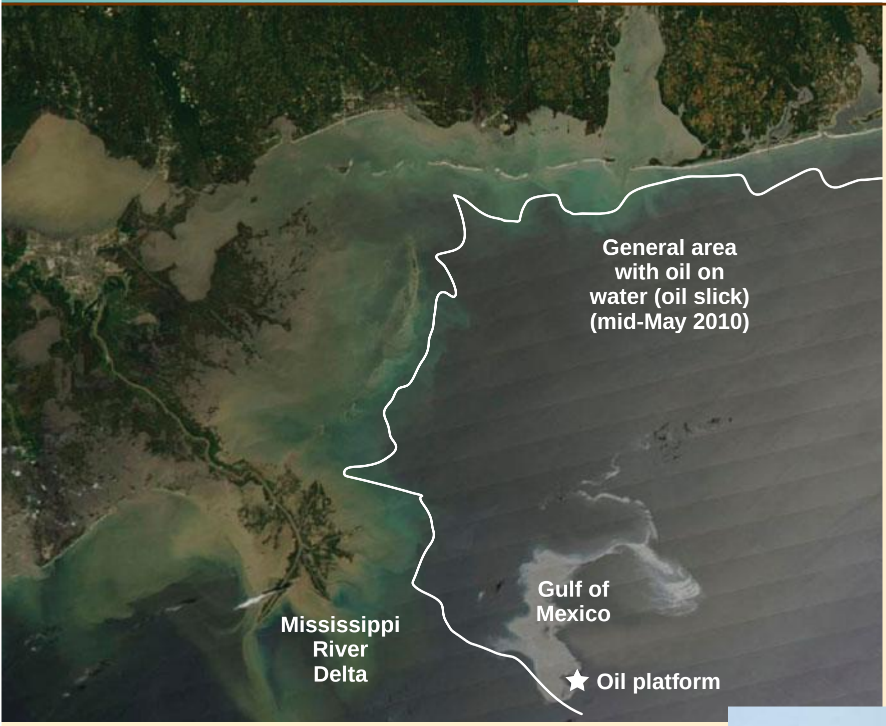
CHAPTER 15

Fossil Fuels and the Environment



LEARNING OBJECTIVES

We rely almost completely on fossil fuels—oil, natural gas, and coal—for our energy needs. However, these are nonrenewable resources, and their production and use have a variety of serious environmental impacts. After reading this chapter, you should understand . . .

- Why we may have serious, unprecedented supply problems with oil and gasoline within the next 20 to 50 years;
- How oil, natural gas, and coal form;
- What the environmental effects are of producing and using oil, natural gas, and coal.

Oil is the most important fossil fuel today, but working in oil fields has never been easy. Drilling for oil is difficult, dangerous and potentially damaging to the environment. On April 20, 2010 a blowout on the platform Deepwater Horizon in the Gulf of Mexico while drilling in water about 1.6 km (1 mile) deep occurred. Explosive gas rose up the well and exploded. Eleven men were killed, the platform destroyed, and oil leaked for 3 months at a rate of 36,000 to 60,000 barrels of oil per day (1 barrel is 42 gallons).By mid-July about 5 million barrels of oil were in the water column or on the surface and moving with the currents. The high altitude image shows the extent of the spill, off the coast of Louisiana, The smaller photo is of a wetland contaminated with oil. The oil by mid-July had washed up in variable amounts as thick oil or tar balls on beaches and coastal wetlands from Texas to Florida.The spill is the largest in U.S. history, far exceeding the Exxon Valdez in Alaska (1989). A temporary cap on the well first stopped the leak on July 17. Relief wells drilled “killed” the well.

CASE STUDY

Peak Oil: Are We Ready for It?

People in the wealthier countries have grown prosperous and lived longer during the past century as a result of abundant low-cost energy in the form of crude oil. The benefits of oil are undeniable, but so are the potential problems they create, from air and water pollution to climate change. In any case, we are about to learn what life will be like with less, more expensive oil. The question is no longer whether the peak in production will come, but when it will come and what the consequences to a society's economics and politics will be.[1] The peak, or **peak oil**, is the time when one-half of Earth's oil has been exploited.

The global history of oil in terms of rate of discovery and consumption is shown in Figure 15.1. Notice that in 1940 five times as much oil was discovered as was consumed; by 1980 the amount discovered equaled the amount consumed; and in the year 2000 the consumption of oil was three times the amount discovered. Obviously, the trend is not sustainable.

The concept of peak oil production is shown in Figure 15.2. We aren't sure what the peak production will be, but let's assume it will be about 40–50 billion barrels (bbl) per year and that the peak will arrive sometime between 2020 and 2050. In 2004 the growth rate for oil production was 3.4%. Moving from the present production rate of about 31 billion barrels per year (85 million bbl per day) to 50 billion barrels in a few decades is an optimistic estimate that may not be realized. Several oil company executives believe that even 40 billion barrels per year will be difficult. For the past several years, production has been flat, at about 30 billion barrels per year, leading some to believe that the peak is close.[2, 3]

When production peaks, and if demand increases, a gap between production and demand will result. If demand exceeds supply, the cost will rise, as it did in 2008. The price of a barrel of oil doubled from 2007 to mid-2008, and a gallon of gasoline in the United States approached $5 (Figure 15.3), causing a lot of anxiety for consumers. However, the latter part of 2008 saw the cost of oil drop more than 50% from its earlier high, and gasoline prices fell below $2 a gallon. The price was about $40/barrel by April 2009, but rose again, to about $65/barrel, by July. The instability in the cost of oil and gasoline in the first years of the 21st century reflects uncertainty about supplies because of wars and the delivery/refining processes.

We have time now to prepare for the eventual peak and to use the fossil fuels we have more carefully during the time of transition to other energy sources. If we have not prepared for the peak, then disruption to society is likely. In the best scenario, the transition from oil will not occur until we have cost-competitive alternatives in place.[2,4] Alternatives for liquid fuels include conservation (using less); producing massive amounts of biofuel from corn, sugarcane, and other plants; turning our vast coal reserves into liquid fuel; and developing other conventional sources of oil, including tar sands and oil shale. With the exception of conservation, all these have potentially significant environmental consequences. We will return to the concept of peak oil in the Critical Thinking exercise at the end of the chapter.

The approaching peak in oil production is a wake-up call, reminding us that although we will not run out of oil,

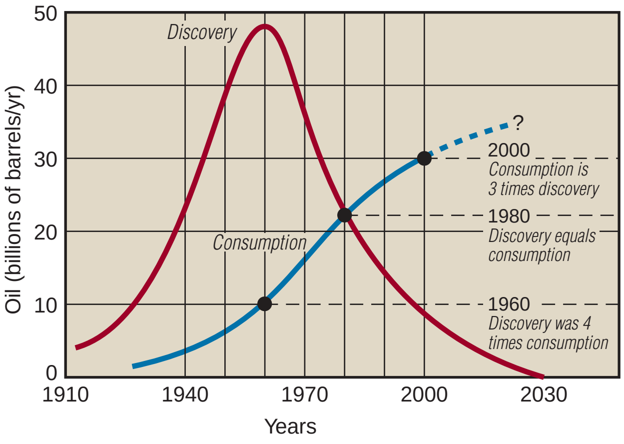


FIGURE 15.1 Discovery of oil peaked around 1960, and consumption exceeded discovery by 1980. *Source:* Modified after K. Alekett, "Oil: A Bumpy Road Ahead," *World Watch 19*, no. 1(2006):10–12.)

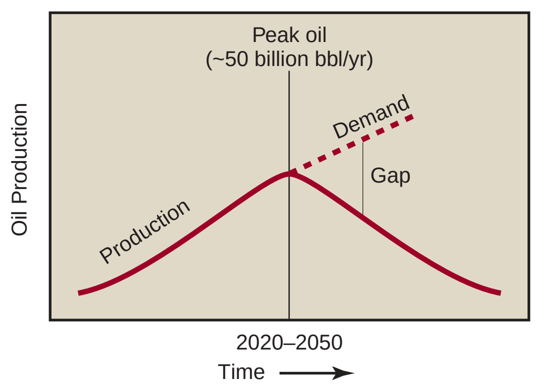


FIGURE 15.2 Idealized diagram of world oil production and peak between 2020 and 2050. When production cannot meet demand, a gap (shortage) develops.

FIGURE 15.3 A California gas station in 2008, at the height of gas pricing.

it will become much more expensive, and that there will be supply problems as demand increases by about 50% in the next 30 years. The peak in world oil production, when it arrives, will be unlike any problem we have faced in the past. The human population will increase by several billion in the coming decades, and countries with growing economies, such as China and India, will consume more oil. China, in fact, expects to double its import of oil in the next five years! Clearly, the social, economic, and political ramifications of peak oil will be enormous. Planning now for ways to conserve oil and transition to alternative energy sources will be critical in the coming decades.[4] We cannot afford to leave the age of oil until alternatives are firmly in place. The remainder of this chapter will discuss the various fossil fuels and their uses.

15.1 Fossil Fuels

Fossil fuels are forms of stored solar energy. Plants are solar energy collectors because they can convert solar energy to chemical energy through photosynthesis (see Chapter 6). The main fossil fuels used today were created from incomplete biological decomposition of dead organic matter (mostly land and marine plants). Buried organic matter that was not completely oxidized was converted by chemical reactions over hundreds of millions of years to oil, natural gas, and coal. Biological and geologic processes in various parts of the geologic cycle produce the sedimentary rocks in which we find these fossil fuels.[5, 6]

The major fossil fuels—crude oil, natural gas, and coal—are our primary energy sources; they provide approximately 90% of the energy consumed worldwide (Figure 15.4). World energy consumption grew about 1.4% in 2008. The largest increase, 7.2%, was in China. In the United States, consumption dropped about 2.8%. Most of the global increase (75%) was due to burning coal in China.[7] Globally, oil and natural gas provide 70 to 80% of the primary energy. Two exceptions are Asia, which uses a lot of coal, and the Middle East, where oil and gas provide nearly all of the energy. In this chapter, we focus primarily on these major fossil fuels. We also briefly discuss two other fossil fuels, oil shale and tar

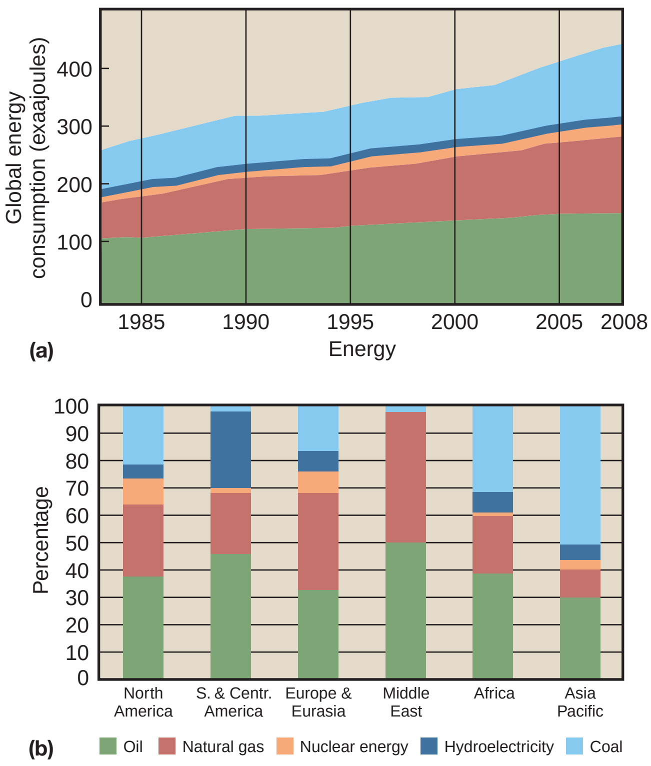


FIGURE 15.4 **(a)** World energy consumption (in exajoules) by primary source from 1983 to 2008; **(b)** world energy consumption by primary sources in 2008. (*Source*: *BP Statistical Review of World Energy 2010.* BP p.l.c.)

sands, that may become increasingly important as oil, gas, and coal reserves are depleted.

15.2 Crude Oil and Natural Gas

Most geologists accept the hypothesis that **crude oil** (petroleum) and **natural gas** are derived from organic materials (mostly plants) that were buried with marine or lake sediments in what are known as *depositional basins*. Oil and gas are found primarily along geologically young tectonic belts at plate boundaries, where large depositional basins are more likely to occur (see Chapter 6). However, there are exceptions, such as in Texas, the Gulf of Mexico, and the North Sea, where oil has been discovered in depositional basins far from active plate boundaries.

The source material, or *source rock*, for oil and gas is fine-grained (less than 1/16 mm, or 0.0025 in., in diameter), organic-rich sediment buried to a depth of at least 500 m (1,640 ft), where it is subjected to increased heat and pressure. The elevated temperature and pressure initiate the chemical transformation of the sediment's organic material into oil and gas. The pressure compresses the sediment; this, along with the elevated temperature in the source rock, initiates the upward migration of the oil and gas, which are relatively light, to a lower-pressure environment (known as the *reservoir rock*). The reservoir rock is coarser-grained and relatively porous (it has more and larger spaces between the grains). Sandstone and porous limestone, which have a relatively high proportion (about 30%) of empty space in which to store oil and gas, are common reservoir rocks.

As mentioned, oil and gas are light; if their upward mobility is not blocked, they will escape to the atmosphere. This explains why oil and gas are not generally found in geologically old rocks. Oil and gas in rocks older than about 0.5 billion years have had ample time to migrate to the surface, where they have either vaporized or eroded away.[6]

The oil and gas fields from which we extract resources are places where the natural upward migration of the oil and gas to the surface is interrupted or blocked by what is known as a *trap* (Figure 15.5). The rock that helps form the trap, known as the *cap rock*, is usually a very fine-grained sedimentary rock, such as shale, composed of silt and clay-sized particles. A favorable rock structure, such as an anticline (arch-shaped fold) or a fault (fracture in the rock along which displacement has occurred), is necessary to form traps, as shown in Figure 15.5. The important concept is that the combination of favorable rock structure and the presence of a cap rock allow deposits of oil and gas to accumulate in the geologic environment, where they are then discovered and extracted.[6]

Petroleum Production

Production wells in an oil field recover oil through both primary and enhanced methods. *Primary production* involves simply pumping the oil from wells, but this method can recover only about 25% of the petroleum in the reservoir. To increase the amount of oil recovered to about 60%, enhanced methods are used. In *enhanced* recovery, steam, water, or chemicals, such as carbon dioxide or nitrogen gas, are injected into the oil reservoir to push the oil toward the wells, where it can be more easily recovered by pumping.

Next to water, oil is the most abundant fluid in the upper part of the Earth's crust. Most of the known, proven oil reserves, however, are in a few fields. *Proven* oil reserves are

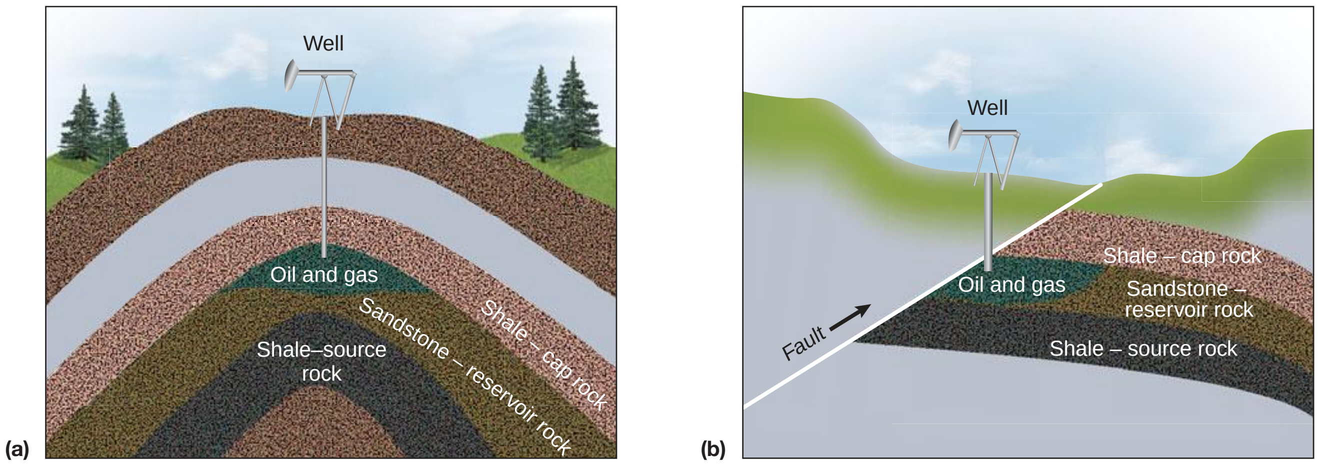


FIGURE 15.5 **Two types of oil and gas traps**: **(a)** anticline and **(b)** fault.

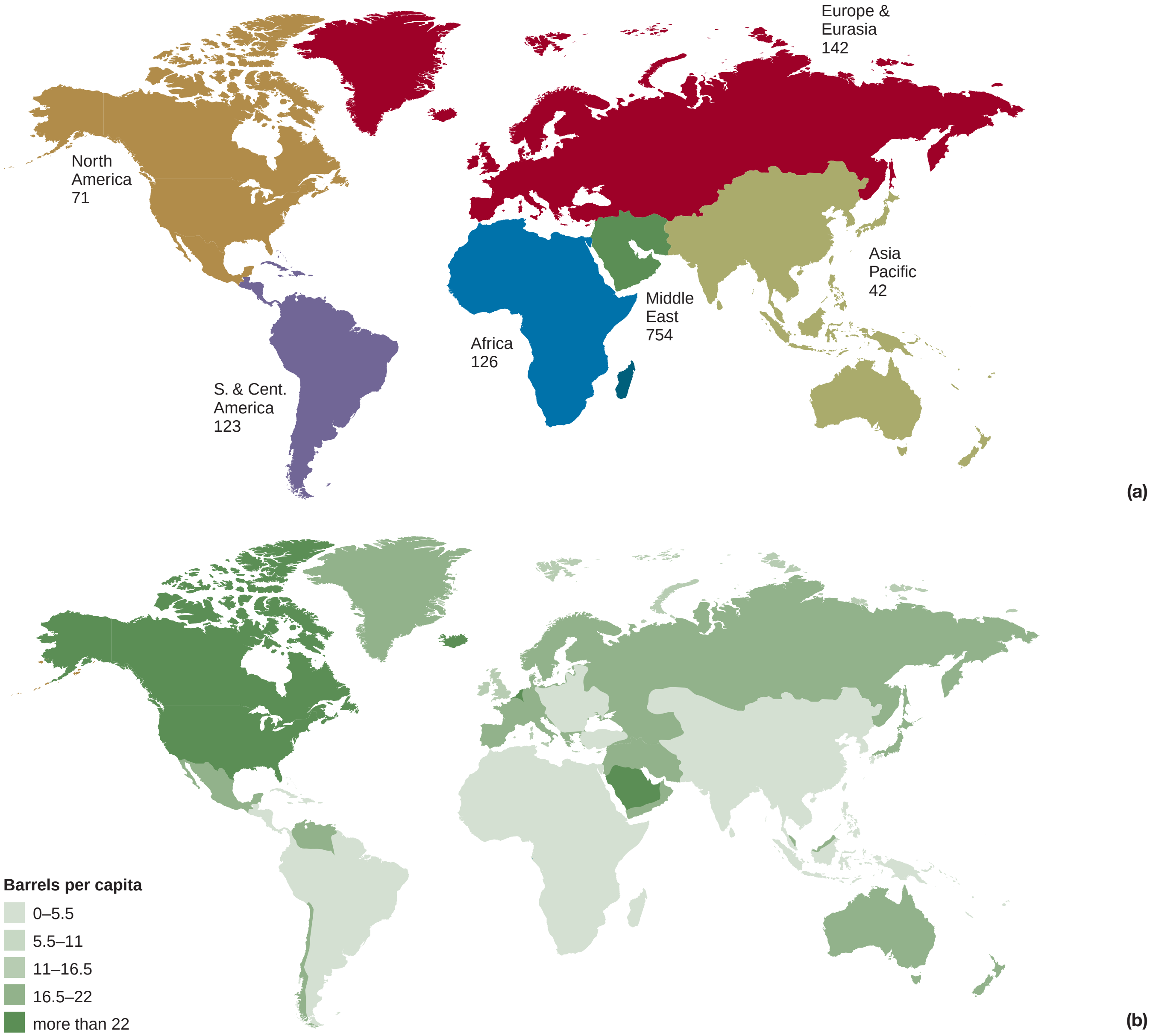


FIGURE 15.6 **(a)** Proven world oil reserves (billions of barrels) in 2008. The Middle East dominates, with 60% of total reserves. **(b)** Consumption of oil per person in 2008. Units are barrels (1 barrel is 42 gallons). (*Source*: *BP Statistical Review of World Energy 2010.* BP p.l.c.)

the part of the total resource that has been identified and can be extracted now at a profit. Of the total reserves, 62% are in 1% of the fields, the largest of which (60% of total known reserves) are in the Middle East (Figure 15.6a). The consumption of oil per person is shown in Figure 15.6b. Notice the domination of energy use in North America. Although new oil and gas fields have recently been and continue to be discovered in Alaska, Mexico, South America, and other areas of the world, the present known world reserves may be depleted in the next few decades.

The total resource always exceeds known reserves; it includes petroleum that cannot be extracted at a profit and petroleum that is suspected but not proved to be present. Several decades ago, the amount of oil that ultimately could be recovered (the total resource) was estimated to be about 1.6 trillion barrels. Today, that estimate is just over 2 trillion barrels.[8] The increases in proven reserves of oil in the last few decades have primarily been due to discoveries in the Middle East, Venezuela, Kazakhstan, and other areas.

Table 15.1 IMPORTS AND EXPORTS OF OIL, 2010

	THOUSAND BARRELS DAILY			
	CRUDE IMPORT	PRODUCTS IMPORT	CRUDE EXPORT	PRODUCTS EXPORT
US	8893	2550	44	1871
Canada	785	320	1938	538
Mexico	9	439	1282	168
S. & Cent. America	504	863	2588	1137
Europe	10308	3177	464	1523
Former Soviet Union	18	67	6868	2197
Middle East	140	219	16510	1916
North Africa	369	209	2232	528
West Africa	1	254	4263	110
East & Southern Africa	439	119	297	6
Australasia	458	358	258	42
China	4086	1041	94	614
India	2928	217	1.9	740
Japan	3545	738	–	345
Singapore	930	1668	47	1505
Other Asia Pacific	4590	2667	807	1252
Unidentified*	–	18	311	430
Total World	38005	14925	38005	14925

Source: *BP Statistical Review of World Energy* (2010.B.P. p.l.c.)

Because so much of the world's oil is in the Middle East, oil revenues have flowed into that area, resulting in huge trade imbalances. Table 15.1 shows the major trade for oil. The United States imports oil from Venezuela, the Middle East, Africa, Mexico, Canada, and Europe. Japan is dependent on oil from the Middle East and Africa.

Oil in the 21st Century

Recent estimates of proven oil reserves suggest that, at present production rates, oil and natural gas will last only a few decades.[7, 9] The important question, however, is not how long oil is likely to last at present and future production rates, but when we will reach peak production. This is important because, following peak production, less oil will be available, leading to shortages and price shocks. World oil production, as mentioned in the opening case study, is likely to peak between the years 2020 and 2050, within the lifetime of many people living today.[10] Even those who think peak oil production in the near future is a myth acknowledge that the peak is coming and that we need to be prepared.[2] Whichever projections are correct, there is a finite amount of time (a few decades or perhaps a bit longer) left in which to adjust to potential changes in lifestyle and economies in a post-petroleum era.[10] We will never entirely run out of crude oil, but people of the world depend on oil for nearly 40% of their energy, and significant shortages will cause major problems.[11]

Consider the following argument that we are heading toward a potential crisis in availability of crude oil:

- We are approaching the time when approximately 50% of the total crude oil available from traditional oil fields will have been consumed.[10] Recent studies suggest that about 20% more oil awaits discovery than predicted a few years ago, and that there is more oil in known fields than earlier thought. However, the volumes of new oil discovered and recovered in known fields will not significantly change the date when world production will peak and a decline in production will begin.[9] This point is controversial. Some experts believe that modern technology for exploration, drilling, and recovery of oil will ensure an adequate supply of oil for the distant future.[8]
- Proven reserves are about 1.3 trillion barrels.[7] It is estimated that approximately 2 trillion barrels of crude oil may ultimately be recovered from remaining oil resources. World production today is about 31 billion barrels per year (85 million barrels per day), and we are using what is left very rapidly.[2]

- Today, for every three barrels of oil we consume, we are finding only one barrel.[11] In other words, output is three times higher than input. However, this could improve in the future.[8]
- Forecasts that predict a decline in oil production are based on the estimated amount of oil that may ultimately be recoverable (2 trillion barrels, nearly two times today's proven reserves), along with projections of new discoveries and rates of future consumption. As already mentioned, it has been estimated that the peak in world crude oil production, about 40 billion bbl/yr, will occur between the years 2020 and 2050.[1,2,9,11] The production of 40 billion bbl/yr is about a 30% increase over 2007. Whether you think this increase is optimistic or pessimistic depends on your view of past oil history, in which oil has survived several predicted shortages, or beliefs that the peak is inevitable sooner than later.[1, 2] Most oil experts believe peak oil is only a few decades away.
- It is expected that U.S. production of oil as we know it now will end by about 2090 and that world production of oil will be nearly exhausted by 2100.[11]

Table 15.1 suggests that world exports of oil are about one-half of world production. We conclude that the other half is often used in the country that produced it. A prospect perhaps as significant as peak oil may be the time when exporting nations no longer have significant oil to export. This will occur in different exporting countries at different times and is sure to cause problems with global supply and demand.

What is an appropriate response to the likelihood that oil production will likely decline in the mid-21st century? First, we need an improved educational program to inform or remind people and governments of the potential depletion of crude oil and the consequences of shortages. Presently, many people seem to be in denial. Planning and appropriate action are necessary to avoid military confrontation (we have already had one oil war), food shortages (oil is used to make the fertilizers modern agriculture depends on), and social disruption. Before significant oil shortages occur, we need to develop alternative energy sources, such as solar energy and wind power, and perhaps rely more on nuclear energy. This is a proactive response to a potentially serious situation.

Natural Gas

We have only begun to seriously search for natural gas and to utilize this resource to its full potential. One reason for the slow start is that natural gas is transported primarily by pipelines, and only in the last few decades have these pipelines been constructed in large numbers. In fact, until recently, natural gas found with petroleum was often simply burned off as waste; in some cases this practice continues.[12]

The worldwide estimate of recoverable natural gas is about 185 trillion cubic meters (m^3), which, at the current rate of world consumption, will last approximately 60 years.[7] Considerable natural gas was recently discovered in the United States, and at present U.S. consumption levels (0.7 trillion m^3 in 2008) this resource is expected to last at least 30 years. Furthermore, new supplies are being found in surprisingly large amounts, particularly at greater depths than those at which oil is found. Optimistic estimates of the total resource suggest that, at current rates of consumption, the supply may last approximately 100 years.[5]

This possibility has important implications. Natural gas is considered a clean fuel; burning it produces fewer pollutants than does burning oil or coal, so it causes fewer environmental problems than do the other fossil fuels. As a result, it is being considered as a possible transition fuel from other fossil fuels (oil and coal) to alternative energy sources, such as solar power, wind power, and hydropower.

Despite the new discoveries and the construction of pipelines, long-term projections for a steady supply of natural gas are uncertain. The supply is finite, and at present rates of consumption it is only a matter of time before the resources are depleted.

Coal-Bed Methane

The processes responsible for the formation of coal include partial decomposition of plants buried by sediments that slowly convert the organic material to coal. This process also releases a lot of methane (natural gas) that is stored within the coal. The methane is actually stored on the surfaces of the organic matter in the coal, and because coal has many large internal surfaces, the amount of methane for a given volume of rock is something like seven times more than could be stored in gas reservoirs associated with petroleum. The estimated amount of coal-bed methane in the United States is more than 20 trillion cubic meters, of which about 3 trillion cubic meters could be recovered economically today with existing technology. At current rates of consumption in the United States, this represents about a five-year supply of methane.[13]

Two areas within the nation's coalfields that are producing methane are the Wasatch Plateau in Utah and the Powder River Basin in Wyoming. The Powder River Basin is one of the world's largest coal basins, and presently an energy boom is occurring in Wyoming, producing an "energy rush." The technology to recover coal-bed methane is a young one, but it is developing quickly. As of early 2003, approximately 10,000 shallow wells were producing methane in the Powder River Basin, and some say there will eventually be about 100,000 wells. The big advantage of the coal-bed methane wells is that they only need to be drilled to shallow depths (about 100 m, or a few hundred feet). Drilling can be done with conventional water-well technology, and the cost is about $100,000 per well, compared to several million dollars for an oil well.[14]

Coal-bed methane is a promising energy source that comes at a time when the United States is importing vast amounts of energy and attempting to evaluate a transition from fossil fuels to alternative fuels. However, coal-bed methane presents several environmental concerns, including (1) disposal of large volumes of water produced when the methane is recovered and (2) migration of methane, which may contaminate groundwater or migrate into residential areas.

A major environmental benefit of burning coal-bed methane, as well as methane from other sources, is that its combustion produces a lot less carbon dioxide than does the burning of coal or petroleum. Furthermore, production of methane gas prior to mining coal reduces the amount of methane that would be released into the atmosphere. Both methane and carbon dioxide are strong greenhouse gases that contribute to global warming. However, because methane produces a lot less carbon dioxide, it is considered one of the main transitional fuels from fossil fuels to alternative energy sources.

Of particular environmental concern in Wyoming is the safe disposal of salty water that is produced with the methane (the wells bring up a mixture of methane and water that contains dissolved salts from contact with subsurface rocks). Often, the water is reinjected into the subsurface, but in some instances the water flows into surface drainages or is placed in evaporation ponds.[13]

Some of the environmental conflicts that have arisen are between those producing methane from wells and ranchers trying to raise cattle on the same land. Frequently, the ranchers do not own the mineral rights; and although energy companies may pay fees for the well, the funds are not sufficient to cover damage resulting from producing the gas. The problem results when the salty water produced is disposed of in nearby streams. When ranchers use the surface water to irrigate crops for cattle, the salt damages the soils, reducing crop productivity. Although it has been argued that ranching is often a precarious economic venture, and that ranchers have in fact been saved by the new money from coal-bed methane, many ranchers oppose coal-bed methane production without an assurance that salty waters will be safely disposed of.

People are also concerned about the sustainability of water resources as vast amounts of water are removed from the groundwater aquifers. In some instances, springs have been reported to have dried up after coal-bed methane extraction in the area.[14] In other words, the "mining" of groundwater for coal-bed methane extraction will remove water that has perhaps taken hundreds of years to accumulate in the subsurface environment.

Another concern is the migration of methane away from the well sites, possibly to nearby urban areas. The problem is that unlike the foul-smelling variety in homes, methane in its natural state is odorless as well as explosive. For example, in the 1970s an urban area near Gallette, Wyoming, had to be evacuated because methane was migrating into homes from nearby coal mines.

Finally, coal-bed methane wells, with their compressors and other equipment, have caused people living a few hundred meters away to report serious and distressing noise pollution.[14]

In sum, coal-bed methane is a tremendous source of energy and relatively clean-burning, but its extraction must be closely evaluated and studied to minimize environmental degradation.

Black Shale (tight) Natural Gas

According to the U.S. Geological Survey, Black Devonian shale over 350 million years old buried a kilometer or so beneath northern Appalachia, contains about 500 trillion cubic feet of natural gas (mostly methane) of which10% or more may be ultimately recovered. The methane is distributed throughout the black shale as an unconventional gas resource compared to gas fields where the methane is in rock pockets often associated with oil. A very large area including parts of Ohio, New York, Pennsylvania, Virginia and Kentucky. Recovery of the methane is costly, because deep wells that turn at depth to a horizontal position are necessary to extract the gas. Water and other chemicals are used to fracture the rocks (hydrofracturing) to recover the gas. An energy rush is now occurring to develop the recovery of tight natural gas. Hundreds of gas wells have already been permitted in Pennsylvania alone. There is concern that drilling and hydrofracturing could result in water pollution, because the fluids used to fracture the rock must be recovered from wells and disposed of before gas production starts. There is also concern that contaminate water could migrate upward and leak from wells to pollute water supplies. The city of New York is very concerned that drilling may contaminated their water supply in upstate New York.[15]

Methane Hydrates

Beneath the seafloor, at depths of about 1,000 meters, there exist deposits of **methane hydrate**, a white, ice-like compound made up of molecules of methane gas (CH_4), molecular "cages" of frozen water. The methane has formed as a result of microbial digestion of organic matter in the sediments of the seafloor and has become trapped in these ice cages. Methane hydrates in the oceans were discovered over 30 years ago and are widespread in both the Pacific and Atlantic oceans. Methane hydrates are also found on land; the first ones discovered were in permafrost areas of Siberia and North America, where they are known as marsh gas.[16]

Methane hydrates in the ocean occur where deep, cold seawater provides high pressure and low temperatures. They are not stable at lower pressure and warmer temperatures. At a water depth of less than about 500 m, methane hydrates decompose rapidly, freeing methane gas from the ice cages to move up as a flow of methane bubbles (like rising helium balloons) to the surface and the atmosphere.

In 1998 researchers from Russia discovered the release of methane hydrates off the coast of Norway. During the release, scientists documented plumes of methane gas as tall as 500 m being emitted from methane hydrate deposits on the seafloor. It appears that there have been large emissions of methane from the sea. The physical evidence includes fields of depressions, looking something like bomb craters, that pockmark the seafloor near methane hydrate deposits. Some of the craters are as large as 30 m deep and 700 m in diameter, suggesting that they were produced by rapid, if not explosive, eruptions of methane.

Methane hydrates in the marine environment are a potential energy resource with approximately twice as much energy as all the known natural gas, oil, and coal deposits on Earth.[16] Methane hydrates are particularly attractive to countries such as Japan that rely exclusively on foreign oil and coal for their fossil fuel needs. Unfortunately, mining methane hydrates will be a difficult task, at least for the near future. The hydrates tend to be found along the lower parts of the continental slopes, where water is often deeper than 1 km. The deposits themselves extend into the seafloor sediments another few hundred meters. Drilling rigs have more problems operating safely at these depths, and developing a way to produce the gas and transport it to land will be challenging.

(a) (b)

FIGURE 15.7 Drilling for oil in **(a)** the Sahara Desert of Algeria; **(b)** the Cook Inlet of southern Alaska.

The Environmental Effects of Oil and Natural Gas

Recovering, refining, and using oil—and to a lesser extent natural gas—cause well-known, documented environmental problems, such as air and water pollution, acid rain, and global warming. People have benefited in many ways from abundant, inexpensive energy, but at a price to the global environment and human health.

Recovery

Development of oil and gas fields involves drilling wells on land or beneath the seafloor (Figure 15.7).

Possible environmental impacts on land include the following:

- Use of land to construct pads for wells, pipelines, and storage tanks and to build a network of roads and other production facilities.
- Pollution of surface waters and groundwater from (1) leaks from broken pipes or tanks containing oil or other oil-field chemicals and (2) salty water (brine) brought to the surface in large volumes with the oil. The brine is toxic and may be disposed of by evaporation in lined pits, which may leak. Alternatively, it may be disposed of by pumping it into the ground, using deep disposal wells outside the oil fields. However, disposal wells may pollute groundwater.
- Accidental release of air pollutants, such as hydrocarbons and hydrogen sulfide (a toxic gas).
- Land subsidence (sinking) as oil and gas are withdrawn.
- Loss or disruption of and damage to fragile ecosystems, such as wetlands or other unique landscapes. This is the center of the controversy over the development of petroleum resources in pristine environments such as the Arctic National Wildlife Refuge in Alaska (see A Closer Look 15.1).

Environmental impacts associated with oil production in the marine environment include the following:

- Oil seepage into the sea from normal operations or large spills from accidents, such as blowouts or pipe ruptures (see photograph opening this chapter). The very serious oil spill in the Gulf of Mexico (April 20, 2010) began from a blowout when equipment designed to prevent a blowout for this well drilled in very deep water (over 1.5 km,1 mile) failed to operate properly. The platform was destroyed by a large explosion and 11 oil workers were killed. By the middle of May oil started to make landfall in Louisiana and other areas, and fishing was shut down over a large area. The oil spread despite the many and continuing efforts (chemical dispersants, skimming and burning among others) to deter the oil from spreading. The spill was the largest and potentially most damaging in U.S. history (see Chapter 19 for a discussion of other oil spills and Chapter 24 for a more detailed case study of the 2010 Gulf spill).
- Release of drilling muds (heavy liquids injected into the borehole during drilling to keep the hole open). These contain heavy metals, such as barium, which may be toxic to marine life.
- Aesthetic degradation from the presence of offshore oil-drilling platforms, which some people consider unsightly.

Refining

Refining crude oil and converting it to products also has environmental impacts. At refineries, crude oil is heated so that its components can be separated and collected (this process is called *fractional distillation*). Other industrial processes then make products such as gasoline and heating oil.

Refineries may have accidental spills and slow leaks of gasoline and other products from storage tanks and pipes. Over years of operation, large amounts of liquid hydrocarbons may be released, polluting soil and groundwater below the site. Massive groundwater-cleaning projects have been required at several West Coast refineries.

Crude oil and its distilled products are used to make fine oil, a wide variety of plastics, and organic chemicals used by society in huge amounts. The industrial processes involved in producing these chemicals have the potential to release a variety of pollutants into the environment.

Delivery and Use

Some of the most extensive and significant environmental problems associated with oil and gas occur when the fuel is delivered and consumed. Crude oil is mostly transported on land in pipelines or across the ocean by tankers; both methods present the danger of oil spills. For example, a bullet from a high-powered rifle punctured the Trans-Alaska Pipeline in 2001, causing a small but damaging oil spill. Strong earthquakes may pose a problem for pipelines in the future, but proper engineering can minimize earthquake hazard. The large 2002 Alaskan earthquake ruptured the ground by several meters where it crossed the Trans-Alaska Pipeline. The pipeline's design prevented damage to the pipeline and to the environment. Although most effects of oil spills are relatively short-lived (days to years), marine spills have killed thousands of seabirds, spoiled beaches for decades (especially beneath the surface of gravel beaches), and caused loss of tourist and fishing revenues (see Chapter 19).

A CLOSER LOOK 15.1

The Arctic National Wildlife Refuge: To Drill or Not to Drill

The Arctic National Wildlife Refuge (ANWR) on the North Slope of Alaska is one of the few pristine wilderness areas remaining in the world (Figure 15.8). The U.S. Geological Survey estimates that the refuge contains about 3 billion barrels

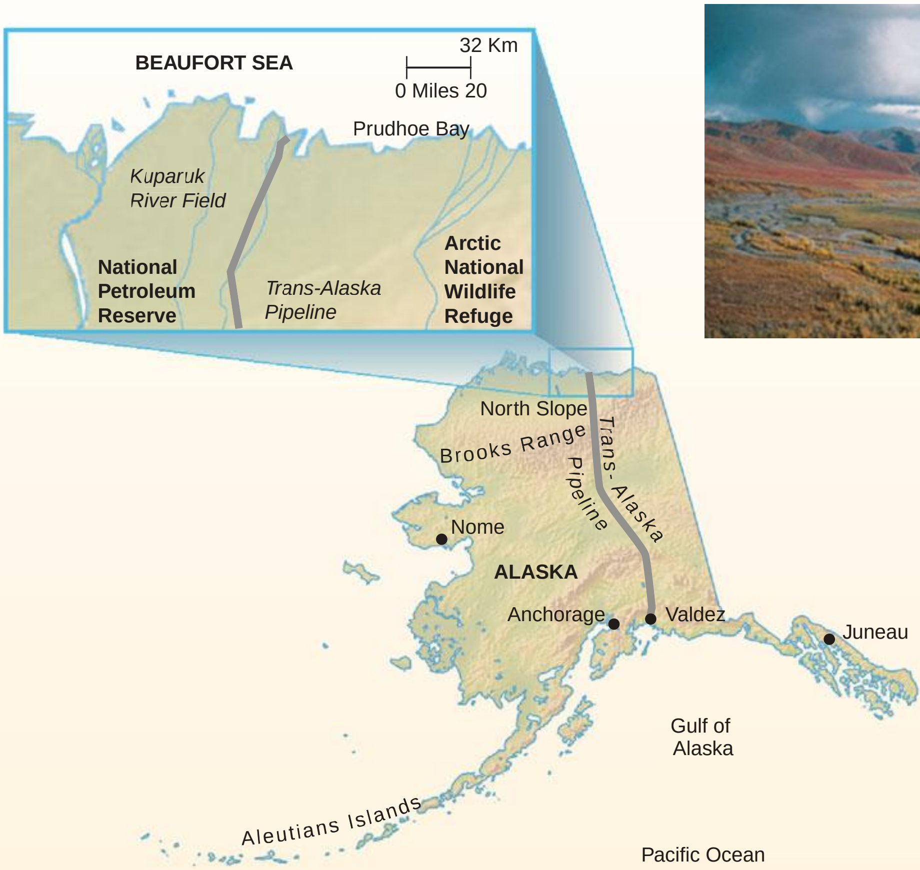
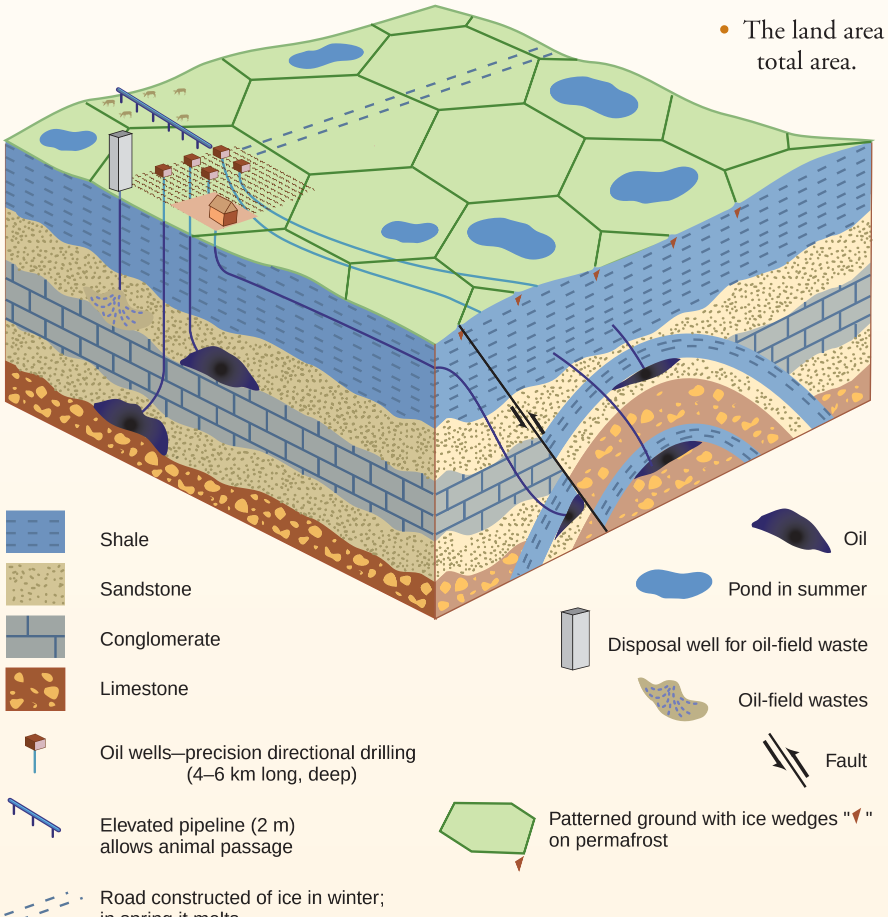


FIGURE 15.8 The Arctic National Wildlife Refuge, on Alaska's North Slope, is valued for its scenery, wildlife, and oil.

of recoverable oil. The United States presently consumes about 20 million barrels of oil per day, so ANWR could provide about a six-month supply if that were the only oil we used. Spread out to supply 1 million barrels per day, the supply at ANWR would last about eight years. According to the oil industry, several times more oil than that can be recovered. The oil industry has long argued in favor of drilling for oil in the ANWR, but the idea has been unpopular for decades among many members of the public and the U.S. government, and no drilling has been permitted. Former president George W. Bush favored drilling in the ANWR, which renewed the controversy over this issue. President Barack Obama is opposed to such drilling.

Arguments in Favor of Drilling in the ANWR

- The United States needs the oil, and it will help us to be more independent of imported oil.
- The unprecedented price increase in oil in 2008 has provided a big economic incentive to develop our domestic oil reserves.
- New oil facilities will bring jobs and dollars to Alaska.
- New exploration tools to evaluate the subsurface for oil pools require far fewer exploratory wells.
- New drilling practices have much less impact on the environment (Figure 15.9a and b). These include (1) constructing roads of ice in the winter that melt in the summer instead of constructing permanent roads; (2) elevating pipelines to allow for animal migration (Figure 15.9c); (3) drilling in various directions from a central location, thus minimizing land needed for wells; and (4) disposing of fluid oil-field wastes by putting them back into the ground to minimize surface pollution.
- The land area affected will be small relative to the total area.



(a)

FIGURE 15.9 **(a)** Those in favor of ANWR drilling argue that new technology can reduce the impact of developing oil fields in the Arctic: Wells are located in a central area and use directional drilling; roads are constructed of ice in the winter, melting to become invisible in summer; pipelines are elevated to allow animals, in this case caribou, to pass through the area; and oil-field and drilling wastes are injected deep underground. (See text for arguments against drilling.) **(b)** Oil wells being drilled on frozen ground (tundra), North Slope of Alaska. **(c)** Caribou passing under a pipeline near the Arctic National Wildlife Refuge in Alaska.


(b)


(c)

- Many Alaskans want the drilling to proceed and point out that oil drilling for 30 years on the North Slope of Alaska (Prudhoe Bay) has not harmed animals or the environment.

Arguments against Drilling in the ANWR

- Advances in technology are irrelevant to the question of whether or not the ANWR should be drilled. Some wilderness should remain wilderness! Drilling will forever change the pristine environment of the North Slope.
- Even with the best technology, oil exploration and development will impact the ANWR. Intensive activity, even in winter on roads constructed of ice, will probably disrupt wildlife.
- Ice roads are constructed from water from the tundra ponds. To build a road 1 km (0.63 mi) long requires about 3,640 m^3 (1 million gallons) of water.
- Heavy vehicles used in exploration permanently scar the ground—even if the ground is frozen hard when the vehicles travel across the open tundra.
- Accidents may occur in even the best facilities.
- Oil development is inherently damaging because it involves a massive industrial complex of people, vehicles, equipment, pipelines, and support facilities.

Our decision about drilling in the Alaska National Wildlife Refuge will reflect both science and values at a basic level. New technology will lessen the environmental impact of oil drilling. How we value the need for energy from oil compared with how we value preservation of a pristine wilderness area will determine our action: to drill or not to drill. The debate is not over yet. The oil crisis of 2008 that drove the price of gasoline to nearly $5 per gallon placed ANWR oil development in the spotlight again.

Air pollution is perhaps the most familiar and serious environmental impact of burning oil. Combustion of gasoline in automobiles produces pollutants that contribute to urban smog. (The adverse effects of smog on vegetation and human health are well documented and are discussed in detail in Chapter 21.)

15.3 Coal

Partially decomposed vegetation, when buried in a sedimentary environment, may be slowly transformed into the solid, brittle, carbonaceous rock we call **coal**. This process is shown in Figure 15.10. Coal is by far the world's most abundant fossil fuel, with a total recoverable resource of about 825 billion metric tons (Figure 15.11). The annual world consumption of coal is about 7 billion metric tons, sufficient for about 120 years at the current rate of use.[7] There are about 18,500 coal mines in the United States with combined reserves of 262 billion tons and 2008 production of 1.2 billion tons. At present rates of mining, U.S. reserves will last nearly 250 years.[7, 17] If, however, consumption of coal increases in the coming decades, the resource will not last nearly as long.[18]

Coal is classified, depending on its energy and sulfur content, as anthracite, bituminous, subbituminous, or lignite (see Table 15.2). The energy content is greatest in anthracite coal and lowest in lignite coal. The distribution of coal in the contiguous United States is shown in Figure 15.12.

The sulfur content of coal is important because low-sulfur coal emits less sulfur dioxide (SO_2) and is therefore more desirable as a fuel for power plants. Most low-sulfur coal in the United States is the relatively low-grade, low-energy lignite and subbituminous coal found west of the Mississippi River. Power plants on the East

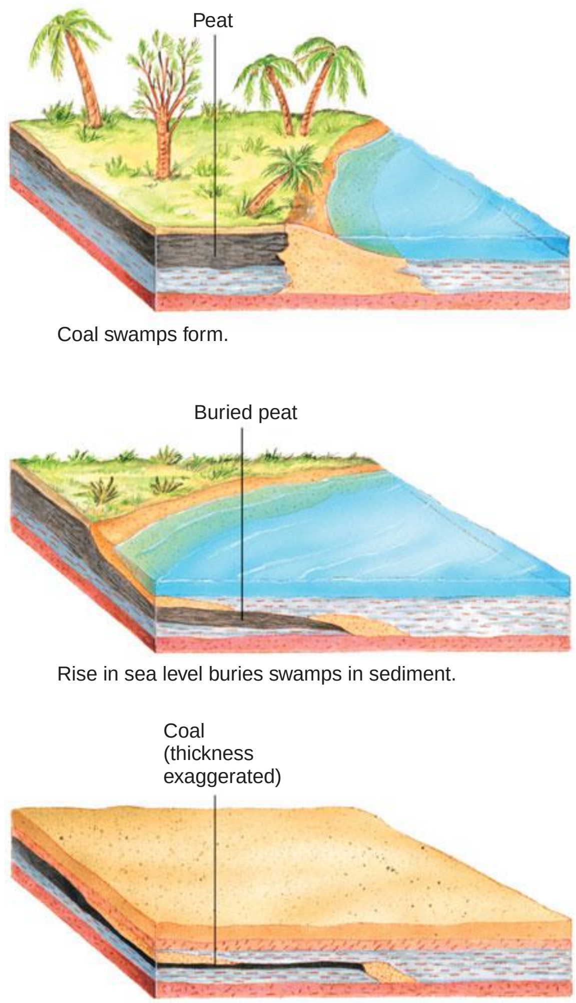


FIGURE 15.10 Processes by which buried plant debris (peat) is transformed into coal.

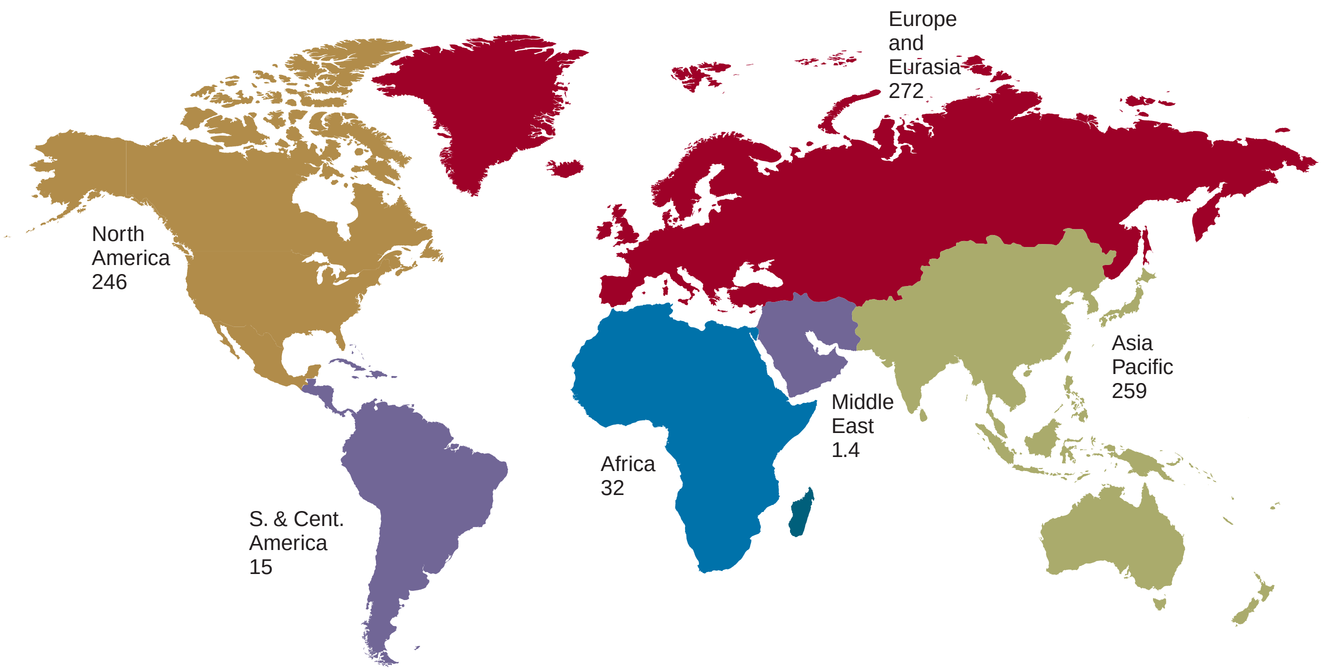


FIGURE 15.11 World coal reserves (billions of tons) in 2008. (*Source*: *BP Statistical Review of World Energy* 2009.B.P. p.l.c.).

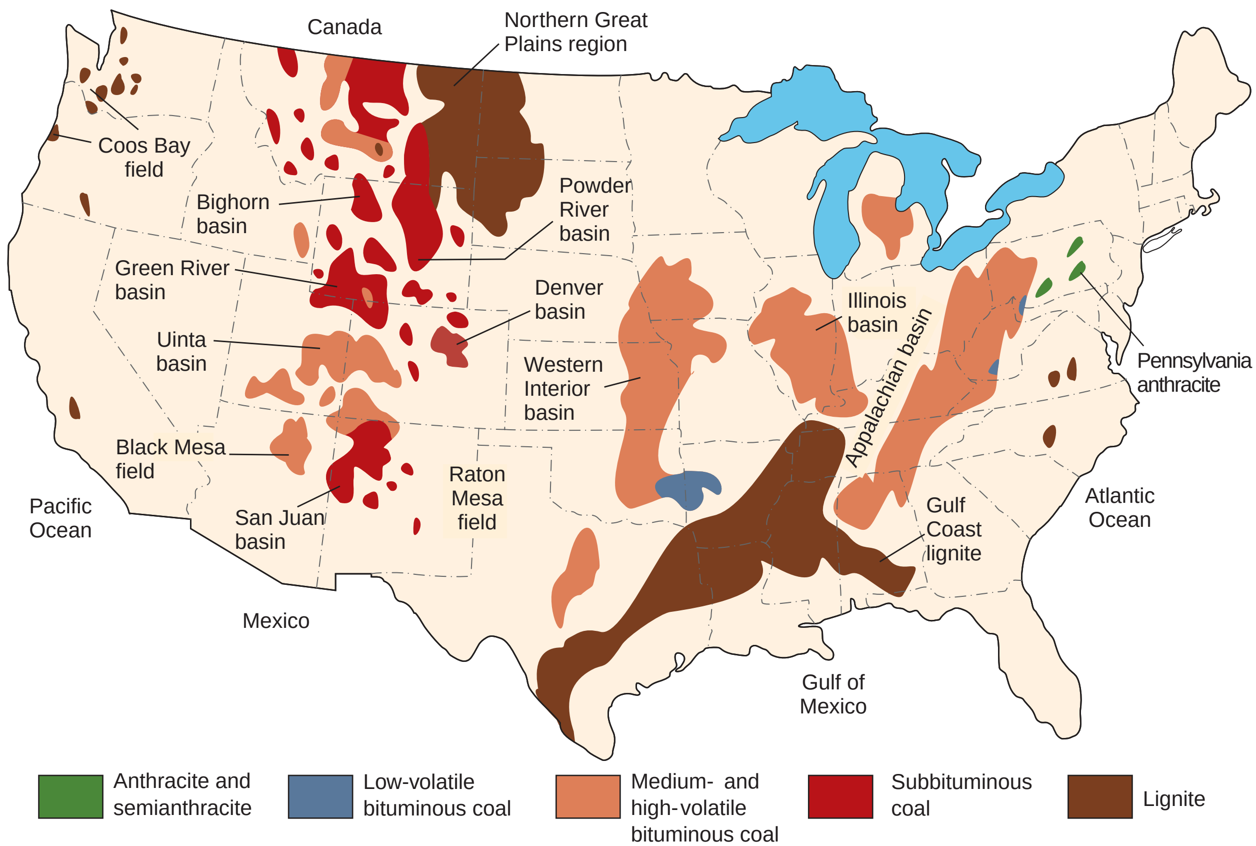


FIGURE 15.12 Coal areas of the contiguous United States. This is a highly generalized map, and numerous relatively small occurrences of coal are not shown. (*Source*: S. Garbini and S.P. Schweinfurth, *U.S. Geological Survey Circular 979, 1986.)*

Coast treat the high-sulfur coal mined in their own region to lower its sulfur content before, during, or after combustion and, thus, avoid excessive air pollution. Although it is expensive, treating coal to reduce pollution may be more economical than transporting low-sulfur coal from the western states.

Table 15.2 U.S. COAL RESOURCES

TYPE OF COAL	RELATIVE RANK	ENERGY OF CONTENT (MILLIONS OF JOULES/KG)	SULFUR CONTENT (%) LOW (0–1)	MEDIUM (1.1–3.0)	HIGH (3 +)
Anthracite	1	30–34	97.1	2.9	–
Bituminous Coal	2	23–34	29.8	26.8	43.4
Subbituminous Coal	3	16–23	99.6	0.4	–
Lignite	4	13–16	90.7	9.3	–

Sources: U.S. Bureau of Mines Circular 8312, 1966: P. Averitt, "Coal" in D.A. Brobst and W.P Pratt, eds., United States Mineral Resources, *U.S. Geological Survey, Professional Paper* 820, pp 133–142.

Coal Mining and the Environment

In the United States, thousands of square kilometers of land have been disturbed by coal mining, and only about half this land has been reclaimed. Reclamation is the process of restoring and improving disturbed land, often by re-forming the surface and replanting vegetation (see Chapter 9). Unreclaimed coal dumps from open-pit mines are numerous and continue to cause environmental problems. Because little reclamation occurred before about 1960, and mining started much earlier, abandoned mines are common in the United States. One surface mine in Wyoming, abandoned more than 40 years ago, caused a disturbance so intense that vegetation has still not been reestablished on the waste dumps. Such barren, ruined landscapes emphasize the need for reclamation.[18]

Strip Mining

Over half of the coal mining in the United States is done by *strip mining*, a surface mining process in which the overlying layer of soil and rock is stripped off to reach the coal. The practice of strip mining started in the late 19th century and has steadily increased because it tends to be cheaper and easier than underground mining. More than 40 billion metric tons of coal reserves are now accessible to surface mining techniques. In addition, approximately 90 billion metric tons of coal within 50 m (165 ft) of the surface are potentially available for strip mining. More and larger strip mines will likely be developed as the demand for coal increases.

The impact of large strip mines varies from region to region, depending on topography, climate, and reclamation practices. One serious problem in the eastern United States that get abundant rainfall is *acid mine drainage*—the drainage of acidic water from mine sites (see Chapter 19). Acid mine drainage occurs when surface water (H_2O) infiltrates the spoil banks (rock debris left after the coal is removed). The water reacts chemically with sulfide minerals, such as pyrite (FeS_2), a natural component of some sedimentary rocks containing coal, to produce sulfuric acid (H_2SO_4). The acid then pollutes streams and groundwater (Figure15.13). Acid water also drains from underground mines and from roads cut in areas where coal and pyrite are abundant, but the problem of acid mine drainage is magnified when large areas of disturbed material remain exposed to surface waters.

FIGURE 15.13 Tar Creek near Miami, Oklahoma, runs orange in 2003 due to contamination by heavy metals from acid mine drainage.

FIGURE 15.14 **Strip coal mine in Wyoming**. The land in the foreground is being mined, and the green land in the background has been reclaimed after mining.

Acid mine drainage from active mines can be minimized by channeling surface runoff or groundwater before it enters a mined area and diverting it around the potentially polluting materials. However, diversion is not feasible in heavily mined regions where spoil banks from unreclaimed mines may cover hundreds of square kilometers. In these areas, acid mine drainage will remain a long-term problem.

Water problems associated with mining are not as pronounced in arid and semiarid regions as they are in wetter regions, but the land may be more sensitive to activities related to mining, such as exploration and road building. In some arid areas of the western and southwestern United States, the land is so sensitive that tire tracks can remain for years. (Indeed, wagon tracks from the early days of the westward migration reportedly have survived in some locations.) To complicate matters, soils are often thin, water is scarce, and reclamation work is difficult.

Strip mining has the potential to pollute or damage water, land, and biological resources. However, good reclamation practices can minimize the damage (Figure 15.14). Reclamation practices required by law necessarily vary by site. Some of the principles of reclamation are illustrated in the case history of a modern coal mine in Colorado (see A Closer Look 15.2).

Large surface coal mining is almost always controversial. One of the most controversial has been the Black Mesa Mine in Arizona. The mine is in the Black Mesa area of the Hopi Reservation and was the only supplier of coal to the very large 1.5-MW Mohave Generating Station, a power plant at Laughlin, Nevada (144 km, or 90 mi, southeast of Las Vegas). The coal was delivered to the plant by a 440-km (275-mi) pipeline that transported slurry (crushed coal and water). The pipeline used over 1 billion gallons of water pumped from the ground per year—water that nourishes sacred springs and water for irrigation. Both the mine and the power plant suspended operation on December 31, 2005.

Mountaintop Removal

Coal mining in the Appalachian Mountains of West Virginia is a major component of the state's economy. However, there is growing environmental concern about a strip-mining technique known as "mountaintop removal" (Figure 15.16). This technique is very effective in obtaining coal as it levels the tops of mountains. But as mountaintops are destroyed, valleys are filled with waste rock and other mine waste, and the flood hazard increases as toxic wastewater is stored behind coal-waste sludge dams. Several hundred mountains have been destroyed, and by 2103 over 3,840 km (2,400 mi) of stream channels will likely have been damaged or destroyed.[19]

In October 2000, one of the worst environmental disasters in the history of mining in the Appalachian Mountains occurred in southeastern Kentucky. About 1 million cubic meters (250 million gallons) of toxic, thick black coal sludge, produced when coal is processed, was released into the environment. Part of the bottom of the impoundment (reservoir) where the sludge was being stored collapsed, allowing the sludge to enter an abandoned mine beneath the impoundment. The abandoned mine had openings to the surface, and sludge emerging from the mine flowed across people's yards and roads into a stream of the Big Sandy River drainage. About 100 km (65 mi) of stream was severely contaminated, killing several hundred thousand fish and other life in the stream.

Mountaintop removal also produces voluminous amounts of coal dust that settles on towns and fields, polluting the land and causing or exacerbating lung diseases, including asthma. Protests and complaints by communities in the path of mining were formerly ignored but are now getting more attention from state mining boards. As people become better educated about mining laws, they are more effective in confronting mining companies to get them to reduce potential adverse consequences of mining. However, much more needs to be done.

Those in favor of mountaintop mining emphasize its value to the local and regional economy. They further argue that only the mountaintops are removed, leaving most of the mountain, with only the small headwater streams filled with mining debris. They go on to say that

A CLOSER LOOK 15.2

The Trapper Mine

The Trapper Mine on the western slope of the Rocky Mountains in northern Colorado is a good example of a new generation of large coal strip mines. The operation, in compliance with mining laws, is designed to minimize environmental degradation, including damage to land farming and to grazing of livestock and big game. A landslide in 2006 impacted 102 hectares (200 acres) of the mine and caused a rethinking of the landslide hazard at the mine.

Over a 35-year period, the mine will produce 68 million metric tons of coal from the 20–24 km (50–60 mi^2) site, to be delivered to a 1,300-MW power plant adjacent to the mine. Today the mine produces about 2 million tons of coal per year, enough power for about half a million homes. Four coal seams, varying in thickness from about 1 to 4 m (3.3–13.1 ft), will be mined. The seams are separated by layers of rock, called overburden (rocks without coal), and there is additional overburden above the top seam of coal. The depth of the overburden varies from 0 to about 50 m (165 ft).

A number of steps are involved in the actual mining. First, bulldozers and scrapers remove the vegetation and topsoil from an area up to 1.6 km long and 53 m wide (1 mi by 175 ft), and the soil is stockpiled for reuse. Then the overburden is removed with a 23-m^3 (800-ft) dragline bucket. Next, the exposed coal beds are drilled and blasted to fracture the coal, which is removed with a backhoe and loaded onto trucks (Figure 15.15). Finally, the cut is filled, the topsoil replaced, and the land either planted with a crop or returned to rangeland.

(a)

(b)

FIGURE 15.15 **(a)** Mining an exposed coal bed at the Trapper Mine, in Colorado; and **(b)** the land during restoration following mining. Topsoil (lower right) is spread prior to planting of vegetation.

At the Trapper Mine, the land is reclaimed without artificially applying water. Precipitation (mostly snow) is about 35 cm/year (about 14 in./year), which is sufficient to reestablish vegetation if there is adequate topsoil. That reclamation is possible at this site emphasizes an important point about reclamation: It is site-specific—what works at one location may not be applicable to other areas. Drainage of reclaimed land has been improved.

Water and air quality are closely monitored at the Trapper Mine. Surface water is diverted around mine pits, and groundwater is intercepted while pits are open. "Settling basins," constructed downslope from the pit, allow suspended solids in the water to settle out before the water is discharged into local streams. Although air quality at the mine can be degraded by dust from the blasting, hauling, and grading of the coal, the dust is minimized by regular sprinkling of water on the dirt roads. Recently, drainage from reclaimed lands has been redesigned to use a sinuous channel rather than a straighter one to slow down sediment deposition, reduce erosion, and minimize maintenance of the channels.

Reclamation at the Trapper Mine has been successful during the first years of operation. In fact, the U.S. Department of the Interior named it one of the best examples of mine reclamation. Although reclamation increases the cost of the coal as much as 50%, it will pay off in the long-range productivity of the land as it is returned to farming and grazing. Wildlife also thrives; the local elk population has significantly increased, and the reclaimed land is home to sharp-tailed grouse, a threatened species.

On the one hand, it might be argued that the Trapper Mine is unique in its combination of geology, hydrology, and topography, which has allowed for successful reclamation. To some extent this is true, and perhaps the Trapper Mine presents an overly optimistic perspective on mine reclamation compared with sites that have less favorable conditions. On the other hand, the success of the mine operation demonstrates that with careful site selection and planning, the development of energy resources can be compatible with other land uses.

FIGURE 15.16 Mountaintop mining in West Virginia has been criticized as damaging to the environment as vegetation is removed, stream channels are filled with rock and sediment, and the land is changed forever.

the mining, following reclamation, produces flat land for a variety of uses, such as urban development, in a region where flat land is mostly on floodplains with fewer potential uses.

Since the adoption of the Surface Mining Control and Reclamation Act of 1977, the U.S. government has required that mined land be restored to support its premining use. The regulations also prohibit mining on prime agricultural land and give farmers and ranchers the opportunity to restrict or prohibit mining on their land, even if they do not own the mineral rights. Reclamation includes disposing of wastes, contouring the land, and replanting vegetation.

Reclamation is often difficult and unlikely to be completely successful. In fact, some environmentalists argue that reclamation success stories are the exception and that strip mining should not be allowed in the semiarid southwestern states because reclamation is uncertain in that fragile environment.

Underground Mining

Underground mining accounts for approximately 40% of the coal mined in the United States and poses special risks both for miners and for the environment. The dangers to miners have been well documented over the years in news stories, books, and films. Hazards include mine shaft collapses (cave-ins), explosions, fires, and respiratory illnesses, especially the well-known black lung disease, which is related to exposure to coal dust, which has killed or disabled many miners over the years.

Some of the environmental problems associated with underground mining include the following:

- Acid mine drainage and waste piles have polluted thousands of kilometers of streams (see Chapter 19).
- Land subsidence can occur over mines. Vertical subsidence occurs when the ground above coal mine tunnels collapses, often leaving a crater-shaped pit at the surface (Figure 15.17). Coal-mining areas in Pennsylvania and West Virginia, for example, are well known for serious subsidence problems. In recent years, a parking lot and crane collapsed into a hole over a coal mine in Scranton, Pennsylvania; and damage from subsidence caused condemnation of many buildings in Fairmont, West Virginia.
- Coal fires in underground mines, either naturally caused or deliberately set, may belch smoke and hazardous fumes, causing people in the vicinity to suffer from a variety of respiratory diseases. For example, in Centralia, Pennsylvania, a trash fire set in 1961 lit nearby underground coal seams on fire. They are still burning today and have turned Centralia into a ghost town.

Transporting Coal

Transporting coal from mining areas to large population centers where energy is needed is a significant environmental issue. Although coal can be converted at the

FIGURE 15.17 Subsidence below coal mines in the Appalachian coal belt.

production site to electricity, synthetic oil, or synthetic gas, these alternatives have their own problems. Power plants for converting coal to electricity require water for cooling, and in semiarid coal regions of the western United States there may not be sufficient water. Furthermore, transmitting electricity over long distances is inefficient and expensive (see Chapter 14). Converting coal to synthetic oil or gas also requires a huge amount of water, and the process is expensive.[20, 21]

Freight trains and coal-slurry pipelines (designed to transport pulverized coal mixed with water) are options to transport the coal itself over long distances. Trains are typically used, and will continue to be used, because they provide relatively low-cost transportation compared with the cost of constructing pipelines. The economic advantages of slurry pipelines are tenuous, especially in the western United States, where large volumes of water to transport the slurry are not easily available.

The Future of Coal

The burning of coal produces nearly 50% of the electricity used and about 25% of the total energy consumed in the United States today. Coal accounts for nearly 90% of the fossil fuel reserves in the United States, and we have enough coal to last at least several hundred years. However, there is serious concern about burning that coal. Giant power plants that burn coal as a fuel to produce electricity in the United States are responsible for about 70% of the total emissions of sulfur dioxide, 30% of the nitrogen oxides, and 35% of the carbon dioxide. (The effects of these pollutants are discussed in Chapter 21.)

Legislation as part of the Clean Air Amendments of 1990 mandated that sulfur dioxide emissions from coal-burning power plants be eventually cut by 70–90%, depending on the sulfur content of the coal, and that nitrogen oxide emissions be reduced by about 2 million metric tons per year. As a result of this legislation, utility companies are struggling with various new technologies designed to reduce emissions of sulfur dioxide and nitrogen oxides from burning coal. Options being used or developed include the following:[21, 22]

- Chemical and/or physical cleaning of coal prior to combustion.
- Producing new boiler designs that permit a lower temperature of combustion, reducing emissions of nitrogen oxides.
- Injecting material rich in calcium carbonate (such as pulverized limestone or lime) into the gases produced by the burning of coal. This practice, known as **scrubbing**, removes sulfur dioxides. In the scrubber—a large, expensive component of a power plant—the carbonate reacts with sulfur dioxide, producing hydrated calcium sulfite as sludge. The sludge has to be collected and disposed of, which is a major problem.
- Converting coal at power plants into a gas (syngas, a methane-like gas) before burning. This technology is being tested and may become commercial by 2013 at the Polk Power Station in Florida. The syngas, though cleaner-burning than coal, is still more polluting than natural gas.
- Converting coal to oil: We have known how to make oil (gasoline) from coal for decades. Until now, it has been thought too expensive. South Africa is doing this now, producing over 150,000 barrels of oil per day from coal, and China in 2009 finished construction of a plant in Mongolia. In the United States, we could produce 2.5 million barrels per day, which would require about 500 million tons of coal per year by 2020. There are environmental consequences, however, as superheating coal to produce oil generates a lot of carbon dioxide (CO_2), the major greenhouse gas.
- Educating consumers about energy conservation and efficiency to reduce the demand for energy and, thus, the amount of coal burned and emissions released.
- Developing zero-emission coal-burning electric power plants. Emissions of particulates, mercury, sulfur dioxides, and other pollutants would be eliminated by physical and chemical processes. Carbon dioxide would be eliminated by injecting it deep into the earth or using a chemical process to sequester it (tie it up) with calcium or magnesium as a solid. The concept of zero emission is in the experimental stages of development.

The bottom line is that as oil prices rise, coal is getting a lot of attention in the attempt to find ways to lessen the economic shock . The real shortages of oil and gas may still be a few years away, but when they come, they will put pressure on the coal industry to open more and larger mines in both the eastern and western coal beds of the United States. Increased use of coal will have significant environmental impacts for several reasons.

First, more and more land will be strip-mined and will therefore require careful and expensive restoration.

Second, unlike oil and gas, burning coal, as already mentioned, produces large amounts of air pollutants. It also creates ash, which can be as much as 20% of the coal burned; boiler slag, a rocklike cinder produced in the furnace; and calcium sulfite sludge, produced from removing sulfur through scrubbing. Coal-burning power plants in the United States today produce about 90 million tons of these materials per year. Calcium sulfite from scrubbing can be used to make wallboard (by converting calcium sulfite to calcium sulfate, which is gypsum) and other products. Gypsum is being produced for wallboard this way in Japan and Germany, but the United States can make wallboard less expensively from abundant natural gypsum deposits. Another waste product, boiler slag, can be used for fill along railroad tracks and at construction projects. Nevertheless, about 75% of the combustion products of burning coal in the United States today end up in waste piles or landfills.

Third, handling large quantities of coal through all stages (mining, processing, shipping, combustion, and final disposal of ash) could have adverse environmental effects. These include aesthetic degradation, noise, dust, and—most significant from a health standpoint—release of toxic or otherwise harmful trace elements into the water, soil, and air. For example, in late December 2008, the retaining structure of an ash pond at the Kingston Fossil Plant in Tennessee failed, releasing a flood of ash and water that destroyed several homes, ruptured a gas line, and polluted a river.[23]

All of these negative effects notwithstanding, it seems unlikely that the United States will abandon coal in the near future because we have so much of it and have spent so much time and money developing coal resources. Some suggest that we should now promote the use of natural gas in preference to coal because it burns so much cleaner, but that raises the valid concern that we might then become dependent on imports of natural gas. Regardless, it remains a fact that coal is the most polluting of all the fossil fuels.

Allowance Trading

An innovative approach to managing U.S. coal resources and reducing pollution is **allowance trading**, through which the Environmental Protection Agency grants utility companies tradable allowances for polluting: One allowance is good for one ton of sulfur dioxide emissions per year. In theory, some companies wouldn't need all their allowances because they use low-sulfur coal or new equipment and methods that have reduced their emissions. Their extra allowances could then be traded and sold by brokers to utility companies that are unable to stay within their allocated emission levels. The idea is to encourage competition in the utility industry and reduce overall pollution through economic market forces.[22]

Some environmentalists are not comfortable with the concept of allowance trading. They argue that although buying and selling may be profitable to both parties in the transaction, it is less acceptable from an environmental viewpoint. They believe that companies should not be able to buy their way out of taking responsibility for pollution problems.

15.4 Oil Shale and Tar Sands

Oil shale and tar sands play a minor role in today's mix of available fossil fuels, but they may be more significant in the future, when traditional oil from wells becomes scarce.

Oil Shale

Oil shale is a fine-grained sedimentary rock containing organic matter (kerogen). When heated to 500°C (900°F) in a process known as *destructive distillation*, oil shale yields up to nearly 60 liters (14 gallons) of oil per ton of shale. If not for the heating process, the oil would remain in the rock. The oil from shale is one of the so-called **synfuels** (from the words *synthetic* and *fuel*), which are liquid or gaseous fuels derived from solid fossil fuels. The best-known sources of oil shale in the United States are found in the Green River formation, which underlies approximately 44,000 km^2 (17,000 mi^2) of Colorado, Utah, and Wyoming.

Total identified world oil shale resources are estimated to be equivalent to about 3 trillion barrels of oil. However, evaluation of the oil grade and the feasibility of economic recovery with today's technology is not complete. Oil shale resources in the United States amount to about 2 trillion bbl of oil, or two-thirds of the world total. Of this, 90%, or 1.8 trillion bbl, is located in the Green River oil shales. The total oil that could be removed from U.S. oil shale deposits is about 100 billion barrels. This exceeds the oil reserves of the Middle East! But extraction is not easy, and environmental impacts would be serious.[24, 25]

The environmental impact of developing oil shale varies with the recovery technique used. Both surface and subsurface mining techniques have been considered. Surface mining is attractive to developers because nearly 90% of the shale oil can be recovered, compared with less than 60% by underground mining. However, waste disposal is a major problem with either surface or subsurface mining. Both require that oil shale be processed, or *retorted* (crushed and heated), at the surface. The volume of waste will exceed the original volume of shale mined by 20–30% because crushed rock has pore spaces and thus more volume than the solid rock had. (If you doubt this, pour some concrete into a milk carton, remove it when it hardens, and break it into small pieces with a hammer. Then try to put the pieces back into the carton.) Thus, the mines from which the shale is removed will not be able to accommodate all the waste, and its disposal will become a problem.[12]

Although it is much more expensive to extract a barrel of oil from shale than to pump it from a well, interest in oil shale was heightened by an oil embargo in 1973 and by fear of continued shortages of crude oil. In the 1980s through the mid-1990s, however, plenty of cheap oil was available, so oil-shale development was put on the back burner. Today, when it is clear that we will face oil shortages in the future, we are seeing renewed interest in oil shale,[25] and it is clear that any steep increases in oil prices will likely heighten this interest. This would result in significant environmental, social, and economic impacts in the oil shale areas, including rapid urbanization to house a large workforce, construction of industrial facilities, and increased demand on water resources.

Tar Sands

Tar sands are sedimentary rocks or sands impregnated with tar oil, asphalt, or bitumen. Petroleum cannot be recovered from tar sands by pumping wells or other usual commercial methods because the oil is too viscous (thick) to flow easily. Oil in tar sands is recovered by first mining the sands—which are very difficult to remove—and then washing the oil out with hot water. It takes about two tons of tar sand to produce one barrel of oil.

About 19% of U.S. oil imports come from Canada, and about one-half of this is from tar sands.[26] Some 75% of the world's known tar sand deposits are in the Athabasca Tar Sands near Alberta, Canada. The total Canadian resource that lies beneath approximately 78,000 km^2 (30,116 mi^2) of land is about 300 billion barrels that might be recovered. About half of this (173 billion barrels) can be economically recovered today.[26] Production of the Athabasca Tar Sands is currently about 1.2 million barrels of synthetic crude oil per day. Production will likely increase to about 3 million barrels per day in the next decade or so.

In Alberta, tar sand is mined in a large open-pit mine (Figure 15.18). The mining process is complicated by the fragile native vegetation, a water-saturated mat known as a muskeg swamp—a kind of wetland that is difficult to remove except when frozen. The mining of the tar sands does have environmental consequences, ranging from a rapid increase in the human population in mining areas to the need to reclaim the land disturbed by the mining. Restoration of this fragile, naturally frozen (permafrost) environment is difficult. There is also a waste-disposal problem because the mined sand material, like the mined oil shale just discussed, has a greater volume than the unmined material. The land surface can be up to 20 m (66 ft) higher after mining than it was originally. The Canadian approach is to require that the land be returned not to its original use but to some equivalent use, such as turning what was forestland into grazing land.[27]

FIGURE 15.18 Mining tar sands north of Fort McMurray in Alberta, Canada. The large shovel-bucket holds about 100 tons of tar sand. It takes about two tons of tar sand to produce one barrel of oil.

CRITICAL THINKING ISSUE

What Will Be the Consequences of Peak Oil?

The summer of 2008 brought record oil prices. By late May the price had risen to $133 per barrel. Each barrel has 42 gallons. That is $3.17 per gallon of oil, before being shipped, refined, and taxed! Consider the following:[28]

1. Oil doubled in price from 2007 to 2008, then dropped to about $70 per barrel as demand declined. The price remains very uncertain.
2. Grain production increased from about 1.8 billion tons to 2.15 billion tons per year from 2002 to 2008.
3. The global food price index rose about 30% from 2007 to 2008. Sugar prices rose about 40% and grain prices about 90%. Wheat that cost about $375 per ton in 2006 soared to more than $900 in 2008. Large discount stores in the United States in 2008 set limits on the amount of rice that a person could purchase.
4. World biofuel (biodiesel and bioethanol) production increased from about 6.4 billion gallons per year in 2000 to just over 20 billion gallons in 2008, and probably will continue to rise rapidly. In the late 1990s the United States used about 5% of corn production for biofuel (ethanol); in 2009 it used 25% for this purpose.
5. Our worldwide safety net of grain stocks on hand declined from about 525 million tons in 2000 to about 300 million tons in 2008.

Critical Thinking Questions

Assume oil prices will remain unstable:

1. Examine Figure 15.19. What are the main points you can conclude from reading the graph? (*Hint:* Look closely at the shape of the curves and the labeling.) Summarize your thoughts.
2. How is the above information linked? (*Hint:* Make linkages between Figure 15.19 and points 1–5 above.) Summarize your thoughts.
3. What will be the differences in the potential economic and environmental impacts on countries ranging from poor to rich?
4. Should the United States stop producing corn for biofuel?
5. Will famine in the future be due to rising food prices? Why? Why not?
6. Do you think food riots may lead to civil wars in some countries?
7. What solutions can you offer to minimize the impacts of increasing energy costs tied to food production and cost?

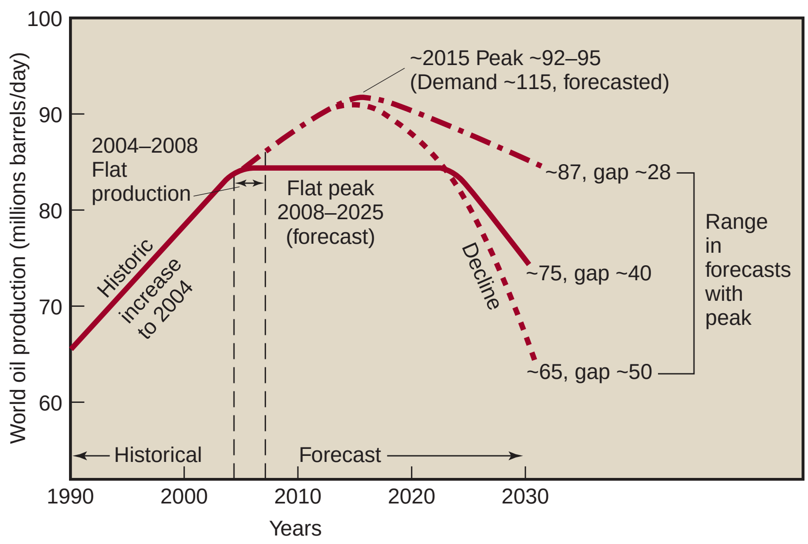


FIGURE 15.19 Peak oil with two scenarios: a long, flat peak with production as it is today; and a sharper peak in about 2015. In either case, there are significant shortages (gap between production and demand). (*Source*: Data from P. Roberts, "Tapped Out," *National Geographic* 213, no. 6 (2008):86–91.)

SUMMARY

- The United States has an energy problem caused by dependence on fossil fuels, especially oil. Maximum global production (peak oil) is expected between 2020 and 2050, followed by a decline in production. The challenge is to plan now for the decline in oil supply and a shift to alternative energy sources.
- Fossil fuels are forms of stored solar energy. Most are created from the incomplete biological decomposition of dead and buried organic material that is converted by complex chemical reactions in the geologic cycle.
- Because fossil fuels are nonrenewable, we will eventually have to develop other sources to meet our energy demands. We must decide when the transition to alternative fuels will occur and what the impacts of the transition will be.
- Environmental impacts related to oil and natural gas include those associated with exploration and development (damage to fragile ecosystems, water pollution, air pollution, and waste disposal); those associated with refining and processing (pollution of soil, water, and air); and those associated with burning oil and gas for energy to power automobiles, produce electricity, run industrial machinery, heat homes, and so on (air pollution).
- Coal is an energy source that is particularly damaging to the environment. The environmental impacts of mining, processing, transporting, and using coal are many. Mining coal can cause fires, subsidence, acid mine drainage, and difficulties related to land reclamation. Burning coal can release air pollutants, including sulfur dioxide and carbon dioxide, and produces a large volume of combustion products and by-products, such as ash, slag, and calcium sulfite (from scrubbing). The environmental objective for coal is to develop a zero-emission power plant.

REEXAMINING THEMES AND ISSUES

Human Population

As the human population (particularly in developed countries, such as the United States) has increased, so has the total impact from the use of fossil fuels. Total impact is the impact per person times the total number of people. Reducing the impact will require that all countries adopt a new energy paradigm emphasizing use of the minimum energy needed to complete a task (end use) rather than the current prodigious overuse of energy.

Sustainability

It has been argued that we cannot achieve sustainable development and maintenance of a quality environment for future generations if we continue to increase our use of fossil fuels. Achieving sustainability will require wider use of a variety of alternative renewable energy sources and less dependence on fossil fuels.

Global Perspective

The global environment has been significantly affected by burning fossil fuels. This is particularly true for the atmosphere, where fast-moving processes operate (see Chapters 20 and 21). Solutions to global problems from burning fossil fuels are implemented at the local and regional levels, where the fuels are consumed.

Urban World

The burning of fossil fuels in urban areas has a long history of problems. Not too many years ago, black soot from burning coal covered the buildings of most major cities of the world, and historical pollution events killed thousands of people. Today, we are striving to improve our urban environments and reduce urban environmental degradation from burning fossil fuels.

People and Nature

Our exploration, extraction, and use of fossil fuels have changed nature in fundamental ways—from the composition of the atmosphere and the disturbance of coal mines to the pollution of ground and surface waters. Some people still buy giant SUVs supposedly to connect with nature, but using them causes more air pollution than do automobiles and, if used off-road, often degrades nature.

Science and Values

Scientific evidence of the adverse effects of burning fossil fuels is well documented. The controversy over their use is linked to our values. Do we value burning huge amounts of fossil fuels to increase economic growth more highly than we value living in a quality environment? Economic growth is possible without damaging the environment; developing a sustainable energy policy that doesn't harm the environment is possible with present technology. What is required are changes in values and lifestyle that are linked to energy production and use, human well-being, and environmental quality.

KEY TERMS

allowance trading **321**
coal **314**
crude oil **306**
fossil fuels **305**
methane hydrate **310**
natural gas **306**
oil shale **321**
peak oil **304**
scrubbing **320**
synfuels **321**
tar sands **322**

STUDY QUESTIONS

1. Assuming that oil production will peak in about 2020 and then decline about 3% per year, when will production be half of that in 2020? What could be the consequences, both good and bad? Why? How might negative consequences be avoided?
2. Compare the potential environmental consequences of burning oil, burning natural gas, and burning coal.
3. What actions can you personally take to reduce consumption of fossil fuels?
4. What environmental and economic problems could result from a rapid transition from fossil fuels to alternative sources?
5. The transition from wood to fossil fuels took about 100 years. How long do you think the transition from fossil fuels to alternative energy sources will take? What will determine the time of transition?
6. What are some of the technical solutions to reducing air-pollutant emissions from burning coal? Which are best? Why?
7. What do you think of the idea of allowance trading as a potential solution to reducing pollution from burning coal?
8. Do you think we can develop a zero-emission coal-burning power plant? What about for natural gas?
9. Discuss how the rising cost of energy is linked to food supply and environmental problems.
10. What are the ethical issues associated with the energy problems? Is a child born in 2050 more important than a child today? Why or why not?

FURTHER READING

Boyl, G., B. Everett, and J. Ramage, ***Energy Systems and Sustainability*** (Oxford (UK): Oxford University Press, 2003). An excellent discussion of fossil fuel.

British Petroleum Company, ***B.P. Statistical Review of World Energy*** (London: British Petroleum Company, 2010). Good, up-to-date statistics on fossil fuels.

CHAPTER 16

Alternative Energy and the Environment

This wind farm in Tarifa, Spain, has a generating capacity of 5 MW produced by just 12 wind turbines.

LEARNING OBJECTIVES

Alternatives to fossil fuels and nuclear energy include biofuels, solar energy, water power, wind power, and geothermal energy. Some of these are already being used, and efforts are under way to develop others. After reading this chapter, you should understand . . .

- The advantages and disadvantages of each kind of alternative energy;
- What passive, active, and photovoltaic solar energy systems are;
- What may be the important fuels of the future;
- Why water power is unlikely to become more important in the future;
- Why wind power has tremendous potential, and how its development and use could affect the environment;
- Whether biofuels are likely to help us move away from fossil fuels;
- What geothermal energy is, and how developing and using it affect the environment.

CASE STUDY

Using Wind Power in New Ways for an Old Application

On March 14, 2008, a new kind of sailing ship, the MV *Beluga SkySails,* completed its maiden voyage of 11,952 nautical miles, sailing from Bremen, Germany, to Venezuela and back carrying heavy industrial equipment (Figure 16.1). *SkySails* is novel in two ways. First of all, it did not use a set of fixed masts with traditional sails that had to be monitored constantly and their settings changed with each variation in the wind, thereby requiring either a large crew or very sophisticated and expensive equipment. Second, wind provided only part of the power—on the maiden voyage 20%—the rest coming from standard marine diesel engines.

Instead, this ship flew a huge kite that spread out over more than 160 square yards. Flying high above the ship, it caught more reliable winds aloft than occur at the surface, and required only a flexible cable to tether it to the ship. Diesel engines provided the steady energy; the kite-sail helped when wind was available, reducing fuel costs by $1,000 a day. With this saving, and also saving the expense of a large crew, *Beluga SkySails* was an economic success. At the end of the voyage, the ship's captain, Lutz Heldt, said, "We can once again actually 'sail' with cargo ships, thus opening a new chapter in the history of commercial shipping."

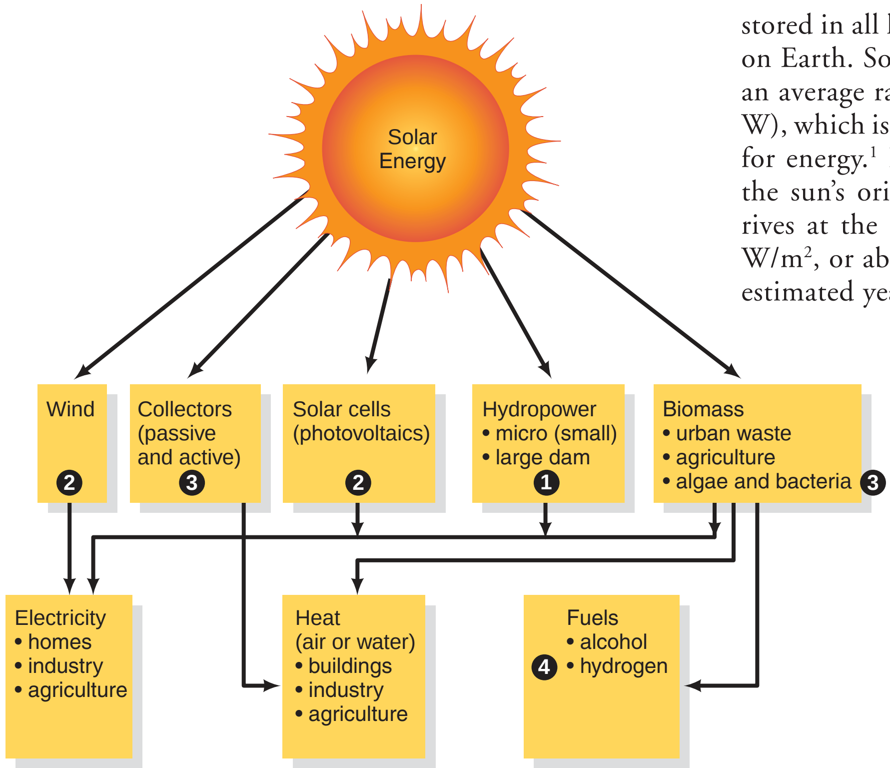
This ship takes another important step in the use of alternative energy, integrating it with another source. Also important is that the kite works *with* natural forces, unlike a traditional sailing ship's rigid masts, which had to withstand the force of the winds. Therefore, the *SkySails* is much less likely to be damaged by storms. These design elements can be helpful as we think through a major transition from fossil fuels to alternative energy.

FIGURE 16.1 Wind power is becoming so popular that it is even making a comeback as a way to propel ships. Here a new kind of sail, actually a cable-tethered kite, helps pull a new ship, the *Beluga SkySails*, through the ocean. (*Source: SkySails* website March 31, 2008. First retrofit SkySails-System aboard a cargo vessel—Initial operation successful SkySails pilot project on board the MS "Michael A." of the WESSELS Reederei GmbH & Co.KG based in Haren/Ems http://www.skysails.info/index.php?id=64&L=1&tx_ttnews[tt_news]=98&tx_ttnews[backP id]=6&cHash=c1a209e350 and http://www.skysails.info/index.php?id=64&L=1&tx_ttnews[tt_news]=104&tx_ttnews[back Pid]=6&cHash=db100ad2b6)

16.1 Introduction to Alternative Energy Sources

As we all know, the primary energy sources today are fossil fuels—they supply approximately 90% of the energy consumed by people. All other sources are considered **alternative energy** and are divided into renewable energy and nonrenewable energy. **Nonrenewable alternative energy** sources include nuclear energy (discussed in Chapter 17) and deep-earth geothermal energy (the energy from the Earth's geological processes). This kind of geothermal energy is considered nonrenewable for the most part because heat can be extracted from Earth faster than it is naturally replenished—that is, output exceeds input (see Chapter 3). Nuclear energy is nonrenewable because it requires a mineral fuel mined from Earth.

The **renewable energy** sources are solar; freshwater (hydro); wind; ocean; low-density, near-surface geothermal; and biofuels. Low-density, near-surface geothermal



1 Produces most electricity from renewable solar energy
2 Rapidly growing, strong potential (Wind and solar are growing at 30% per year.)
3 Used today; important energy source
4 Potentially a very important fuel to transition from fossil fuels

FIGURE 16.2 Routes of various types of renewable solar energy.

is simply solar energy stored by soil and rock near the surface. It is widespread and easily obtained and is renewed by the sun. Biofuels are made from biomass (crops, wood, and so forth). Renewable energy sources are often discussed as a group because they all derive from the sun's energy (Figure 16.2). We consider them renewable because they are regenerated by the sun within a time period useful to people.

The total energy we may be able to extract from alternative energy sources is enormous. For example, the estimated recoverable energy from solar energy is about 75 times as much as all the people of the world use each year. The estimated recoverable energy from wind alone is comparable to current global energy consumption.

16.2 Solar Energy

The total amount of solar energy reaching Earth's surface is tremendous. For example, on a global scale, ten weeks of solar energy is roughly equal to the energy stored in all known reserves of coal, oil, and natural gas on Earth. Solar energy is absorbed at Earth's surface at an average rate of 90,000 terawatts (1 TW equals 10^{12} W), which is about 7,000 times the total global demand for energy.[1] In the United States, on average, 13% of the sun's original energy entering the atmosphere arrives at the surface (equivalent to approximately 177 W/m^2, or about 16 W/ft^2, on a continuous basis). The estimated year-round availability of solar energy in the United States is shown in Figure 16.3. However, solar energy is site-specific, and detailed observation of a potential site is necessary to evaluate the daily and seasonal variability of its solar energy potential.[2]

Solar energy may be used by passive or active solar systems. **Passive solar energy systems** do not use mechanical pumps or other active technologies to move air or water. Instead, they typically use architectural designs that enhance the absorption of solar energy (Figure 16.4). Since the rise of civilization, many societies have used passive solar energy (see Chapter 22). Islamic architects, for example, have traditionally used passive solar energy in hot climates to cool buildings.

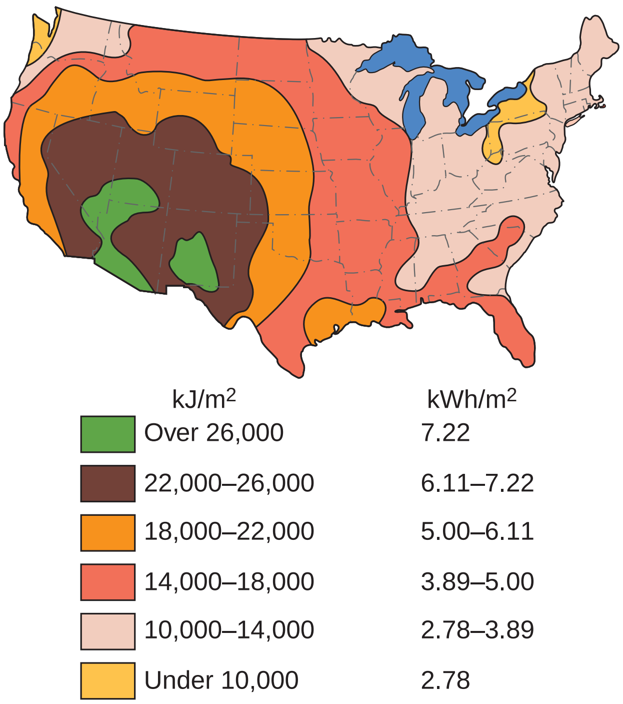
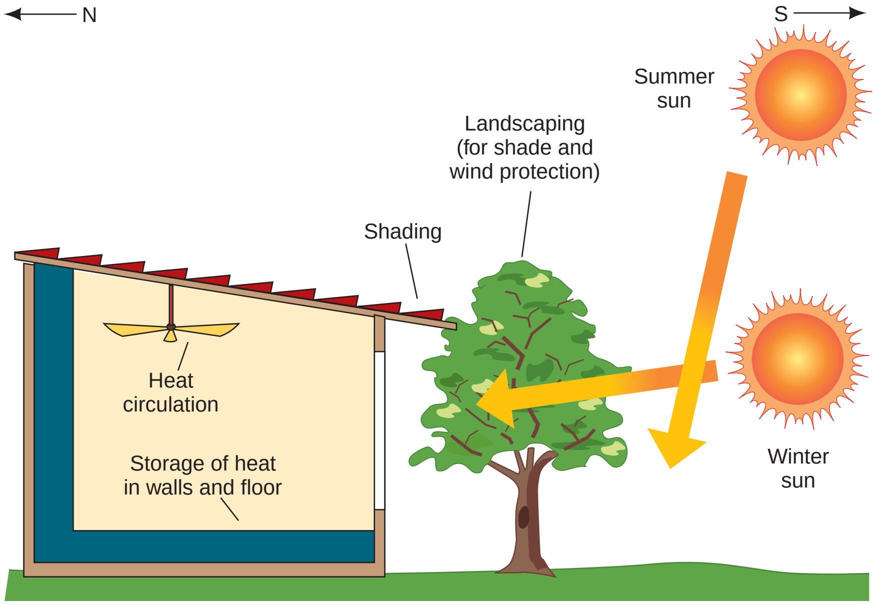


FIGURE 16.3 Estimated solar energy for the contiguous United States. (*Source*: Modified from Solar Energy Research Institute, 1978.)



(a)

(b)

FIGURE 16.4 **(a)** Essential elements of passive solar design. High summer sunlight is blocked by the overhang, but low winter sunlight enters the south-facing window. Deciduous trees shade the building in the summer and allow sunlight to warm it in the winter. These are best located on the southside in the northern hemisphere. Other features are designed to facilitate the storage and circulation of passive solar heat. **(b)** The design of this home uses passive solar energy. Sunlight enters through the windows and strikes a specially designed masonry wall that is painted black. The masonry wall heats up and radiates this heat, warming the house during the day and into the evening. The house is deep set into the ground, which provides winter and summer insolation. It is in a dry climate with few deceduous tres; hence conifers provide some shading. (*Source*: Moran, Morgan, and Wiersma, *Introduction to Environmental Science* [New York: Freeman, 1986]. Copyright by W.H. Freeman & Company. Reprinted with permission.)

Passive Solar Energy

Thousands of buildings in the United States—not just in the sunny Southwest but in other parts of the country, such as New England—now use passive solar systems. Passive solar energy promotes cooling in hot weather and retaining heat in cold weather. Methods include (1) overhangs on buildings to block summer (high-angle) sunlight but allow winter (low-angle) sunlight to penetrate and warm rooms; (2) building a wall that absorbs sunlight during the day and radiates heat that warms the room at night; (3) planting deciduous trees on the sunny side of a building. In summer, these shade and cool the building; in the winter, with the leaves gone, they let the sunlight in.

Passive solar energy also provides natural lighting to buildings through windows and skylights. Modern window glass can have a special glazing that transmits visible light, blocks infrared, and provides insulation.

Active Solar Energy

Active solar energy systems require mechanical power, such as electric pumps, to circulate air, water, or other fluids from solar collectors to a location where the heat is stored and then pumped to where the energy is used.

Solar Collectors

Solar collectors to provide space heating or hot water are usually flat, glass-covered plates over a black background where a heat-absorbing fluid (water or some other liquid) is circulated through tubes (Figure 16.5). Solar radiation enters the glass and is absorbed by the

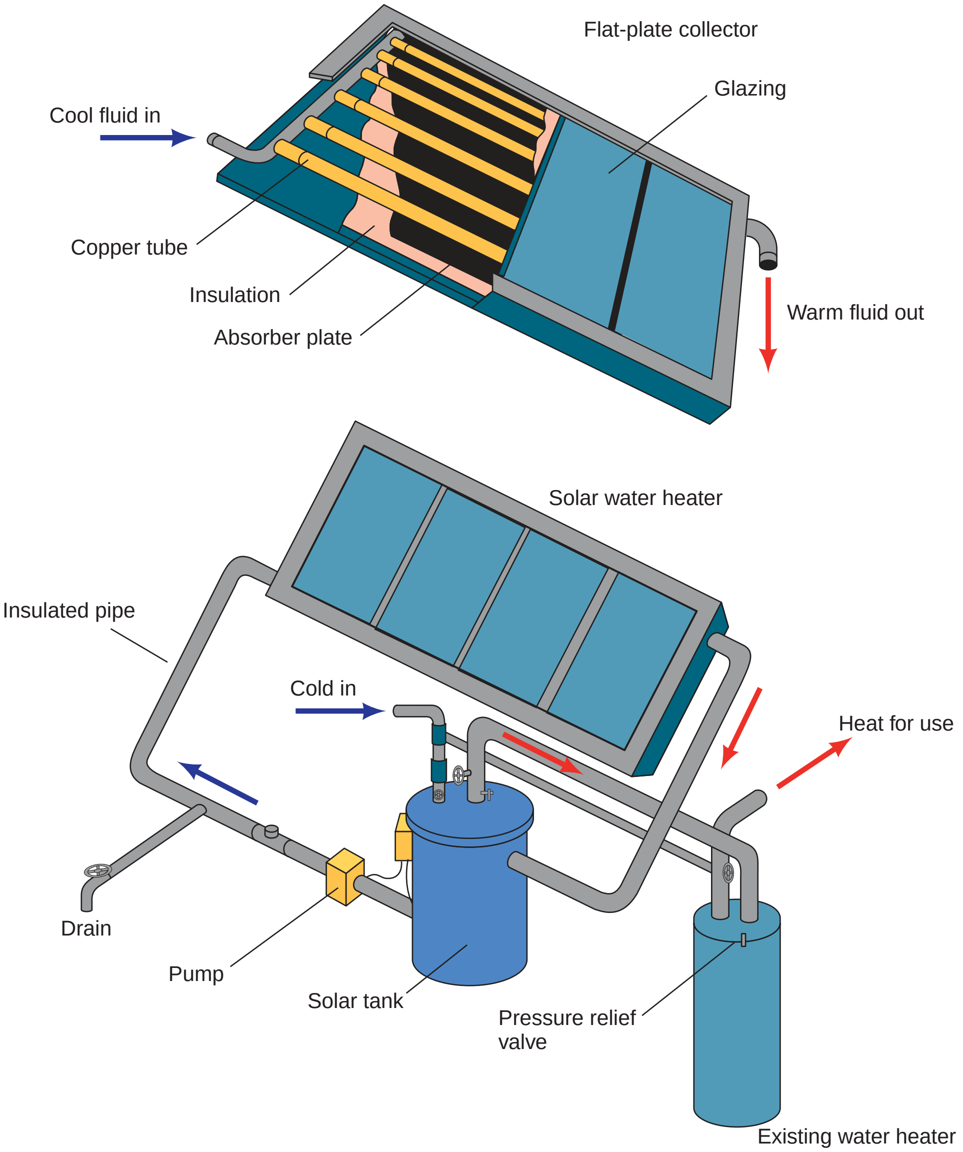


FIGURE 16.5 Detail of a flat-plate solar collector and pumped solar water heater. (*Source*: Farallones Institute, *The Integral Urban House* [San Francisco: Sierra Club Books, 1979]. Copyright 1979 by Sierra Club Books. Reprinted with permission.)

black background. Heat is emitted from the black material, heating the fluid in the tubes.

A second type of solar collector, the evacuated tube collector, is similar to the flat-plate collector, except that each tube, along with its absorbing fluid, passes through a larger tube that helps reduce heat loss. The use of solar collectors is expanding very rapidly; the global market grew about 50% from 2001 to 2004. In the United States, solar water-heating systems generally pay for themselves in only four to eight years.[3]

Photovoltaics

Photovoltaics convert sunlight directly into electricity (Figure 16.6). The systems use solar cells, also called *photovoltaic cells,* made of thin layers of semiconductors (silicon or other materials) and solid-state electronic components with few or no moving parts.

Photovoltaics are the world's fastest growing source of energy, with a growth rate of about 35% per year (doubling every two years). In the United States, the amount of photovoltaics shipped increased 90% between 2007 and 2008, with an average increase of 64% a year since

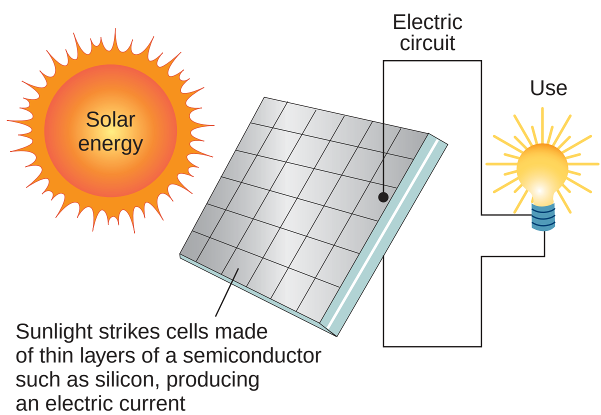


FIGURE 16.6 Idealized diagram illustrating how photovoltaic solar cells work.

(a)  (b)

FIGURE 16.7 **(a)** Panels of photovoltaic cells are used here to power a small refrigerator to keep vaccines cool. The unit is designed to be carried by camels to remote areas in Chad. **(b)** Photovoltaics are used to power emergency telephones along a highway on the island of Tenerife in the Canary Islands. [*Source:* **(a)** H. Gruyaeart/Magnum Photos. Inc. **(b)** Ed Keller]

2005.[4] The photovoltaic industry is expected to grow to $30 billion by 2010.[4]

Solar cell technology is advancing rapidly. While a few decades ago they converted only about 1 or 2% of sunlight into electricity, today they convert as much as 20%. The cells are constructed in standardized modules and encapsulated in plastic or glass, which can be combined to produce systems of various sizes so that power output can be matched to the intended use. Electricity is produced when sunlight strikes the cell. The different electronic properties of the layers cause electrons to flow out of the cell through electrical wires.

Large photovoltaic installations may be connected to an electrical grid. Off-the-grid applications can be large or small and include powering satellites and space vehicles, and powering electric equipment, such as water-level sensors, meteorological stations, and emergency telephones in remote areas (Figure 16.7).

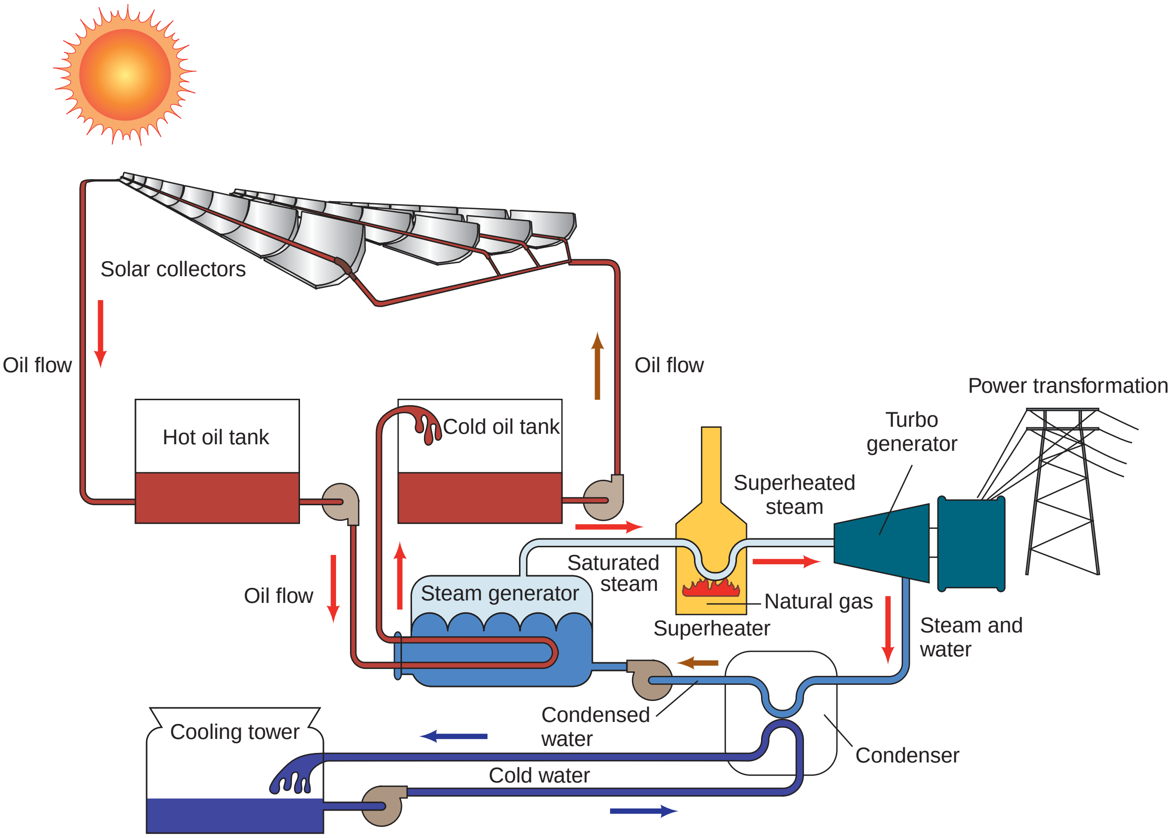
Off-the-grid photovoltaics are emerging as a major contributor to developing countries that can't afford to build electrical grids or large central power plants that burn fossil fuels. One company in the United States is manufacturing photovoltaic systems that power lights and televisions at an installed cost of less than $400 per household.[5] About half a million homes, mostly in villages not linked to a countrywide electrical grid, now receive their electricity from photovoltaic cells.[6]

Solar Thermal Generators

Solar thermal generators focus sunlight onto water-holding containers. The water boils and is used to run such machines as conventional steam-driven electrical generators. These include solar power towers, shown in Figure 16.8. The first large-scale test of using sunlight to boil water and using the steam to run an electric

FIGURE 16.8 Solar power tower at Barstow, California. Sunlight is reflected and concentrated at the central collector, where the heat is used to produce steam to drive turbines and generate electric power. [*Source:* Photograph by Daniel B. Botkin.]

(a)



(b)

FIGURE 16.9 **(a)** Acciona solar thermal power plant, south of Las Vegas, which uses more than 180,000 parabolic mirrors to concentrate sunlight onto pipes containing a fluid that is heated above 300°C. The heated fluid, in turn, boils water, and the steam runs a conventional electrical generating turbine. **(b)** Diagram illustrating how such a system works. (*Source*: Courtesy of LUZ International.)

generator was "Solar One," funded by the U.S. Department of Energy. It was built in 1981 by Southern California Edison and operated by that company along with the Los Angeles Department of Water & Power and the California Energy Commission. Sunlight was concentrated onto the top of the tower by 1,818 large mirrors (each about 20 feet in diameter) that were mechanically linked to each other and tracked the sun. At the end of 1999, this power tower was shut down, in part because the plant was not economically competitive with other sources of electricity. New solar thermal generators are being built with very large output (Figure 16.9).

More recently, solar devices that heat a liquid and produce electricity from steam have used many mirrors without a tower, each mirror concentrating sunlight onto a pipe containing the liquid (as shown in Figures 16.8 and 16.9). This is a simpler system and has been considered cheaper and more reliable.[2]

Solar Energy and the Environment

The use of solar energy generally has a relatively low impact on the environment, but there are some environmental concerns nonetheless. One concern is the large variety of metals, glass, plastics, and fluids used in the manufacture and use of solar equipment. Some of these substances may cause environmental problems through production and by accidental release of toxic materials.

16.3 Converting Electricity from Renewable Energy into a Fuel for Vehicles

An obvious question about solar energy, as well as energy from wind, oceans, and freshwater, is how to convert this energy into a form that we can easily transport and can use to power our motor vehicles. Basically, there are two choices: Store the electricity in batteries and use electrical vehicles, or transfer the energy in the electricity to a liquid or gaseous fuel. Of the latter, the simplest is hydrogen.

An electrical current can be used to separate water into hydrogen and oxygen. Hydrogen can power fuel cells (see A Closer Look 16.1). As the hydrogen is combined again with oxygen, electrons flow between negative and positive poles—that is, an electric current is generated. Hydrogen can be produced using solar and other renewable energy sources and, like natural gas, can be transported in pipelines and stored in tanks. Furthermore, it is a clean fuel; the combustion of hydrogen produces water, so it does not contribute to global warming, air pollution, or acid rain. Hydrogen gas may be an important fuel of the future.[7] It is also possible to do additional chemical conversions, combining hydrogen with the carbon in carbon dioxide to produce methane (a primary component of natural gas) and then combining that with oxygen to produce ethanol, which can also power motor vehicles.

A CLOSER LOOK 16.1

Fuel Cells—An Attractive Alternative

Even if we weren't going to run out of fossil fuels, we would still have to deal with the fact that burning fossil fuels, particularly coal and fuels used in internal combustion engines (cars, trucks, ships, and locomotives), causes serious environmental problems. This is why we are searching not only for alternative energy sources but for those that are environmentally benign ways to convert a fuel to useable ways to generate power.[8] One promising technology uses fuel cells, which produce fewer pollutants, are relatively inexpensive, and have the potential to store and produce high-quality energy.

Fuel cells are highly efficient power-generating systems that produce electricity by combining fuel and oxygen in an electrochemical reaction. (They are not sources of energy but a way to convert energy to a useful form.) Hydrogen is the most common fuel type, but fuel cells that run on methanol, ethanol, and natural gas are also available. Traditional generating technologies require combustion of fuel to generate heat, then convert that heat into mechanical energy (to drive pistons or turbines), and convert the mechanical energy into electricity. With fuel cells, however, chemical energy is converted directly into electricity, thus increasing second-law efficiency (see Chapter 17) while reducing harmful emissions.

The basic components of a hydrogen-burning fuel cell are shown in Figure 16.10. Both hydrogen and oxygen are added to the fuel cell in an electrolyte solution. The hydrogen and oxygen remain separated from one another, and a platinum membrane prevents electrons from flowing directly to the positive side of the fuel cell. Instead, they are routed through an external circuit,

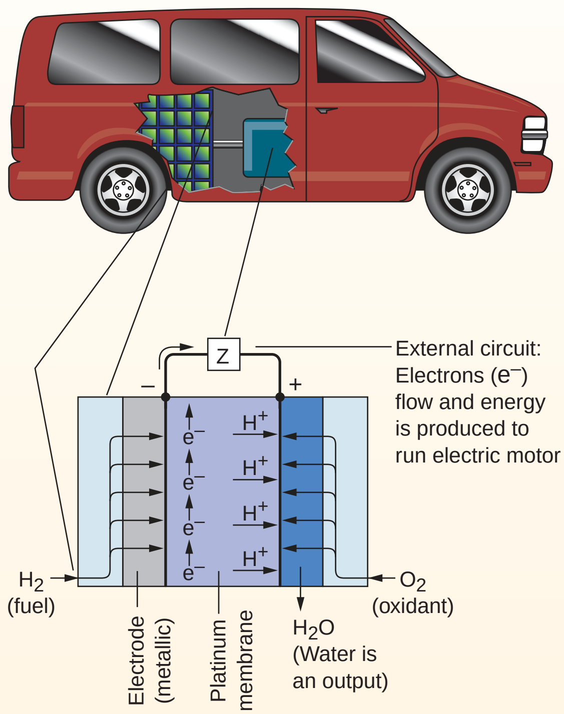


FIGURE 16.10 Idealized diagram showing how a fuel cell works and its application to power a vehicle.

and along the way from the negative to the positive electrode, they are diverted into an electrical motor, supplying current to keep the motor running.[9, 10] To maintain this reaction, hydrogen and oxygen are added as needed. When hydrogen is used in a fuel cell, the only waste product is water.[11]

Fuel cells are efficient and clean, and they can be arranged in a series to produce the appropriate amount of energy for a particular task. In addition, the efficiency of a fuel cell is largely independent of its size and energy output. They can also be used to store energy to be used as needed. Fuel cells are used in many locations. For example, they power buses at Los Angeles International Airport and in Vancouver. They also power a few buses in east San Francisco Bay[13] and provide heat and power at Vandenberg Air Force Base in California.[12] But this experimental technology is expensive, with buses estimated to cost more than $1 million each.[14]

Technological improvements in producing hydrogen are certain, and the fuel price of hydrogen may be substantially lower in the future.[15]

16.4 Water Power

Water power is a form of stored solar energy that has been successfully harnessed since at least the time of the Roman Empire. Waterwheels that convert water power to mechanical energy were turning in Western Europe in the Middle Ages. During the 18th and 19th centuries, large waterwheels provided energy to power grain mills, sawmills, and other machinery in the United States.

Today, hydroelectric power plants use the water stored behind dams. In the United States, hydroelectric plants generate about 80,000 MW of electricity—about 10% of the total electricity produced in the nation. In some countries, such as Norway and Canada, hydroelectric power plants produce most of the electricity used. Figure 16.11a shows the major components of a hydroelectric power station.

Hydropower can also be used to store energy produced by other means, through the process of pump storage (Figure 16.11b and c). During times when demand for power is low, excess electricity produced from oil, coal, or nuclear plants is used to pump water uphill to a higher reservoir (high pool). When demand for electricity is high (on hot summer days, for instance), the stored water flows back down to a low pool through generators to help provide energy. The advantage of pump storage lies in the timing of energy production and use. However, pump storage facilities are generally considered ugly, especially at low water times.

Small-Scale Systems

In the coming years, the total amount of electrical power produced by running water from large dams will probably not increase in the United States, where most of the acceptable dam sites are already in use and some dams are being dismantled (see Chapter 18). However, small-scale hydropower systems, designed for individual homes, farms, or small industries, may be more common in the future. These small systems, known as microhydropower systems, have power output of less than 100 kW.[16]

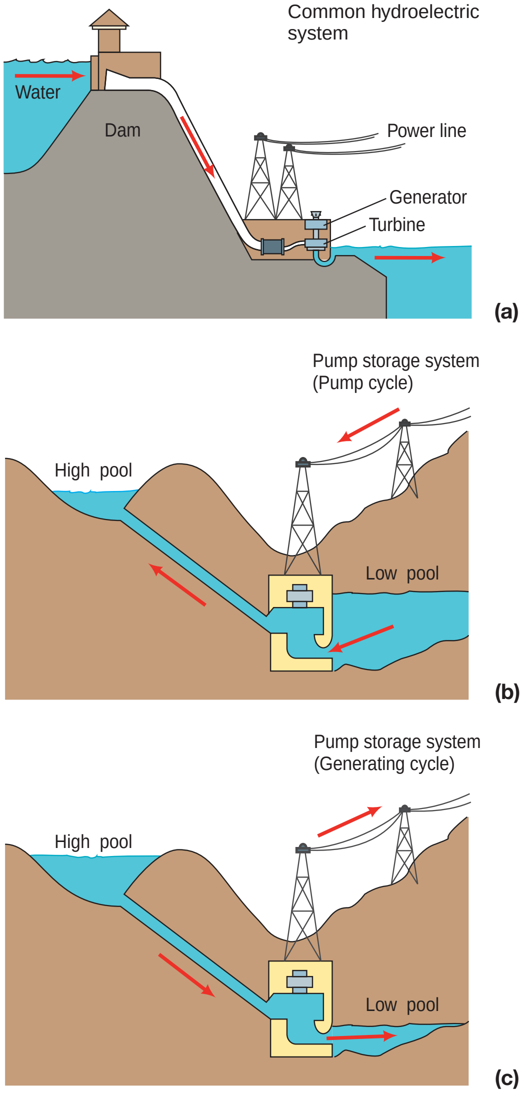


FIGURE 16.11 **(a)** Basic components of a hydroelectric power station. **(b)** A pump storage system. During light power load, water is pumped from low pool to high pool. **(c)** During peak power load, water flows from high pool to low pool through a generator. (*Source*: Modified from the Council on Environmental Quality, *Energy Alternatives: A Comparative Analysis* [Norman: University of Oklahoma Science and Policy Program, 1975].)

Many locations have potential for producing small-scale electrical power, either through small dams or by placing turbines in the free-flowing waters of a river. This is particularly true in mountainous areas, where energy from stream water is often available. Microhydropower development is site-specific, depending on local regulations, economic situations, and hydrologic limitations. Hydropower can be used to generate either electrical power or mechanical power to run machinery. Its use may help reduce the high cost of importing energy and may also help small operations become more independent of local utility providers. However, these systems can interfere with freshwater ecosystems, including fish habitats, and can take away from landscape beauty.

Because small dams can damage stream environments by blocking fish passage and changing downstream flow, careful consideration must be given to their construction. A few small dams cause little environmental degradation beyond the specific sites, but a large number of dams can have an appreciable impact on a region. (This principle applies to many forms of technology and development. The impact of a single development may be nearly negligible over a broad region; but as the number of such developments increases, the total impact may become significant.)

Water Power and the Environment

Water power is clean power in that it requires no burning of fuel, does not pollute the atmosphere, produces no radioactive or other waste, and is efficient. However, there are environmental prices to pay (see Chapter 21):

- Large dams and reservoirs flood large tracts of land that could have had other uses. For example, towns and agricultural lands may be lost.
- Dams block the migration of some fish, such as salmon, and the dams and reservoirs greatly alter habitats for many kinds of fish.
- Dams trap sediment that would otherwise reach the sea and eventually replenish the sand on beaches.
- Reservoirs with large surface areas increase evaporation of water compared to pre-dam conditions. In arid regions, evaporative loss of water from reservoirs is more significant than in more humid regions.
- For a variety of reasons, many people do not want to turn wild rivers into a series of lakes.

For all these reasons, and because many good sites for dams already have one, the growth of large-scale water power in the future (with the exception of a few areas, including Africa, South America, and China) appears limited. Indeed, in the United States there is an emerging social movement to remove dams. Hundreds of dams, especially those with few useful functions, are being considered for removal, and a few have already been removed (see Chapters 18 and 19). The U.S. Department of Energy forecasts that electrical generation from large hydropower dams will decrease significantly.

16.5 Ocean Energy

A lot of energy is involved in the motion of waves, currents, and tides in oceans. Many have dreamed of harnessing this energy, but it's not easy, for the obvious reasons that ocean storms are destructive and ocean waters are corrosive. The most successful development of energy from the ocean has been **tidal power**. Use of the water power of ocean tides can be traced back to the Roman occupation of Great Britain around Julius Caesar's time, when the Romans built a dam that captured tidal water and let it flow out through a waterwheel. By the 10th century, tides were used once again to power coastal mills in Britain.[17] However, only in a few places with favorable topography—such as the north coast of France, the Bay of Fundy in Canada, and the northeastern United States—are the tides strong enough to produce commercial electricity. The tides in the Bay of Fundy have a maximum range of about 15 m (49 ft). A minimum range of about 8 m (26 ft) appears necessary with present technology for development of tidal power.

To harness tidal power, a dam is built across the entrance to a bay or an estuary, creating a reservoir. As the tide rises (flood tide), water is initially prevented from entering the bay landward of the dam. Then, when there is sufficient water (from the oceanside high tide) to run the turbines, the dam is opened, and water flows through it into the reservoir (the bay), turning the blades of the turbines and generating electricity. When the bay is filled, the dam is closed, stopping the flow and holding the water in that reservoir. When the tide falls (ebb tide), the water level in the reservoir is higher than that in the ocean. The dam is then opened to run the turbines (which are reversible), and electric power is produced as the water is let out of the reservoir. Figure 16.12 shows the Rance tidal power plant

FIGURE 16.12 Tidal power station on the river Rance near Saint-Malo, France.

on the north coast of France. Constructed in the 1960s, it is the first and largest modern tidal power plant and has remained in operation since. The plant at capacity produces about 240,000 kW from 24 power units spread out across the dam. At the Rance power plant, most electricity is produced from the ebb tide, which is easier to control.

Tidal power, too, has environmental impacts. The dam changes the hydrology of a bay or an estuary, which can adversely affect the vegetation and wildlife. The dam restricts upstream and downstream passage of fish, and the periodic rapid filling and emptying of the bay as the dam opens and closes with the tides rapidly changes habitats for birds and other organisms.

16.6 Wind Power

Wind power, like solar power, has evolved over a long time. From early Chinese and Persian civilizations to the present, wind has propelled ships and has driven windmills to grind grain and pump water. In the past, thousands of windmills in the western United States were used to pump water for ranches. More recently, wind has been used to generate electricity. The trouble is, wind tends to be highly variable in time, place, and intensity.[18]

Basics of Wind Power

Winds are produced when differential heating of Earth's surface creates air masses with differing heat contents and densities. The potential for energy from the wind is large, and thus wind "prospecting" has become an important endeavor. On a national scale, regions with the greatest potential are the Pacific Northwest coastal area, the coastal region of the northeastern United States, and a belt within the Great Plains extending from northern Texas through the Rocky Mountain states and the Dakotas (Figure 16.13). Other windy sites include mountain areas in North Carolina and the northern Coachella Valley in Southern California. A site with average wind velocity of about 18 kilometers per hour (11 mph) or greater is considered a good prospect for wind energy development, although starting speeds for modern wind turbines can be considerably lower.[19]

In any location, the wind's direction, velocity, and duration may be quite variable, depending on local topography and temperature differences in the atmosphere. For example, wind velocity often increases over hilltops and when wind is funneled through a mountain pass (Figure 16.14). The increase in wind velocity over a mountain is due to a vertical convergence of wind, whereas in a pass the increase is partly due to a horizontal convergence. Because the shape of a mountain or a pass is often related to the local or regional geology, prospecting for wind energy is a geologic as well as a geographic and meteorological task. The wind energy potential of a region or site is determined by instruments that measure and monitor over time the strength, direction, and duration of the wind.

Significant improvements in the size of windmills and the amount of power they produce occurred from the late 1800s to the present, when many European countries and the United States became interested in

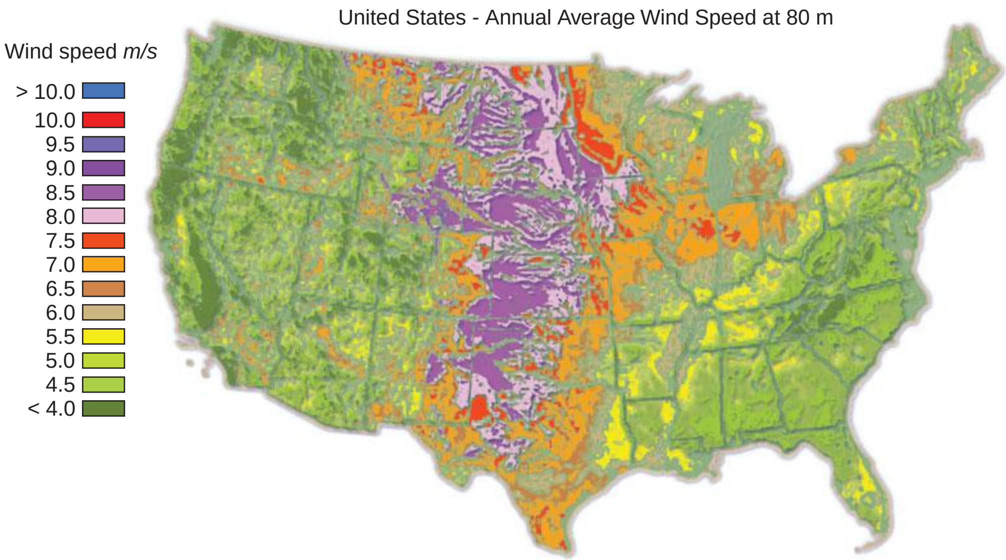


FIGURE 16.13 Wind energy potential in the United States.

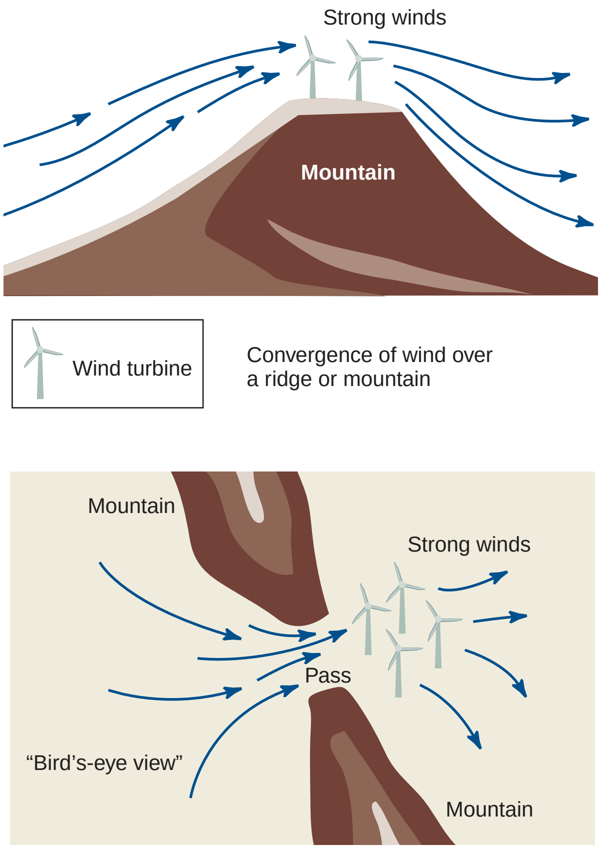


FIGURE 16.14 Idealized diagram showing how wind energy is concentrated by topography.

large-scale generators driven by wind. In the United States in the first half of the 20th century, thousands of small, wind-driven generators were used on farms. Most of these small windmills generated approximately 1 kW of power, which is much too little to be considered for central power-generation needs. Interest in wind power declined for several decades prior to the 1970s because of the abundance of cheap fossil fuels. Since the 1980s, interest in building windmills has revived greatly.

Today, wind energy is the cheapest form of alternative energy. Electricity produced from wind often costs less than that from natural gas and coal. Worldwide, wind power's generating capacity exceeded 120,000 megawatts in 2008. The United States has just taken over first place in having the largest installed wind energy capacity, now ahead of Germany, which had been the leader for a number of years, followed by Spain, China, India, and Italy.[20] U.S. wind power capacity reached 34,000 MW in 2007 (the most recent year for which data are available), increasing 33% a year on average since 2003.[21] Modern wind turbines are big, as much as 70 m (230 feet) high, as tall as a 23-story building, and have a generating capacity of more than 1 million watts—enough electricity for 500 modern U.S. homes (Figure 16.15).[22]

Much of the electricity produced from these large turbines is connected to the electrical grid, and many of them are installed in what are called "wind farms," which are providing large amounts of electricity. One of the biggest in the United States is the Horse Hollow Wind Energy Center near Abilene, Texas, owned and operated by Florida Power & Light. It has 421 wind turbines with a total generating capacity of 735 megawatts, enough to meet the electricity needs of approximately 220,000 homes, and enough for all domestic use for a city the size of Austin, Texas. (To put this in perspective, one large fossil fuel plant or nuclear power plant produces about 1,000 MW.) The Horse Hollow wind turbines are spread widely across approximately 47,000 acres, and the land is used for both ranching and energy production.[23]

Wind Power and the Environment

Wind energy does have a few disadvantages:

- Wind turbines can kill birds. (Birds of prey, such as hawks and falcons, are particularly vulnerable.)
- Wind turbines and wind farms may degrade an area's scenery.

However, although wind farms must often compete with other land uses, in many cases wind turbines can share land used for farms, military bases, and other facilities. Everything considered, wind energy has a relatively low environmental impact.

FIGURE 16.15 Windmills on a wind farm near Altamont, California, a mountain pass region east of San Francisco.

The Future of Wind Power

Wind power's continued use is certain. As noted earlier, the use of wind energy has been growing approximately 33% per year, nearly ten times faster than oil use. It is believed that there is sufficient wind energy in Texas, South Dakota, and North Dakota to satisfy the electricity needs of the entire United States. Consider the implications for nations such as China. China burns tremendous amounts of coal at a heavy environmental cost that includes exposing millions of people to hazardous air pollution. In rural China, exposure to the smoke from burning coal in homes has increased the rate of lung cancer by a factor of nine or more. China could probably double its current capacity to generate electricity with wind alone![24]

Wind energy supplies 1.5% of the world's demand for electricity, and its growth rate of more than 30% indicates that it could be a major supplier of power in the relatively near future.[25] One scenario suggests that wind power could supply 10% of the world's electricity in the coming decades and, in the long run, could provide more energy than hydropower, which today supplies approximately 20% of the electricity in the world. The wind energy industry has created thousands of jobs in recent years. Worldwide, more than half a million people are employed in wind energy, and according to the World Wind Energy Association, wind energy "creates many more jobs than centralized, nonrenewable energy sources."[26] Technology, meanwhile, is producing more efficient wind turbines, thereby reducing the price of wind power. All told, wind power is becoming a major investment opportunity.

16.7 Biofuels

Biofuel is energy recovered from biomass (organic matter). We can divide biofuels into three groups: firewood, organic wastes, and crops grown to be converted into liquid fuels.

Biofuels and Human History

Biomass is the oldest fuel used by humans. Our Pleistocene ancestors burned wood in caves to keep warm and cook food. Biofuels remained a major source of energy throughout most of the history of civilization. When North America was first settled, there was more wood fuel than could be used. Forests often were cleared for agriculture by girdling trees (cutting through the bark all the way around the base of a tree) to kill them and then burning the forests.

Until the end of the 19th century, wood was the major fuel source in the United States. During the mid-20th century, when coal, oil, and gas were plentiful, burning wood became old-fashioned and quaint, done just for pleasure in an open fireplace even though most of the heat went up the chimney. Now, with other fuels reaching a limit in abundance and production, there is renewed interest in using natural organic materials for fuel.

More than 1 billion people in the world today still use wood as their primary source of energy for heat and cooking. [13] But although firewood is the most familiar and most widely used biomass fuel, there are many others. In India and other countries, cattle dung is burned for cooking. Peat, a form of compressed dead vegetation, provides heating and cooking fuel in northern countries, such as Scotland, where it is abundant.

In recent years, however, biofuels have become controversial. Do biofuels offer a net benefit or disbenefit? (See Table 16.1.) In brief:

- Using wastes as a fuel is a good way to dispose of them. Making them takes more energy than they yield—but on the other hand, they reduce the amount of energy we must obtain from other sources.
- Firewood that regenerates naturally or in plantations that require little energy input will remain an important energy source in developing nations and locally in industrialized nations.
- Despite pressure from some agricultural corporations and some governments to promote crops grown solely for conversion into liquid fuels (called agrifuels), at present these are poor sources of energy. Most scientific research shows that producing agrifuels takes more energy than they yield. In some cases, there appears to be a net benefit, but the energy produced per unit of land area is low, much lower than can be obtained from solar and wind.

What it boils down to is that photosynthesis, though a remarkable natural process, is less efficient than modern photovoltaic cells in converting sunlight to electricity. Some algae and bacteria appear to provide a net energy benefit and can yield ethanol directly, but production of ethanol from these sources is just beginning and is experimental.[27]

Biofuels and the Environment

The conversion of farmland from food crops to biofuels appears to be one of the main reasons that food prices have risen rapidly worldwide, and that worldwide food production no longer exceeds demand. It also has environmental effects.

Biofuel agriculture competes for water with all other uses, and the main biofuel crops require heavy use of artificial fertilizers and pesticides.

Biofuels are supposed to reduce the production of greenhouse gases, but when natural vegetation is removed to grow biofuel crops, the opposite may be the case. The environmental organization Friends of the Earth says

Table 16.1 SELECTED EXAMPLES OF BIOMASS ENERGY SOURCES, USES, AND PRODUCTS

SOURCES	EXAMPLES	USES/PRODUCTS	COMMENT
Forest Products	Wood, chips	Direct burning,[a] charcoal[b]	Major source today in developing countries
Agriculture residues	Coconut husks, sugarcane waste, corncobs, peanut shells	Direct burning	Minor source
Energy crops	Sugarcane, corn, sorghum	Ethanol (alcohol)[c], gasification[d]	Ethanol is major source of fuel in Brazil for automobiles
Algae and bacteria	Special farms	Experimental	
Trees	Palm oil	Biodiesel	Fuel for vehicles
Animal residues	Manure	Methane[e]	Used to run farm machinery
Urban waste	Waste paper, organic household waste	Direct burning of methane from wastewater treatment or from landfills[f]	Minor source

[a]Principal biomass conversion.

[b] Secondary product from burning wood.

[c] Ethanol is an alcohol produced by fermentation, which uses yeast to convert carbohydrates into alcohol in fermentation chambers (distillery).

[d] Biogas from gasification is a mixture of methane and carbon dioxide produced by pyroclytic technology, Which is a thermochemical process that breaks down solid biomass into an oil-like liquid and almost pure carbon char.

[e] Methane is produced by anaerobic fermentation in a digester.

[f] Naturally produced in landfills by anaerobic fermentation.

that as much as 8% of the world's annual CO_2 emissions can be attributed to draining and deforesting peatlands in Southeast Asia to create palm plantations. The organization estimates that in Indonesia alone 44 million acres have been cleared for these plantations, an area equal to more than 10% of all the cropland in the United States, as large as Oklahoma and larger than Florida.[28]

The use of biofuels can pollute the air and degrade the land. For most of us, the smell of smoke from a single campfire is part of a pleasant outdoor experience. Under certain weather conditions, however, woodsmoke from many campfires or chimneys in narrow valleys can lead to air pollution. The use of biomass as fuel places pressure on an already heavily used resource. A worldwide shortage of firewood is adversely affecting natural areas and endangered species. For example, the need for firewood has threatened the Gir Forest in India, the last remaining habitat of the Indian lion (not to be confused with the Indian tiger). The world's forests will also shrink and in some cases vanish if our need for their products exceeds their productivity.

Biofuels do have some potential benefits. One is that certain kinds of crops, such as nuts produced by trees, may provide a net energy benefit in environments that are otherwise not suited to the growth of food crops. For example, some remote mountainous areas of China may become productive of biofuels. But this is not commonly the case.[29]

Another environmental plus is that combustion of biofuels generally releases fewer pollutants, such as sulfur dioxide and nitrogen oxides, than does combustion of coal and gasoline. This is not always the case for burning urban waste, however. Although plastics and hazardous materials are removed before burning, some inevitably slip through the sorting process and are burned, releasing air pollutants, including heavy metals. There is a conflict in our society as to whether it is better, in terms of the environment, to burn urban waste to recover energy and risk some increase in air pollution, or dump these wastes in landfills, which can then pollute soil and groundwater.

16.8 Geothermal Energy

There are two kinds of **geothermal energy**: deep-earth, high-density; and shallow-earth, low-density. The first makes use of energy within the Earth. The second is a form of solar energy: When the sun warms the surface soils, water, and rocks, some of this heat energy is gradually transmitted down into the ground.

The first kind of geothermal energy—deep-earth, high-density—is natural heat from the interior of the Earth. It is mined and then used to heat buildings and generate electricity. The idea of harnessing Earth's internal heat goes back more than a century. As early as 1904, geothermal power was used in Italy. Today, Earth's natural internal heat is being used to generate electricity in 21 countries, including Russia, Japan, New Zealand, Iceland, Mexico, Ethiopia, Guatemala, El Salvador, the Philippines, and the United States. Total worldwide production is approaching 9,000 MW (equivalent to nine large, modern coal-burning or nuclear power plants)—double the amount in 1980. Some 40 million people today receive their electricity from geothermal energy at a cost competitive with that of other energy sources. In El Salvador, geothermal energy is supplying 25% of the total electric energy used. However, at the global level, geothermal energy accounts for less than 0.15% of the total energy supply.[30]

This kind of geothermal energy may be considered a nonrenewable energy source when rates of extraction are greater than rates of natural replenishment. However, geothermal energy has its origin in the natural heat production within Earth, and only a small fraction of the vast total resource base is being used today. Although most geothermal energy production involves tapping high-heat sources, people are also using the low-temperature geothermal energy of groundwater in some applications.

FIGURE 16.16 Geysers Geothermal Field, north of San Francisco, California, is the largest geothermal power operation in the world and produces energy directly from steam.

Geothermal Systems

The average heat flow from the interior of the Earth is very low, about 0.06 watts per square meter (W/m^2). This amount is trivial compared with the 177 W/m^2 from sunlight at the surface, but in some areas the heat flow is high enough to be useful.[31] For the most part, high heat flow occurs mostly at plate tectonic boundaries (see Chapter 5), including oceanic ridge systems (divergent plate boundaries) and areas where mountains are being uplifted and volcanic islands are forming (convergent plate boundaries). You can see the effects of such natural heat flow at Yellowstone National Park. On the basis of geologic criteria, several types of hot geothermal systems (with temperatures greater than about 80°C, or 176°F) have been defined.

Some communities in the United States, including Boise, Idaho, and Klamath Falls, Oregon, are using deep-earth, high-density geothermal heating systems. A common type of geothermal system uses hydrothermal convection, where the circulation of steam and/or hot water transfers heat from the depths to the surface. An example is the Geysers Geothermal Field, 145 km (90 mi) north of San Francisco. It is the largest geothermal power operation in the world (Figure 16.16), producing about 1,000 MW of electrical energy. At the Geysers, the hot water is maintained in part by injecting treated wastewater from urban areas into hot rocks.

The second kind of geothermal energy—shallow-earth, low-density—is at much lower temperatures than geothermal sources and is used not to produce electricity but for heating buildings and swimming pools, and for heating soil to boost crop production in greenhouses. The potential for this kind of energy is huge, and it is cheap to obtain.[32] Such systems are extensively used in Iceland.

It may come as a surprise to learn that most groundwater can be considered a source of shallow-earth, low-density geothermal energy. It is geothermal because the normal heat flow from the sun to the Earth keeps the temperature of groundwater, at a depth of 100 m (320 ft), at about 13°C (55°F). This is cold for a shower but warmer than winter temperatures in much of the United States, where it can help heat a house. In warmer regions, with summer temperatures of 30–35°C (86–95°F), groundwater at 13°C is cool and thus can be used to provide air conditioning, as it does today in coastal Florida and elsewhere. In summer, heat can be transferred from the warm air in a building to the cool groundwater. In winter, when the outdoor temperature is below about 4°C (40°F), heat can be transferred from the groundwater to the air in the building, reducing the need for heating from other sources. "Heat pumps" for this kind of heat transfer are used in warm locations such as Florida and as far north as Juneau, Alaska, but are limited by extreme temperatures and can't function in the cold winters of northern New Hampshire or interior Alaska, such as in Fairbanks. (Juneau, on the coast, has a much more moderate climate because of the influence of the ocean waters.)

Geothermal Energy and the Environment

Deep-earth, high-density, geothermal energy development produces considerable thermal pollution from its hot wastewaters, which may be saline and highly corrosive. Other environmental problems associated with this kind of geothermal energy use include on-site noise, emissions of gas, and disturbance of the land at drilling sites, disposal sites, roads and pipelines, and power plants. The good news is that the use of deep-earth, high-density geothermal energy releases almost 90% less carbon dioxide and sulfur dioxide than burning coal releases to produce the same amount of electricity.[33] Furthermore, development of geothermal energy does not require large-scale transportation of raw materials or refining of chemicals, as development of fossil fuels does. Nor does geothermal energy produce the atmospheric pollutants associated with burning fossil fuels or the radioactive waste associated with nuclear energy.

Even so, deep-earth, high-density geothermal power is not always popular. For instance, on the island of Hawaii, where active volcanoes provide abundant near-surface heat, some argue that the exploration and development of geothermal energy degrade the tropical forest as developers construct roads, build facilities, and drill wells. In Hawaii, geothermal energy also raises religious and cultural issues. Some people, for instance, are offended by the use of the "breath and water of Pele," the volcano goddess, to make electricity. This points out the importance of being sensitive to the values and cultures of people where development is planned.

The Future of Geothermal Energy

By 2008, the United States produced only 7,500 MW of geothermal energy.[34] Globally, the likelihood is that high-density, deep-earth geothermal can be only a minor contributor to world energy demand, but that low-density, shallow-earth geothermal can be a major source of alternative and renewable energy.[35]

CRITICAL THINKING ISSUE

Should Wind Turbines Be Installed in Nantucket Sound?

In 2001, Cape Wind Associates proposed the Cape Wind Project, which would install 130 wind turbines, each higher than the Statue of Liberty, on floating offshore platforms distributed in Nantucket Sound (Figure 16.17), between Nantucket Island and the coast of Massachusetts. The 130 turbines would cover more than 62 square kilometers (24 square miles) and therefore would not be very close together. The turbines are expected to generate enough electricity for 420,000 homes, but although originally proposed in 2001, work on the $1 billion project has yet to begin. The federal government has received more than 40,000 comments about it, the greatest number ever about an alternative energy project,[31] and in response has held 50 public hearings.

Fishermen have expressed concern about possible effects on fish habitats, including spawning grounds. Shippers have expressed concern about possible dangers to commercial shipping. And some residents of Cape Cod, Martha's Vineyard, and Nantucket have opposed the project on aesthetic grounds—that the wind turbines will spoil the scenery.[36] The late senator Edward M. Kennedy, Democrat of Massachusetts, was one of the leaders in the fight against it, as is his nephew, Robert Kennedy Jr.[37]

Nantucket Sound is about 30 km (19 miles) wide between Nantucket Island and the mainland, while visibility at ground level is only about 19 kilometers (12 miles— limited by the curvature of the Earth). Thus, the turbines would be scattered points in the distance from either shore. They would, however, be visible from ships and boats passing through the channel, such as the yachts of wealthy residents on holiday.

It is worth noting that in the meantime, a Dutch company, Blue H, USA LLC, announced plans in March 2008 to put 120 turbines on floats 23 miles south of Martha's Vineyard and 45 miles west of New Bedford, farther away from the view of residents.[38] Further complicating matters, the National Park Service says that Nantucket Sound is eligible for listing on the National Register of Historic Places. And two tribes, the Mashpee Wampanoag of Cape Cod and the Aquinnah Wampanoag

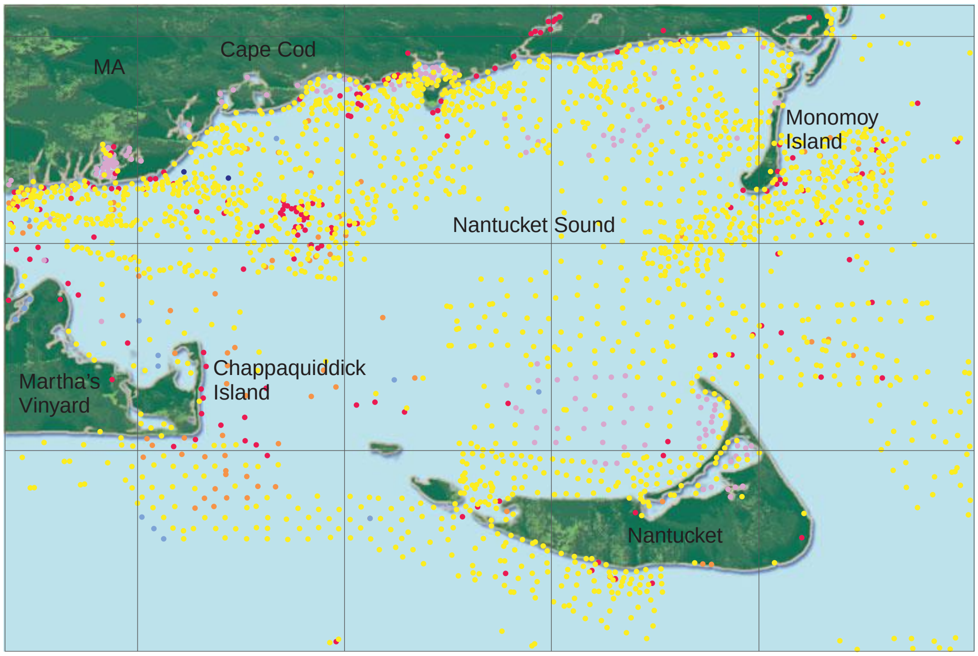


FIGURE 16.17 Map of Nantucket Sound.

of Martha's Vineyard, make two claims against the development: that it might be built over ancestral burial grounds and might interfere with a ritual that requires an unobstructed view of the sunrise.[39]

Critical Thinking Questions

1. Which of the arguments against the Cape Wind Project do you think is most justified? Explain your answer.
   a. The effect on scenic beauty
   b. The effect on fisheries
   c. The traditional cultural practices of Native Americans
2. Since another project would place 120 turbines farther away from the view of residents, what would justify continuation of the Cape Wind Project?
3. Do you think the Cape Wind Project could be important as a precedent for other offshore wind energy projects in the United States? Why or why not?
4. On balance, do you support the Cape Wind Project or oppose it? Explain your answer.

SUMMARY

- The use of renewable alternative energy sources, such as wind and solar energy, is growing rapidly. These energy sources do not cause air pollution, health problems, or climate changes. They offer our best chance to replace fossil fuels and develop a sustainable energy policy.
- Passive solar energy systems often involve architectural designs that enhance absorption of solar energy without requiring mechanical power or moving parts.
- Some active solar energy systems use solar collectors to heat water for homes.
- Systems to produce heat or electricity include power towers and solar farms.
- Photovoltaics convert sunlight directly into electricity.
- Hydrogen gas may be an important fuel of the future, especially when used in fuel cells.
- Water power today provides about 10% of the total electricity produced in the United States. Except in some developing nations, good sites for large dams are already in use. Water power is clean, but there is an environmental price to pay in terms of disturbance of ecosystems, sediment trapped in reservoirs, loss of wild rivers, and loss of productive land.
- Wind power has tremendous potential as a source of electrical energy in many parts of the world. Many

utility companies are using wind power as part of energy production or as part of long-term energy planning. Environmental impacts of wind installations include loss of land, killing of birds, and degradation of scenery.

- Biofuels are of three kinds: firewood, wastes, and crops grown to produce fuels. Firewood has been important historically and will remain so in many developing nations and many rural parts of developed nations. Burning wastes is a good way to dispose of them, and their energy is a useful by-product. Crops grown solely as biofuels appear to be a net energy sink or of only marginal benefit, at considerable environmental costs, including competition for land, water, and fertilizers, and the use of artificial pesticides. At present they are not a good option.
- Geothermal energy, natural heat from Earth's interior, can be used as an energy source. The environmental effects of developing geothermal energy relate to specific site conditions and the type of heat—steam, hot water, or warm water. Environmental impacts may involve on-site noise, industrial scars, emission of gas, and disposal of saline or corrosive waters.

REEXAMINING THEMES AND ISSUES

Human Population

As the human population continues to increase, so does global demand for energy. Environmental problems from increased use of fossil fuels could be minimized by controlling population growth, increasing conservation efforts, and using alternative, renewable energy sources that do not harm the environment.

Sustainability

Use of fossil fuels is not sustainable. To plan for energy sustainability, we need to rely more on alternative energy sources that are naturally renewable and do not damage the environment. To do otherwise is antithetical to the concept of sustainability.

Global Perspective

To evaluate the potential of alternative energy sources, we need to understand global Earth systems and identify regions likely to produce high-quality alternative energy that could be used in urban regions of the world.

Urban World

Alternative renewable energy sources have a future in our urban environments. For example, the roofs of buildings can be used for passive solar collectors or photovoltaic systems. Patterns of energy consumption can be regulated through use of innovative systems such as pump storage to augment production of electrical energy when demand is high in urban areas.

People and Nature

Many environmentalists perceive alternative energy sources, such as solar and wind, as being linked more closely with nature than are fossil fuels, nuclear energy, or even water power. This is because solar and wind energy development requires less human modification of the environment. Solar and wind energy allow us to live more in harmony with the environment, and thus we feel more connected to the natural world.

Science and Values

We are seriously considering alternative energy today because we value environmental quality and energy independence and want to plan for a future when we run out of fossil fuels. Recognizing that burning fossil fuels creates many serious environmental problems and that petroleum will soon become less available, we are trying to increase our scientific knowledge and improve our technology to meet our energy needs for the future while minimizing environmental damage. Our present science and technology can lead to a sustainable energy future, but we will need to change our values and our behavior to achieve it.

KEY TERMS

STUDY QUESTIONS

1. What types of government incentives might encourage use of alternative energy sources? Would their widespread use affect our economic and social environment?

2. Your town is near a large river that has a nearly constant water temperature of about 15°C (60°F). Could the water be used to cool buildings in the hot summers? How? What would be the environmental effects?

3. Which has greater future potential for energy production, wind or water power? Which causes more environmental problems? Why?

4. What are some of the problems associated with producing energy from biomass?

5. It is the year 2500, and natural oil and gas are rare curiosities that people see in museums. Given the technologies available today, what would be the most sensible fuel for airplanes? How would this fuel be produced to minimize adverse environmental effects?

6. When do you think the transition from fossil fuels to other energy sources will (or should) occur? Defend your answer.

FURTHER READING

Botkin, D.B., ***Powering the Future: A Scientist's Guide to Energy Independence*** (Indianapolis, IN: Pearson FT Press, 2010).

Boyle, G., ***Renewable Energy*** (New York: Oxford University Press, 2004, paperback).

Scudder, T., ***The Future of Large Dams: Dealing with Social, Environmental, Institutional and Political Costs*** (London: Earthscan, 2006). The author has been a member of a World Bank team that tried to make a new dam and reservoir in Laos environmentally and culturally sound. The book is one of the best summaries of the present limitations of water power.

CHAPTER 17

Nuclear Energy and the Environment

Indian Point Energy Center is a two-unit (originally three-unit) nuclear power plant installation on the eastern shore of the Hudson River within 24 miles of New York City. It must be relicensed, and, as the lower photograph shows, this is creating a major controversy about whether such an installation should be near tens of millions of people.

LEARNING OBJECTIVES

As one of the alternatives to fossil fuels, nuclear energy generates a lot of controversy. After reading this chapter, you should understand . . .

- What nuclear fission is and the basic components of a nuclear power plant;
- Nuclear radiation and its three major types;
- How radioisotopes affect the environment, and the major pathways of radioactive materials in the environment.
- The relationships between radiation doses and health;
- The advantages and disadvantages of nuclear power;
- What the future of nuclear power is likely to be.

CASE STUDY

Indian Point: Should a Nuclear Power Installation Operate Near One of America's Major Cities?

In 1962, after a series of contentious public hearings, Consolidated Edison began operating the first of three nuclear reactors at Indian Point, on the eastern shore of the Hudson River in Buchanan, New York, 38 km (24 mi) north of New York City. Indian Point's second and third reactors began operating in 1974 and 1976, respectively. The first unit had major problems and was finally shut down in 1974. The second and third have been operating since then, but their licenses run out in 2013 and 2015, respectively, and under U.S. law nuclear power plants must be relicensed. All three units are owned by Entergy Nuclear Northeast, a subsidiary of Entergy Corporation.

Twenty million people live within 80 km (50 miles) of this power plant, and this causes considerable concern. Joan Leary Matthews, a lawyer for the New York State Department of Environmental Conservation, said that "whatever the chances of a failure at Indian Point, the consequences could be catastrophic in ways that are almost too horrific to contemplate."[1]

The federal Nuclear Regulatory Commission (NRC) announced the beginning of the relicensing process on May 2, 2007. By 2008 the relicensing of the plant had become a regional controversy, opposed by the New York State government, Westchester County (where the plant is located), and a number of nongovernmental environmental organizations. The plant has operated for almost 50 years, so what's the problem?

There have been some: In 1980, one of the plant's two units filled with water (an operator's mistake). In 1982, the same unit's steam generator piping leaked and released radioactive water. In 1999, it shut down unexpectedly, but operators didn't realize it until the next day, when the batteries that automatically took over ran down. In April 2007, a transformer burned in the second unit, radioactive water leaked into groundwater, and the source of the leak was difficult to find. Most recently, in 2009, a leak in the cooling system allowed 100,000 gallons of water to escape from the main system. Uneasiness about the plant's location increased after the terror attack on September 11, 2001. One of the hijacked jets flew close to the plant, and diagrams of unspecified nuclear plants in the United States have since been found in al Qaeda hideouts in Afghanistan.[2]

Proponents of nuclear power say these are minor problems, and there has been no major one. As far as they can tell, the plant is safe. The Energy Policy Act of 2005 promoted nuclear energy, and the Obama administration is moving ahead with federal funding of nuclear power plants. For 2010, the administration has allocated $18.5 billion for new "next-generation" nuclear power plants. Others, however, such as New York State's attorney general Andrew Cuomo, believe the location is just too dangerous, and he has asked the Nuclear Regulatory Commission to deny Indian Point's relicensing, saying that it has "a long and troubling history of problems."

The conflict at Indian Point illustrates the worldwide debate about nuclear energy. Growing concern about fossil fuels has led to calls for increased use of nuclear power despite unanswered questions and unsolved problems regarding its use. This chapter provides a basis for you to decide whether nuclear power could be, and should be, a bigger supplier of energy in the future. We begin with the basics about the nature of nuclear energy, then go on to explore nuclear reactors, radiation, accidents, waste management, and the future of nuclear power.

17.1 Current Role of Nuclear Power Plants in World Energy Production

Today, nuclear power provides about 17% of the world's electricity and 4.8% of the total energy. In the United States, 104 nuclear power plants produce about 20% of the country's electricity and about 8% of the total energy used (Figure 17.1).[3] Worldwide, there are 436 operating nuclear power plants.[4] Nations differ greatly in the amount of energy they obtain from these plants. France ranks first, with about 80% of its electricity produced by nuclear energy (Table 17.1). The United States ranks tenth in the percentage of electricity it obtains from nuclear power plants.

Most of the world's nuclear power plants are in North America, Western Europe, Russia, China, and In-

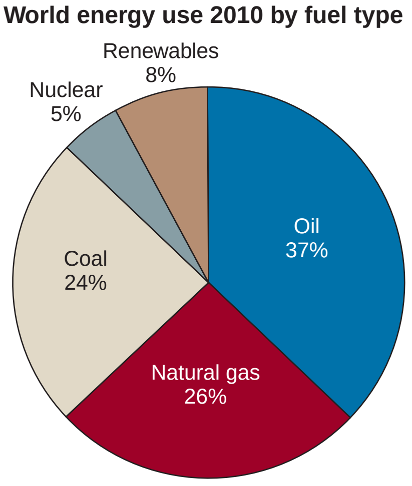


FIGURE 17.1 World energy use. (*Source*: D.B. Botkin, 2010.)

Table 17.1 LEADING NATIONS IN THE USE OF NUCLEAR ENERGY

COUNTRY	% TOTAL ELECTRICITY	GENERATION (MILLION KWH)
France	78%	368,188
Belgium	60%	41,927
Sweden	43%	61,395
Spain	36%	56,060
S. Korea	36%	58,138
Ukraine	33%	75,243
Germany	29%	153,476
Japan	28%	249,256
United Kingdom	28%	89,353
United States	19%	610,365
Canada	18%	94,823
Russia	12%	119,186
World Totals*	18%	2,167,515

(*Source*: D.B. Botkin, 2010.)

dia (Figure 17.2). Most of the U.S. nuclear power plants are in the eastern half of the nation (Figure 17.3). The very few west of the Mississippi River are in Washington, California, Arizona, Nebraska, Kansas, and Texas. The last nuclear plant to be completed in the United States went on line in 1996. However, since the early 1990s, U.S. nuclear plants have added over 23,000 MW, equivalent to the output of 23 large fossil fuel–burning power plants. The electricity produced from nuclear power plants increased 33% between 1980 and 2001, because only two thirds of their capacity was used in 1980, but this increased to more than 90% by 2002. Even if all these power plants operated at only 66% of their capacity, this would be the equivalent of building four new nuclear power plants.

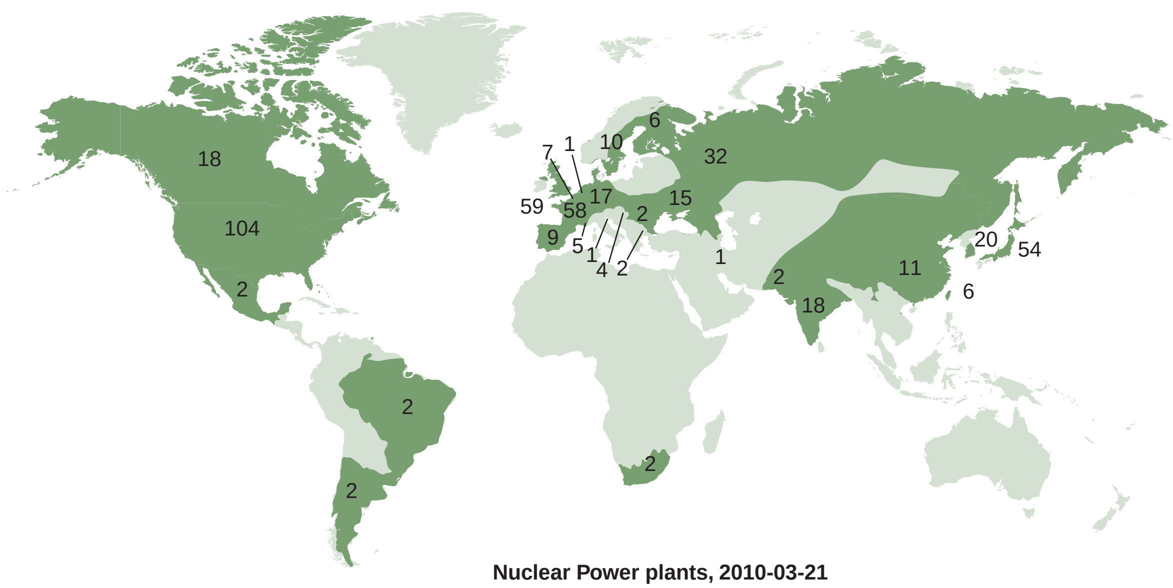


FIGURE 17.2 Where major nuclear power plants are worldwide. (*Source*: Informationskreis KernEnergie, Berlin.)

FIGURE 17.3 Where nuclear power plants are in the United States. (*Source*: http://www.insc.anl.gov/pwrmaps/)

17.2 What Is Nuclear Energy?

Hard as it may be to believe, **nuclear energy** is the energy contained in an atom's nucleus. Two nuclear processes can be used to release that energy to do work: fission and fusion. Nuclear **fission** is the splitting of atomic nuclei, and nuclear **fusion** is the fusing, or combining, of atomic nuclei. A by-product of both fission and fusion is the release of enormous amounts of energy. (Radiation and related terms are explained in A Closer Look 17.1. You may also wish to review the discussion of matter and energy in Chapter 14's A Closer Look 14.1.)

Nuclear energy for commercial use is produced by splitting atoms in **nuclear reactors**, which are devices that produce controlled nuclear fission. In the United States, almost all of these reactors use a form of uranium oxide as fuel.

Nuclear *fusion*, despite decades of research to try to develop it, remains only a theoretical possibility.

Conventional Nuclear Reactors

The first human-controlled nuclear fission, demonstrated in 1942 by Italian physicist Enrico Fermi at the University of Chicago, led to the development of power plants that could use nuclear energy to produce electricity. Today, in addition to power plants to supply electricity for homes and industry, nuclear reactors power submarines, aircraft carriers, and icebreaker ships.

Nuclear fission produces much more energy per kilogram of fuel than other fuel-requiring sources, such as biomass and fossil fuels. For example, 1 kilogram (2.2 lb) of uranium oxide produces about the same amount of heat as 16 metric tons of coal.

Three types—isotopes—of uranium occur in nature: uranium-238, which accounts for approximately 99.3% of all natural uranium; uranium-235, which makes up about 0.7%; and uranium-234, about 0.005%. However, uranium-235 is the only naturally occurring fissionable (or *fissile*) material and is therefore essential to the production of nuclear energy. A process called *enrichment* increases the concentration of uranium-235 from 0.7% to about 3%. This enriched uranium is used as fuel.

The spontaneous decay of uranium atoms emits neutrons. Fission reactors split uranium-235 by neutron bombardment. This releases more neutrons than it took to create the first splitting (Figure 17.4). These released neutrons strike other uranium-235 atoms, releasing still more neutrons, other kinds of radiation, fission products, and heat. This is the "chain reaction" that is so famous, both for nuclear power plants and nuclear bombs— as the process continues, more and more uranium is split, releasing more neutrons and more heat. The neutrons released are fast-moving and must be slowed down slightly (*moderated*) to increase the probability of fission.

All nuclear power plants use coolants to remove excess heat produced by the fission reaction. The rate of generation of heat in the fuel *must match* the rate at which heat is carried away by the coolant. Major nuclear accidents have occurred when something went wrong with the balance and heat built up in the reactor core.[5] The well-known term **meltdown** refers to a nuclear accident in which the coolant system fails, allowing the nuclear fuel to become so hot that it forms a molten mass that breaches the containment of the reactor and contaminates the outside environment with radioactivity.

The nuclear steam-supply system includes heat exchangers (which extract heat produced by fission) and primary coolant loops and pumps (which circulate the

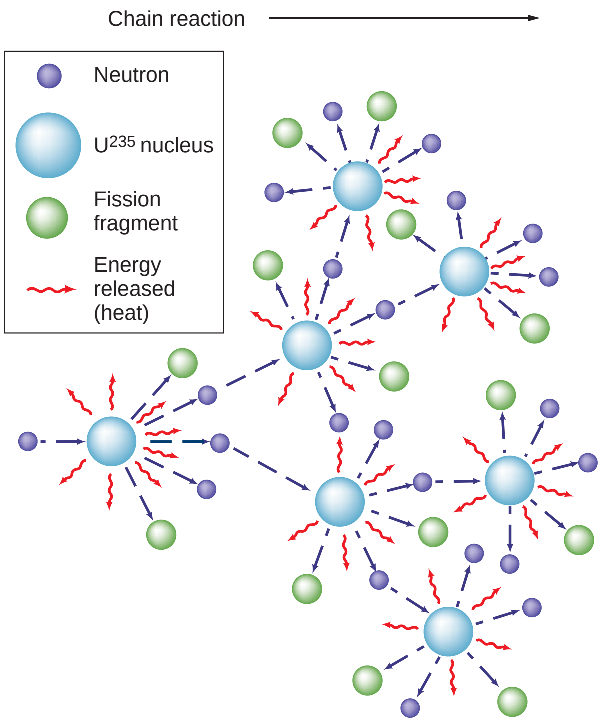


FIGURE 17.4 Fission of uranium-235. A neutron strikes the U-235 nucleus, producing fission fragments and free neutrons and releasing heat. The released neutrons may then strike other U-235 atoms, releasing more neutrons, fission fragments, and energy. As the process continues, a chain reaction develops.

coolant through the reactor). The heat is used to boil water, releasing steam that runs conventional steam-turbine electrical generators (Figure 17.5). In most common reactors, ordinary water is used as the coolant as well as the moderator. Reactors that use ordinary water are called "light water reactors" because there is also "heavy water," which combines deuterium with oxygen.[6]

Most reactors now in use consume more fissionable material than they produce and are known as **burner reactors**. Figure 17.6 shows the main components of a reactor: the core (consisting of fuel and moderator), control rods, coolant, and reactor vessel. The core is enclosed in the heavy, stainless-steel reactor vessel; then, for safety and security, the entire reactor is contained in a reinforced-concrete building.

In the reactor core, fuel pins—enriched uranium pellets in hollow tubes (3–4 m long and less than 1 cm, or 0.4 in., in diameter)—are packed together (40,000 or more in a reactor) in fuel subassemblies. A minimum fuel concentration is necessary to keep the reactor *critical*—that is, to achieve a self-sustaining chain reaction.

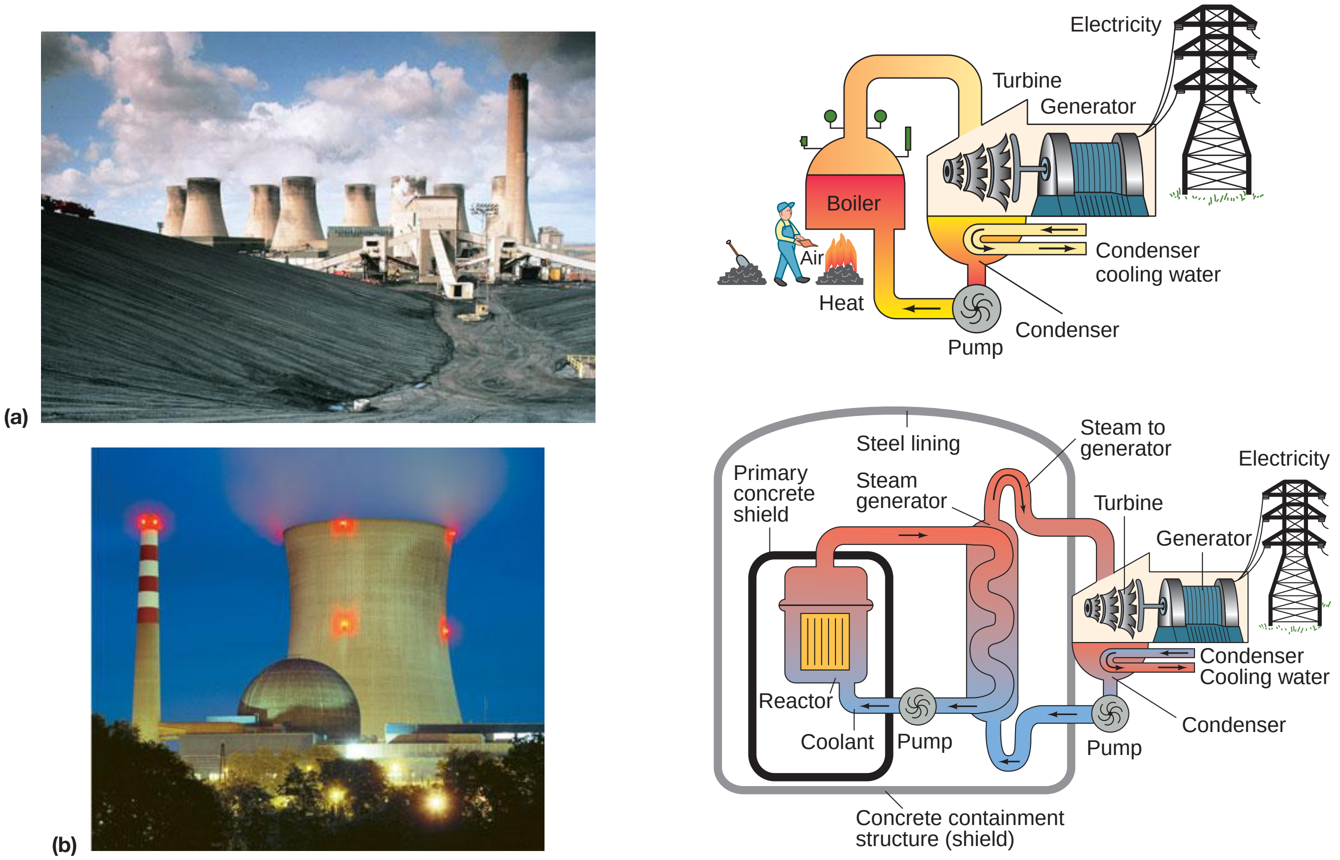


FIGURE 17.5 Comparison of **(a)** a fossil-fuel power plant and **(b)** a nuclear power plant with a boiling-water reactor. Notice that the nuclear reactor has exactly the same function as the boiler in the fossil-fuel power plant. The coal-burning plant **(a)** is Ratcliffe-on-Saw, in Nottinghamshire, England, and the nuclear power station **(b)** is in Leibstadt, Switzerland. (*Source*: American Nuclear Society, *Nuclear Power and the Environment*, 1973.)

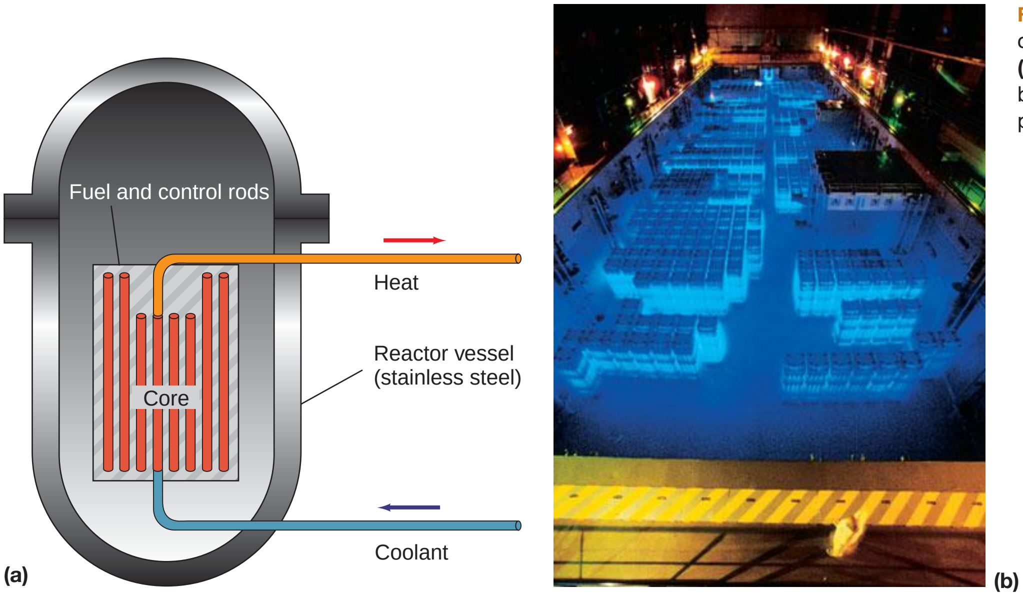


FIGURE 17.6 **(a)** Main components of a nuclear reactor. **(b)** Glowing spent fuel elements being stored in water at a nuclear power plant.

A CLOSER LOOK 17.1

Radioactive Decay

To many people, radiation is a subject shrouded in mystery. They feel uncomfortable with it, learning from an early age that nuclear energy may be dangerous because of radiation and that nuclear fallout from detonation of atomic bombs can cause widespread human suffering. One thing that makes radiation scary is that we cannot see it, taste it, smell it, or feel it. In this closer look, we try to demystify some aspects of radiation by discussing the process of radiation, or radioactivity.

First, we need to understand that radiation is a natural process, as old as the universe. Understanding the process of radiation involves understanding the **radioisotope**, a form of a chemical element that spontaneously undergoes **radioactive decay**. During the decay process, the radioisotope changes from one isotope to another and emits one or more kinds of radiation (Figure 17.7).

You may recall from Chapter 6 that isotopes are atoms of an element that have the same atomic number (the number of protons in the nucleus) but that vary in atomic mass number (the number of protons plus neutrons in the nucleus). For example, two isotopes of uranium are $^{235}U_{92}$ and $^{238}U_{92}$. The atomic number for both isotopes of uranium is 92 (revisit Figure 6.8); however, the atomic mass numbers are 235 and 238. The two different uranium isotopes may be written as uranium-235 and uranium-238 or ^{235}U and ^{238}U.

An important characteristic of a radioisotope is its *half-life*, the time required for one-half of a given amount of the isotope to decay to another form. Uranium-235 has a half-life of 700 million years, a very long time indeed! Radioactive carbon-14 has a half-life of 5,570 years, which is in the intermediate range, and radon-222 has a relatively short half-life of 3.8 days. Other radioactive isotopes have even shorter half-lives; for example, polonium-218 has a half-life of about 3 minutes, and still others have half-lives as short as a fraction of a second.

There are three major kinds of nuclear radiation: *alpha particles, beta particles*, and *gamma rays*. An alpha particle consists of two protons and two neutrons (a helium nucleus) and has the greatest mass of the three types of radiation (Figure 17.7a). Because alpha particles have a relatively high mass, they do not travel far. In air, alpha particles can travel approximately 5–8 cm (about 2–3 in.) before they stop. However, in living tissue, which is much denser than air, they can travel only about 0.005–0.008 cm (0.002–0.003 in.). Because this is a very short distance, they can't cause damage to living cells unless they originate very close to the cells. Also, alpha particles can be stopped by a sheet or so of paper.

Beta particles are electrons and have a mass of 1/1,840 of a proton. Beta decay occurs when one of the protons or

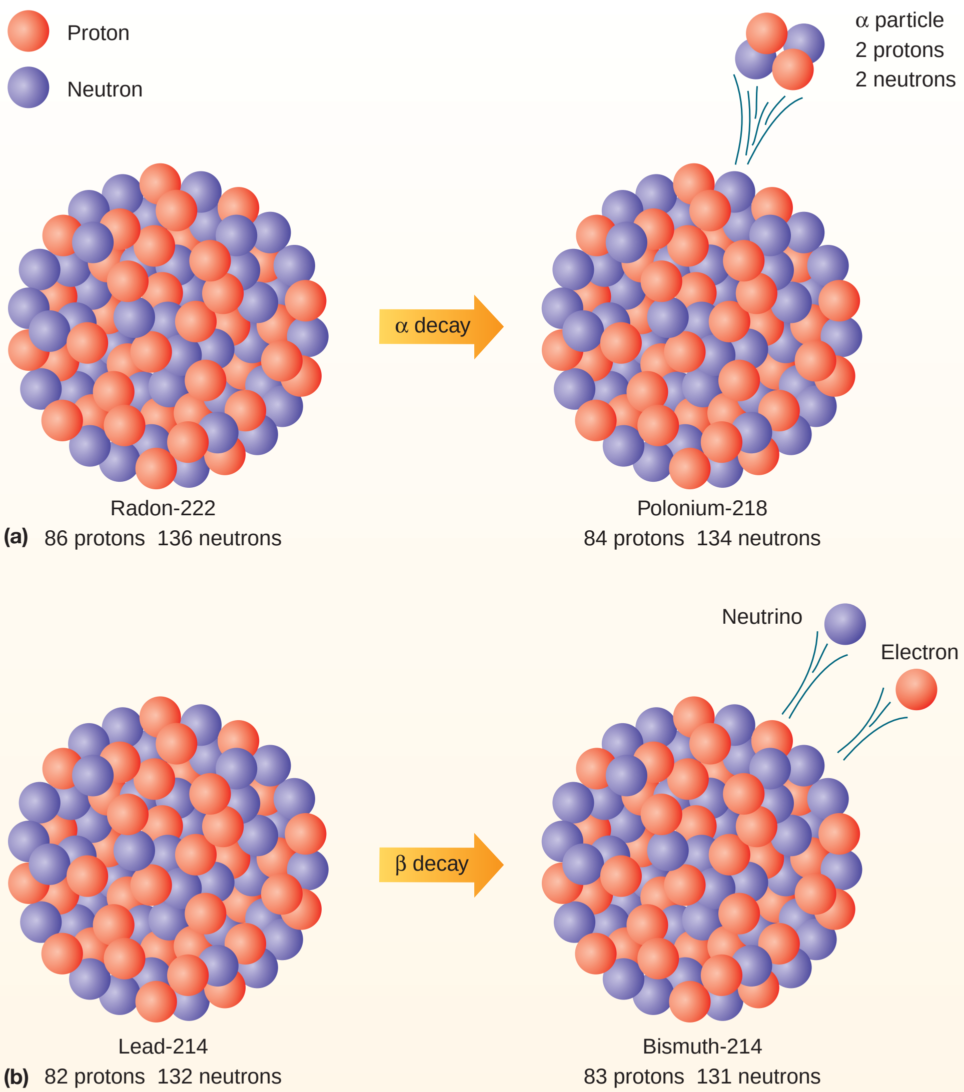


FIGURE 17.7 (Idealized diagrams showing **(a)** alpha and **(b)** beta decay processes. (*Source*: D. J. Brenner, *Radon: Risk and Remedy* [New York: Freeman, 1989]. Copyright 1989 by W.H. Freeman & Company. Reprinted with permission.)

neutrons in the nucleus of an isotope spontaneously changes. What happens is that a proton turns into a neutron, or a neutron is transformed into a proton (Figure 17.7b). As a result of this process, another particle, known as a *neutrino*, is also ejected. A neutrino is a particle with no *rest mass* (the mass when the particle is at rest with respect to an observer).[8] Beta particles travel farther through air than the more massive alpha particles but are blocked by even moderate shielding, such as a thin sheet of metal (aluminum foil) or a block of wood.

The third and most penetrating type of radiation comes from *gamma decay*. When gamma decay occurs, a gamma ray, a type of electromagnetic radiation, is emitted from the isotope. Gamma rays are similar to X-rays but are more energetic and penetrating; and of all types of radiation, they travel the longest average distance. Protection from gamma rays requires thick shielding, such as about a meter of concrete or several centimeters of lead.

Each radioisotope has its own characteristic emissions: Some emit only one type of radiation; others emit a mixture. In addition, the different types of radiation have different toxicities (potential to harm or poison). In terms of human health and the health of other organisms, alpha radiation is most toxic when inhaled or ingested. Because alpha radiation is stopped within a very short distance by living tissue, much of the damaging radiation is absorbed by the tissue. When alpha-emitting isotopes are stored in a container, however, they are relatively harmless. Beta radiation has intermediate toxicity, although most beta radiation is absorbed by the body when a beta emitter is ingested. Gamma emitters are dangerous inside or outside the body; but when they are ingested, some of the radiation passes out of the body.

Each radioactive isotope has its own half-life. Isotopes with very short half-lives are present only briefly, whereas those with long half-lives remain in the environment for long periods. Table 17.2 illustrates the general pattern for decay in terms of the elapsed half-lives and the fraction remaining. For example, suppose we start with 1g polonium-218 with a half-life of approximately 3 minutes. After an elapsed time of 3 minutes, 50% of the polonium-218 remains. After 5 elapsed half-lives, or 15 minutes, only 3% is still present; and after 10 elapsed half-lives (30 minutes),

Table 17.2 GENERALIZED PATTERN OF RADIOACTIVE DECAY

ELAPSED HALF-LIFE	FRACTION REMAINING	PERCENT REMAINING
0	—	100
1	1/2	50
2	1/4	25
3	1/8	13
4	1/16	6
5	1/32	3
6	1/64	1.5
7	1/128	0.8
8	1/256	0.4
9	1/512	0.2
10	1/1024	0.1

0.1% is still present. Where has the polonium gone? It has decayed to lead-214, another radioactive isotope, which has a half-life of about 27 minutes. The progression of changes associated with the decay process is often known as a *radioactive decay chain*. Now suppose we had started with 1 g uranium-235, with a half-life of 700 million years. Following 10 elapsed half-lives, 0.1% of the uranium would be left—but this process would take 7 billion years.

Some radioisotopes, particularly those of very heavy elements such as uranium, undergo a series of radioactive decay steps (a decay chain) before finally becoming stable, nonradioactive isotopes. For example, uranium decays through a series of steps to the stable nonradioactive isotope of lead. A decay chain for uranium-238 (with a half-life of 4.5 billion years) to stable lead-206 is shown in Figure 17.8. Also listed are the half-lives and types of radiation that occur during the transformations. Note that the simplified radioactive decay chain shown in Figure 17.8 involves 14 separate transformations and includes several environmentally important radioisotopes, such as radon-222, polonium-218, and lead-210. The decay from one radioisotope to another is often stated in terms of parent and daughter products. For example, uranium-238 is the parent of daughter product thorium-234.

Radioisotopes with short half-lives initially have a more rapid rate of change (nuclear transformation) than do radioisotopes with long half-lives. Conversely, radioisotopes with long half-lives have a less intense and slower initial rate of nuclear transformation but may be hazardous much longer.[9]

To sum up, when considering radioactive decay, two important facts to remember are (1) the half-life and (2) the type of radiation emitted.

Radioactive Elements	Radiation Emitted			Half-life		
	Alpha	Beta	Gamma	Minutes	Days	Years
Uranium-238 ↓	☢		☢			4.5 billion
Thorium-234 ↓		☢	☢		24.1	
Protactinium-234 ↓		☢	☢	1.2		
Uranium-234 ↓	☢		☢			247,000
Thorium-230 ↓	☢		☢			80,000
Radium-226 ↓	☢		☢			1,622
Radon-222 ↓	☢				3.8	
Polonium-218 ↓	☢	☢		3.0		
Lead-214 ↓		☢	☢	26.8		
Bismuth-214 ↓		☢	☢	19.7		
Polonium-214 ↓	☢			0.00016 (sec)		
Lead-210 ↓		☢	☢			22
Bismuth-210 ↓		☢			5.0	
Polonium-210 ↓	☢		☢		138.3	
Lead-206	None			Stable		

FIGURE 17.8 Uranium-238 decay chain. (*Source*: F. Schroyer, ed., *Radioactive Waste*, 2nd printing [American Institute of Professional Geologists, 1985].)

A stable fission chain reaction in the core is maintained by controlling the number of neutrons that cause fission. Control rods, which contain materials that capture neutrons, are used to regulate the chain reaction. As the control rods are moved out of the core, the chain reaction increases; as they are moved into the core, the reaction slows. Full insertion of the control rods into the core stops the fission reaction.[7]

17.3 Nuclear Energy and the Environment

The **nuclear fuel cycle** begins with the mining and processing of uranium, its transportation to a power plant, its use in controlled fission, and the disposal of radioactive waste. Ideally, the cycle should also include the reprocessing of spent nuclear fuel, and it must include the decommissioning of power plants. Since much of a nuclear power plant becomes radioactive over time from exposure to radioisotopes, disposal of radioactive wastes eventually involves much more than the original fuel.

Throughout this cycle, radiation can enter and affect the environment (Figure 17.9).

Problems with the Nuclear Fuel Cycle

- Uranium mines and mills produce radioactive waste that can expose mining workers and the local environment to radiation. Radioactive dust produced at mines and mills can be transported considerable distances by wind and water, so pollution can be widespread. Tailings—materials removed by mining but not processed—are generally left at the site, but in some instances radioactive mine tailings were used in foundations and other building materials, contaminating dwellings.
- Uranium-235 enrichment and the fabrication of fuel assemblies also produce radioactive waste that must be carefully handled and disposed of.
- Site selection and construction of nuclear power plants in the United States are highly controversial. The environmental review process is extensive and expensive, often centering on hazards related to such events as earthquakes.
- The power plant or reactor is the site most people are concerned about because it is the most visible part of the cycle. It is also the site of past accidents, including partial meltdowns that have released harmful radiation into the environment.
- The United States does not reprocess spent fuel from reactors to recover uranium and plutonium at this time. However, many problems are associated with the handling and disposal of nuclear waste, as discussed later in this chapter.
- Waste disposal is controversial because no one wants a nuclear waste disposal facility nearby. The problem is that no one has yet figured out how to isolate nuclear waste for the millions of years that it remains hazardous.

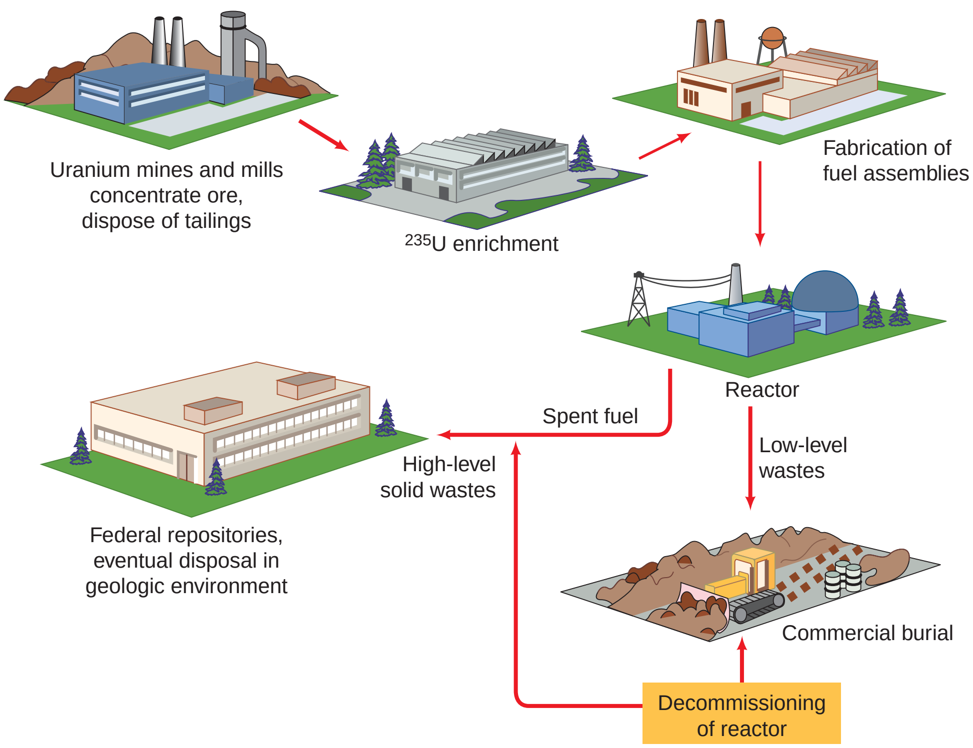


FIGURE 17.9 Idealized diagram showing the nuclear fuel cycle for the U.S. nuclear energy industry. Disposal of tailings, which because of their large volume may be more toxic than high-level waste, was treated casually in the past. (*Source*: Office of Industry Relations, The Nuclear Industry, 1974.)

- Nuclear power plants have a limited lifetime, usually estimated at only several decades, but decommissioning a plant (removing it from service) or modernizing it is a controversial part of the cycle and one with which we have little experience. For one thing, like nuclear waste, contaminated machinery must be safely disposed of or securely stored indefinitely.

Decommissioning or refitting a nuclear plant will be very expensive (perhaps several hundred million dollars) and is an important aspect of planning for the use of nuclear power. It will cost more to dismantle a nuclear reactor than to build it. At present, as we saw in this chapter's opening case study, power companies are filing to extend the licenses of several nuclear power plants that were originally slated to be decommissioned and taken down.

In addition to the above list of hazards in transporting and disposing of radioactive material, there are potential hazards in supplying other nations with reactors. Terrorist activity and the possibility of irresponsible people in governments add risks that are not present in any other form of energy production. For example, Kazakhstan inherited a large nuclear weapons testing facility, covering hundreds of square kilometers, from the former Soviet Union. The soil in several sites contains "hot spots" of plutonium that pose a serious problem of toxic contamination. The facility also poses a security problem. There is international concern that this plutonium could be collected and used by terrorists to produce "dirty" bombs (conventional explosives that disperse radioactive materials). There may even be enough plutonium to produce small nuclear bombs.

Nuclear energy may indeed be one answer to some of our energy needs, but with nuclear power comes a level of responsibility not required by any other energy source.

17.4 Nuclear Radiation in the Environment, and Its Effects on Human Health

Ecosystem Effects of Radioisotopes

As explained in A Closer Look 17.1, a radioisotope is an isotope of a chemical element that spontaneously undergoes radioactive decay. Radioisotopes affect the environment in two ways: by emitting radiation that affects other materials and by entering the normal pathways of mineral cycling and ecological food chains.

The explosion of a nuclear weapon does damage in many ways. At the time of the explosion, intense radiation of many kinds and energies is sent out, killing organisms directly. The explosion generates large amounts of radioactive isotopes, which are dispersed into the environment. Nuclear bombs exploding in the atmosphere produce a huge cloud that sends radioisotopes directly into the stratosphere, where the radioactive particles are widely dispersed by winds. Atomic fallout—the deposit of these radioactive materials around the world—was an environmental problem in the 1950s and 1960s, when the United States, the former Soviet Union, China, France, and Great Britain were testing and exploding nuclear weapons in the atmosphere.

The pathways of some of these isotopes illustrate the second way in which radioactive materials can be dangerous in the environment: They can enter ecological food chains (Figure 17.10). Let's consider an example. One of the radioisotopes emitted and sent into the stratosphere by atomic explosions was cesium-137. This radioisotope was deposited in relatively small concentrations but was widely dispersed in the Arctic region of North America. It fell on reindeer moss, a lichen that is a primary winter food of the caribou. A strong seasonal trend in the levels of cesium-137 in caribou was discovered; the level was highest in winter, when reindeer moss was the principal food, and lowest in summer. Eskimos who obtained a high percentage of their protein from caribou ingested the radioisotope by eating the meat, and their bodies concentrated the cesium. The more that members of a group depended on caribou as their primary source of food, the higher the level of the isotope in their bodies.

People are exposed to a variety of radiation sources from the sky, the air, and the food we eat (Figure 17.11). We receive natural background radiation from cosmic rays entering Earth's atmosphere from space, and from naturally occurring radioisotopes in soil and rock. The average American receives about 2 to 4 mSv/yr. Of this, about 1 to 3 mSv/yr, or 50–75%, is natural. The differences are primarily due to elevation and geology. More cosmic radiation from outer space (which delivers about 0.3–1.3 mSv/yr) is received at higher elevations.

Radiation from rocks and soils (such as granite and organic shales) containing radioactive minerals delivers about 0.3 to 1.2 mSv/yr. The amount of radiation delivered from rocks, soils, and water may be much larger in areas where radon gas (a naturally occurring radioactive gas) seeps into homes. As a result, mountain states that also have an abundance of granitic rocks, such as Colorado, have greater background radiation than do states that have a lot of limestone bedrock and are low in elevation, such as Florida. Despite this general pattern, locations in Florida where phosphate deposits occur have above-average background radiation because of a relatively high uranium concentration in the phosphate rocks.[10]

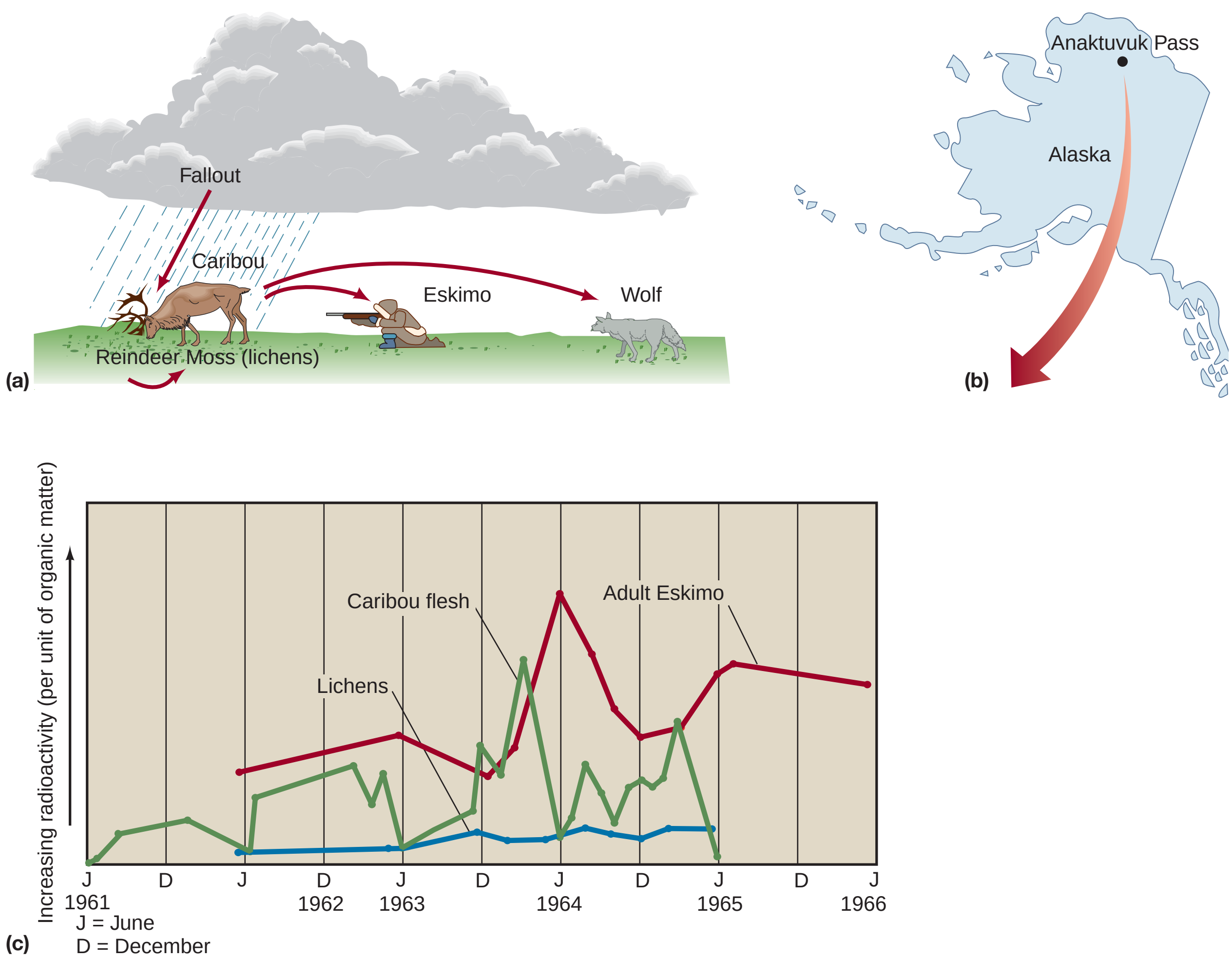


FIGURE 17.10 Cesium-137 released into the atmosphere by atomic bomb tests was part of the fallout deposited on soil and plants. **(a)** The cesium fell on lichens, which were eaten by caribou. The caribou were in turn eaten by Eskimos. **(b)** Measurements of cesium were taken in the lichens, caribou, and Eskimo in the Anaktuvuk Pass of Alaska. **(c)** The cesium was concentrated by the food chain. Peaks in concentrations occurred first in the lichens, then in the caribou, and last in the Eskimos. (*Source*: [c] W.G. Hanson, "Cesium-137 in Alaskan Lichens, Caribou, and Eskimos," *Health Physics* 13 [1967]: 383–389. Copyright 1967 by Pergamon Press. Reprinted with permission.)

The amount of radiation we receive from our own bodies and other people is about 1.35 mSv/yr. Two sources are naturally occurring radioactive potassium-40 and carbon-14, which are present in our bodies and produce about 0.35 mSv/yr. Potassium is an important electrolyte in our blood, and one isotope of potassium (potassium-40) has a very long half-life. Although potassium-40 makes up only a very small percentage of the total potassium in our bodies, it is present in all of us. In short, we are all slightly radioactive, and if you choose to share your life with another person, you are also exposing yourself to a little bit more radiation.

To understand the effects of radiation, you need to be acquainted with the units used to measure radiation and the amount or dose of radiation that may cause a health problem. These are explained in A Closer Look 17.2.

Sources of low-level radiation from our modern technology include X-rays for medical and dental purposes, which may deliver an average of 0.8–0.9 mSv/yr; nuclear weapons testing, approximately 0.04 mSv/yr; the burning of fossil fuels, such as coal, oil, and natural gas, 0.03 mSv/yr; and nuclear power plants (under normal operating conditions), 0.002 mSv/yr.[12]

Your occupation and lifestyle can affect the annual dose of radiation you receive. If you fly at high altitudes in jet aircraft, you receive an additional small dose of radiation—about 0.05 mSv for each flight across the

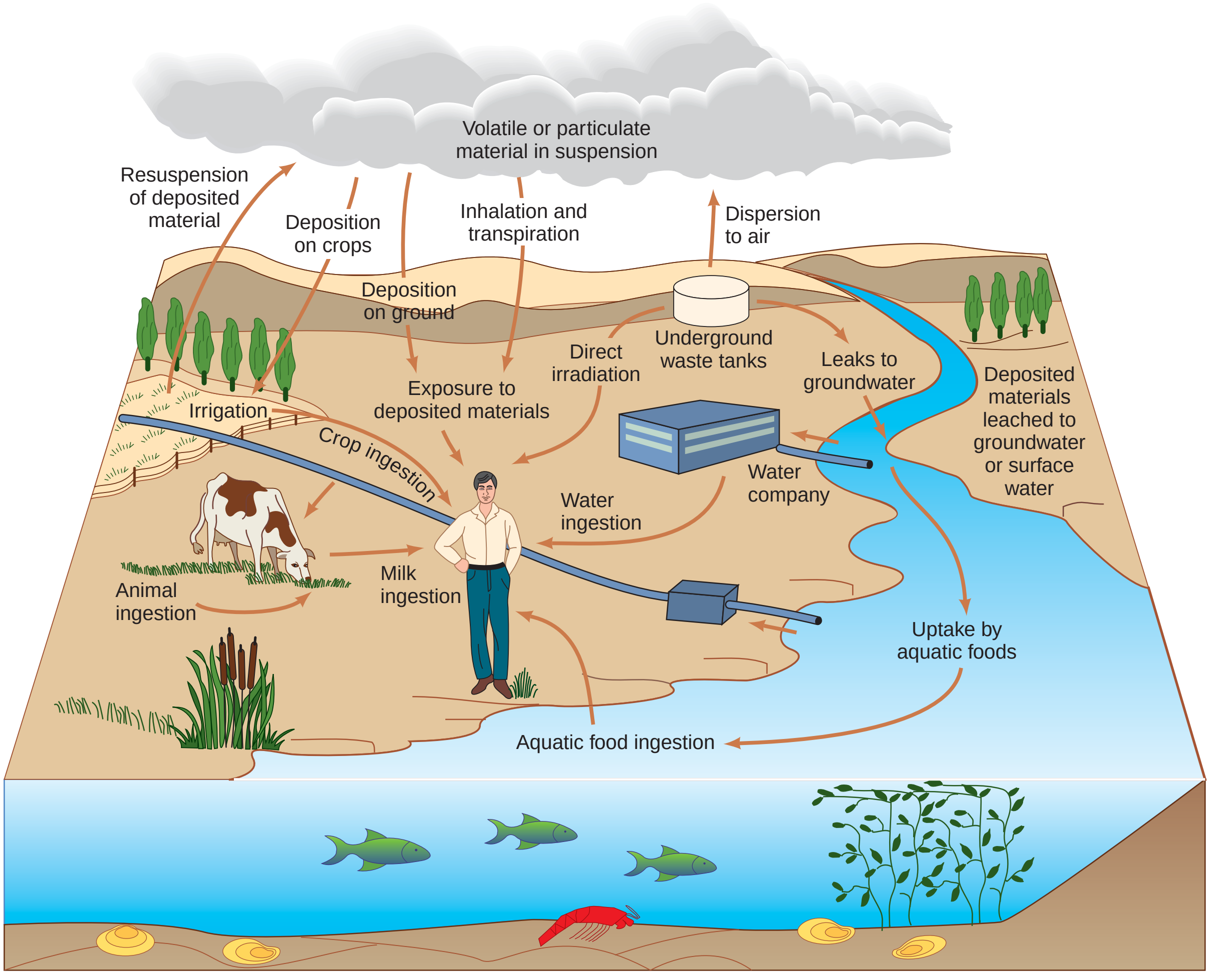


FIGURE 17.11 How radioactive substances reach people. (*Source*: F. Schroyer, ed., *Radioactive Waste*, 2nd printing [American Institute of Professional Geologists, 1985].)

A CLOSER LOOK 17.2

Radiation Units and Doses

The units used to measure radioactivity are complex and somewhat confusing. Nevertheless, a modest acquaintance with them is useful in understanding and talking about radiation's effects on the environment.

A commonly used unit for radioactive decay is the *curie* (Ci), a unit of radioactivity defined as 37 billion nuclear transformations per second. The curie is named for Marie Curie and her husband, Pierre, who discovered radium in the 1890s. They also discovered polonium, which they named after Marie's homeland, Poland. The harmful effects of radiation were not known at that time, and both Marie Curie and her daughter died of radiation-induced cancer.[11] Her laboratory (Figure 17.12) is still contaminated today.

In the International System (SI) of measurement, the unit commonly used for radioactive decay is the *becquerel* (Bq), which is one radioactive decay per second. Units of measurement often used in discussions of radioactive isotopes, such as radon-222, are becquerels per cubic meter and *picocuries* per liter (pC/l). A picocurie is one-trillionth (10^{-12}) of a curie. Becquerels per cubic meter or picocuries

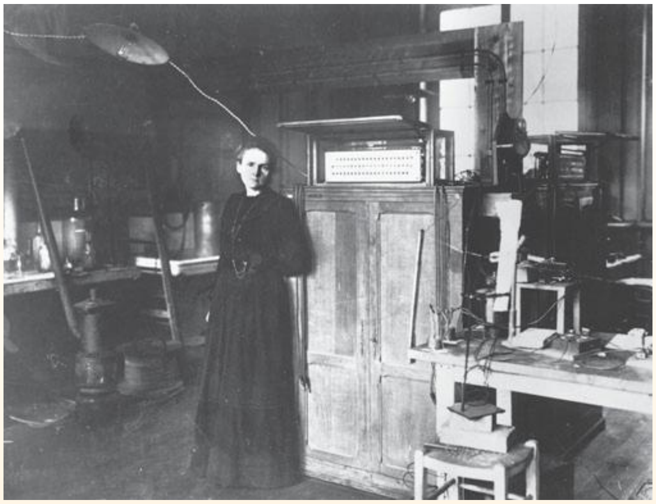


FIGURE 17.12 Marie Curie in her laboratory.

per liter are therefore measures of the number of radioactive decays that occur each second in a cubic meter or liter of air.

When dealing with the environmental effects of radiation, we are most interested in the actual dose of radiation delivered by radioactivity. That dose is commonly measured in terms of *rads* (rd) and *rems*. In the International System, the corresponding units are *grays* (Gy) and *sieverts* (Sv). Rads and grays are the units of the absorbed dose of radiation; 1 gray is equivalent to 100 rads. Rems and sieverts are units of equivalent dose, or effective equivalent dose, where 1 sievert is 100 rems. The energy retained by living tissue that has been exposed to radiation is called the *radiation absorbed dose*, which is where the term *rad* comes from. Because different types of radiation have different penetrations and thus cause different degrees of damage to living tissue, the rad is multiplied by a factor known as the *relative biological effectiveness* to produce the rem or sievert units. When very small doses of radioactivity are being considered, the millirem (mrem) or millisievert (mSv)—that is, one-thousandth (0.001) of a rem or sievert—is used. For gamma rays, the unit commonly used is the roentgen ®, or, in SI units, coulombs per kilogram (C/kg).

United States. If you work at a nuclear power plant, you can receive up to about 3 mSv/yr. Living next door to a nuclear power plant adds 0.01 mSv/year, and sitting on a bench watching a truck carrying nuclear waste pass by would add 0.001 mSv to your annual exposure. Sources of radiation are summarized in Figure 17.13*a*, assuming an annual total of 3 mSv/yr.[13, 14] The amount of radiation received at certain job sites, such as nuclear power plants and laboratories where X-rays are produced, is closely monitored. At such locations, personnel wear badges that indicate the dose of radiation received.

Figure 17.13 shows some of the common sources of radiation to which we are exposed. Notice that exposure to radon gas can equal what people were exposed to as a result of the Chernobyl nuclear power accident, which occurred in the Soviet Union in 1986. In other words, in some homes, people are exposed to about the same radiation as that experienced by the people evacuated from the Chernobyl area.

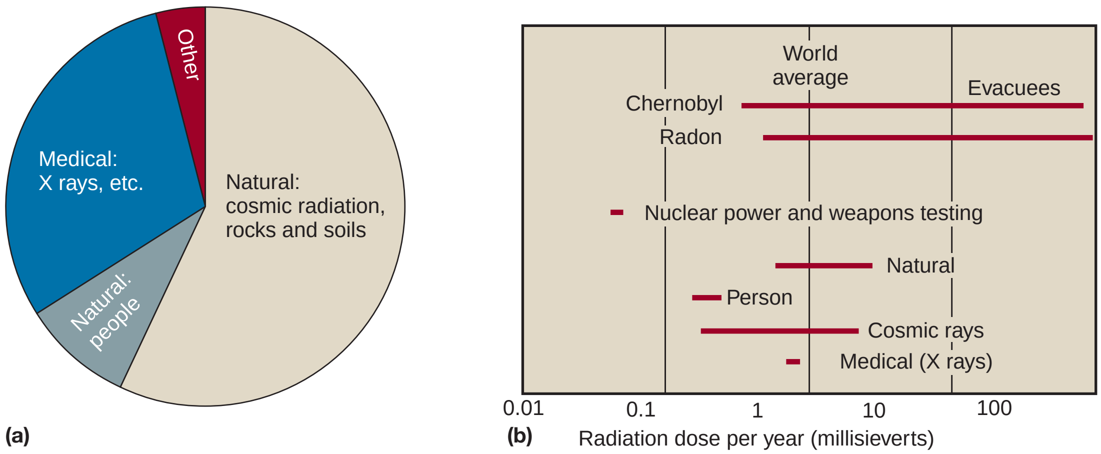


FIGURE 17.13 **(a)** Sources of radiation received by people; assumes annual dose of 3.0 mSv/yr, with 66% natural and 33% medical and other (occupational, nuclear weapons testing, television, air travel, smoke detectors, etc.). (*Sources*: U.S. Department of Energy, 1999; *New Encyclopedia Britannica*, 1997. Radiation V26, p. 487.) **(b)** Range in annual radiation dose to people from major sources. (*Source*: Data in part from A.V. Nero Jr., "Controlling Indoor Air Pollution," *Scientific American* 258[5] [1998]: 42–48.)

Radiation Doses and Health

The most important question in studying radiation exposure in people is: At what point does the exposure or dose becomes a hazard to health? (See again A Closer Look 17.2.) Unfortunately, there are no simple answers to this seemingly simple question. We do know that a dose of about 5,000 mSv (5 sieverts) is considered lethal to 50% of people exposed to it. Exposure to 1,000–2,000 mSv is sufficient to cause health problems, including vomiting, fatigue, potential abortion of pregnancies of less than two months' duration, and temporary sterility in males. At 500 mSv, physiological damage is recorded. The maximum allowed dose of radiation per year for workers in industry is 50 mSv, approximately 30 times the average natural background radiation we all receive.[15] For the general public, the maximum permissible annual dose (for infrequent exposure) is set in the United States at 5 mSv, about three times the annual natural background radiation.[16] For continuous or frequent exposure, the limit for the general public is 1 mSv.

Most information about the effects of high doses of radiation comes from studies of people who survived the atomic bomb detonations in Japan at the end of World War II. We also have information about people exposed to high levels of radiation in uranium mines, workers who painted watch dials with luminous paint containing radium, and people treated with radiation therapy for disease.[17] Starting around 1917 in New Jersey, approximately 2,000 young women were employed painting watch dials with luminous paint. To maintain a sharp point on their brushes, they licked them and as a result were swallowing radium, which was in the paint. By 1924, dentists in New Jersey were reporting cases of jaw rot; and within five years radium was known to be the cause. Many of the women died of anemia or bone cancer.[18]

Workers in uranium mines who were exposed to high levels of radiation have been shown to suffer a significantly higher rate of lung cancer than the general population. Studies show that there is a delay of 10 to 25 years between the time of exposure and the onset of disease.

Although there is vigorous, ongoing debate about the nature and extent of the relationship between radiation exposure and cancer mortality, most scientists agree that radiation can cause cancer. Some scientists believe that there is a linear relationship, such that any increase in radiation beyond the background level will produce an additional hazard. Others believe that the body can handle and recover from low levels of radiation exposure but that health effects (toxicity) become apparent beyond some threshold. The verdict is still out on this subject, but it seems prudent to take a conservative viewpoint and accept that there may be a linear relationship. Unfortunately, chronic health problems related to low-level exposure to radiation are neither well known nor well understood.

Radiation has a long history in the field of medicine. Drinking waters that contain radioactive materials goes back to Roman times. By 1899, the adverse effects of radiation had been studied and were well known; and in that year, the first lawsuit for malpractice in using X-rays was filed. Because science had shown that radiation could destroy human cells, however, it was a logical step to conclude that drinking water containing radioactive material such as radon might help fight diseases such as stomach cancer. In the early 1900s it became popular to drink water containing radon, and the practice was supported by doctors, who stated that there were no known toxic effects. Although we now know that was incorrect, radiotherapy, which uses radiation to kill cancer cells in humans, has been widely and successfully used for a number of years.[19]

17.5 Nuclear Power Plant Accidents

Although the chance of a disastrous nuclear accident is estimated to be very low, the probability that an accident will occur increases with every reactor put into operation. According to the U.S. Nuclear Regulatory Commission's performance goal for a single reactor, the probability of a large-scale core meltdown in any given year should be no greater than 0.01%—one chance in 10,000. However, if there were 1,500 nuclear reactors (about three and a half times the present world total), a meltdown could be expected (at the low annual probability of 0.01%) every seven years. This is clearly an unacceptable risk.[20] Increasing safety by about 10 times would result in lower, more manageable risk, but the risk would still be appreciable because the potential consequences remain large.

Next, we discuss the two most well-known nuclear accidents, which occurred at the Three Mile Island and Chernobyl reactors. It is important to understand that these serious accidents resulted in part from human error.

Three Mile Island

One of the most dramatic events in the history of U.S. radiation pollution occurred on March 28, 1979, at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania. The malfunction of a valve, along with human errors (thought to be the major problem), resulted in a partial core meltdown. Intense radiation was released to the interior of the containment structure. Fortunately, the containment structure functioned as designed, and only a relatively small amount of radiation was released into the environment. Average exposure from the radiation emitted into the atmosphere has been estimated at 1 mSv, which is low in terms of the amount required to cause acute toxic effects. Average exposure to radiation in the surrounding area is estimated to have been approximately 0.012 mSv, which is only about 1% of the natural background radiation that people receive. However, radiation levels were much higher near the site. On the third day after the accident, 12 mSv/hour were measured at ground level near the site. By comparison, the average American receives about 2 mSv/year from natural radiation.

Because the long-term chronic effects of exposure to low levels of radiation are not well understood, the effects of Three Mile Island exposure, though apparently small, are difficult to estimate. However, the incident revealed many potential problems with the way U.S. society dealt with nuclear power. Historically, nuclear power had been considered relatively safe, so the state of Pennsylvania was unprepared to deal with the accident. For example, there was no state bureau for radiation help, and the state Department of Health did not have a single book on radiation medicine (the medical library had been dismantled two years earlier for budgetary reasons). One of the major impacts of the incident was fear, yet there was no state office of mental health, and no staff member from the Department of Health was allowed to sit in on important discussions following the accident.[21]

Chernobyl

Lack of preparedness to deal with a serious nuclear power plant accident was dramatically illustrated by events that began unfolding on Monday morning, April 28, 1986. Workers at a nuclear power plant in Sweden, frantically searching for the source of elevated levels of radiation near their plant, concluded that it was not their installation that was leaking radiation; rather, the radioactivity was coming from the Soviet Union by way of prevailing winds. When confronted, the Soviets announced that an accident had occurred at a nuclear power plant at Chernobyl two days earlier, on April 26. This was the first notice to the world of the worst accident in the history of nuclear power generation.

It is speculated that the system that supplied cooling waters for the Chernobyl reactor failed as a result of human error, causing the temperature of the reactor core to rise to over 3,000°C (about 5,400°F), melting the uranium fuel, setting fire to the graphite surrounding the fuel rods that were supposed to moderate the nuclear reactions, and causing explosions that blew off the top of the building over the reactor. The fires produced a cloud of radioactive particles that rose high into the atmosphere. There were 237 confirmed cases of acute radiation sickness, and 31 people died of radiation sickness.[22]

In the days following the accident, nearly 3 billion people in the Northern Hemisphere received varying amounts of radiation from Chernobyl. With the exception of the 30-km (19-mi) zone surrounding Chernobyl, the world human exposure was relatively small. Even in Europe, where exposure was highest, it was considerably less than the natural radiation received during one year.[23]

In that 30-km zone, approximately 115,000 people were evacuated, and as many as 24,000 people were estimated to have received an average radiation dose of 0.43 Sv (430 mSv).

It was expected, based on results from Japanese A-bomb survivors, that approximately 122 spontaneous leukemias would occur during the period from 1986 through 1998.[24] Surprisingly, as of late 1998, there was no significant increase in the incidence of leukemia, even among the most highly exposed people. However, an increased incidence of leukemia could still become manifest in the future.[25] Meanwhile, studies have found that since the accident the number of childhood thyroid cancer cases per year has risen steadily in Belarus, Ukraine, and the Russian Federation, the three countries most affected by Chernobyl. A total of 1,036 thyroid cancer cases have been diagnosed in children under 15 in the region. These cancer cases are believed to be linked to the released radiation from the accident, but other factors, such as environmental pollution, may also play a role. It is predicted that a few percent of the roughly 1 million children exposed to the radiation eventually will contract thyroid cancer. Outside the 30 km zone, the increased risk of contracting cancer is very small and not likely to be detected from an ecological evaluation.

To date, 4,000 deaths can be directly attributed to the Chernobyl accident, and according to one estimate, Chernobyl will ultimately be responsible for approximately 16,000 to 39,000 deaths. Proponents of nuclear power point out that this is fewer than the number of deaths caused each year by burning coal.[26, 27]

Vegetation within 7 km of the power plant was either killed or severely damaged by the accident. Pine trees examined in 1990 around Chernobyl showed extensive tissue damage and still contained radioactivity. The distance between annual rings (a measure of tree growth) had decreased since 1986.

Scientists returning to the evacuated zone in the mid-1990s found, to their surprise, thriving and expanding animal populations. Species such as wild boar, moose, otters, waterfowl, and rodents seemed to be enjoying a population boom in the absence of people. The wild boar population had increased tenfold since the evacuation. These animals may be paying a genetic price for living within the contaminated zone, but so far the benefit of excluding humans apparently outweighs the negatives associated with radioactive contamination. The area now resembles a wildlife reserve.

In areas surrounding Chernobyl, radioactive materials continue to contaminate soils, vegetation, surface water, and groundwater, presenting a hazard to plants

FIGURE 17.14 Guard halting entry of people into the forbidden zone evacuated in 1986 as a result of the Chernobyl nuclear accident.

and animals. The evacuation zone may be uninhabitable for a very long time unless some way is found to remove the radioactivity (Figure 17.14). For example, the city of Prypyat, 5 km from Chernobyl, which had a population of 48,000 prior to the accident, is a "ghost city." It is abandoned, with blocks of vacant apartment buildings and rusting vehicles. Roads are cracking and trees are growing as new vegetation transforms the urban land back to green fields.

The final story of the world's most serious nuclear accident is yet to completely unfold.[28] Estimates of the total cost of the Chernobyl accident vary widely, but it will probably exceed $200 billion.

Although the Soviets were accused of not paying attention to reactor safety and of using outdated equipment, people are still wondering if such an accident could happen again elsewhere. Because more than 400 nuclear power plants are producing power in the world today, the answer has to be yes. It is difficult to get an exact account of nuclear power plant accidents that have released radiation into the environment since the first nuclear power plants were built in the 1960s. This is partly because of differences in what is considered a significant radiation emission. As best as can be estimated, there appear to have been 20 to 30 such incidents worldwide—at least that is the range of numbers released to the public. Therefore, although Chernobyl is the most serious nuclear accident to date, it certainly was not the first and is unlikely to be the last. Although the probability of a serious accident is very small at a particular site, the consequences may be great, perhaps posing an unacceptable risk to society. This is really not so much a scientific issue as a political one involving values.

Advocates of nuclear power argue that nuclear power is safer than other energy sources, that many more deaths are caused by air pollution from burning fossil fuels than by nuclear accidents. For example, the 16,000 deaths that might eventually be attributed to Chernobyl are fewer than the number of deaths caused each year by air pollution from burning coal.[29] Those arguing against nuclear power say that as long as people build nuclear power plants and manage them, there will be the possibility of accidents. We can build nuclear reactors that are safer, but people will continue to make mistakes, and accidents will continue to happen.

17.6 Radioactive-Waste Management

Examination of the nuclear fuel cycle (refer back to Figure 17.9) illustrates some of the sources of waste that must be disposed of as a result of using nuclear energy to produce electricity. Radioactive wastes are by-products of using nuclear reactors to generate electricity. The U.S. Federal Energy Regulatory Commission (FERC) defines three categories of radioactive waste: mine tailings, low-level, and high-level. Other groups list a fourth category: transuranic wastes.[30] In the western United States, more than 20 million metric tons of abandoned tailings will continue to produce radiation for at least 100,000 years.

Low-Level Radioactive Waste

Low-level radioactive waste contains radioactivity in such low concentrations or quantities that it does not present a significant environmental hazard if properly handled. Low-level waste includes a wide variety of items, such as residuals or solutions from chemical processing; solid or liquid plant waste, sludges, and acids; and slightly contaminated equipment, tools, plastic, glass, wood, and other materials.[31]

Low-level waste has been buried in near-surface burial areas in which the hydrologic and geologic conditions were thought to severely limit the migration of radioactivity.[32] However, monitoring has shown that several U.S. disposal sites for low-level radioactive waste have not adequately protected the environment, and leaks of liquid waste have polluted groundwater. Of the original six burial sites, three closed prematurely by 1979 due to unexpected leaks, financial problems, or loss of license, and as of 1995 only two remaining government low-level nuclear-waste repositories were still operating in the United States, one in Washington and the other in South Carolina. In addition, a private facility in Utah, run by Envirocare, accepts low-level waste. Construction of new burial sites, such as the Ward Valley site in southeastern California, has been met with strong public opposition, and controversy continues as to whether low-level radioactive waste can be disposed of safely.[33]

Transuranic Waste

As noted earlier, it is useful to also list separately **transuranic waste**, which is waste contaminated by man-made radioactive elements, including plutonium, americum, and einsteineum, that are heavier than uranium and are produced in part by neutron bombardment of uranium in reactors. Most transuranic waste is industrial trash, such as clothing, rags, tools, and equipment, that has been contaminated. The waste is low-level in terms of its intensity of radioactivity, but plutonium has a long half-life and must be isolated from the environment for about 250,000 years. Most transuranic waste is generated from the production of nuclear weapons and, more recently, from cleanup of former nuclear weapons facilities.

Some nuclear weapons transuranic wastes (as of 2000) are being transported to a disposal site near Carlsbad, New Mexico, and to date more than 5,000 shipments have been delivered.[34] The waste is isolated at a depth of 655 m (2,150 ft) in salt beds (rock salt) that are several hundred meters thick (Figure 17.15). Rock salt at the New Mexico site has several advantages:[35, 36, 37]

- The salt is about 225 million years old, and the area is geologically stable, with very little earthquake activity.
- The salt has no flowing groundwater and is easy to mine. Excavated rooms in the salt, about 10 m wide and 4 m high, will be used for disposal.
- Rock salt flows slowly into mined openings. The waste-filled spaces in the storage facility will be naturally closed by the slow-flowing salt in 75 to 200 years, sealing the waste.

The New Mexico disposal site is important because it is the first geologic disposal site for radioactive waste in the United States. As a pilot project, it will be evaluated very carefully. Safety is the primary concern. Procedures have been established to transport the waste to the disposal site as safely as possible and place it underground in the disposal facility. Because the waste will be hazardous for many thousands of years, it was decided that warnings had to be created that would be understandable to future peoples no matter what their cultures and languages. But of course it is unclear today whether any such sign will actually communicate anything to people thousands of years from now.[38]

High-Level Radioactive Waste

High-level radioactive waste consists of commercial and military spent nuclear fuel; uranium and plutonium derived from military reprocessing; and other radioactive nuclear weapons materials. It is extremely toxic, and a sense of urgency surrounds its disposal as the total volume of spent fuel accumulates. At present, in the United States, tens of thousands of metric tons of high-level waste are being stored at more than a hundred sites in 40 states. Seventy-two of the sites are commercial nuclear reactors.[39, 40, 41]

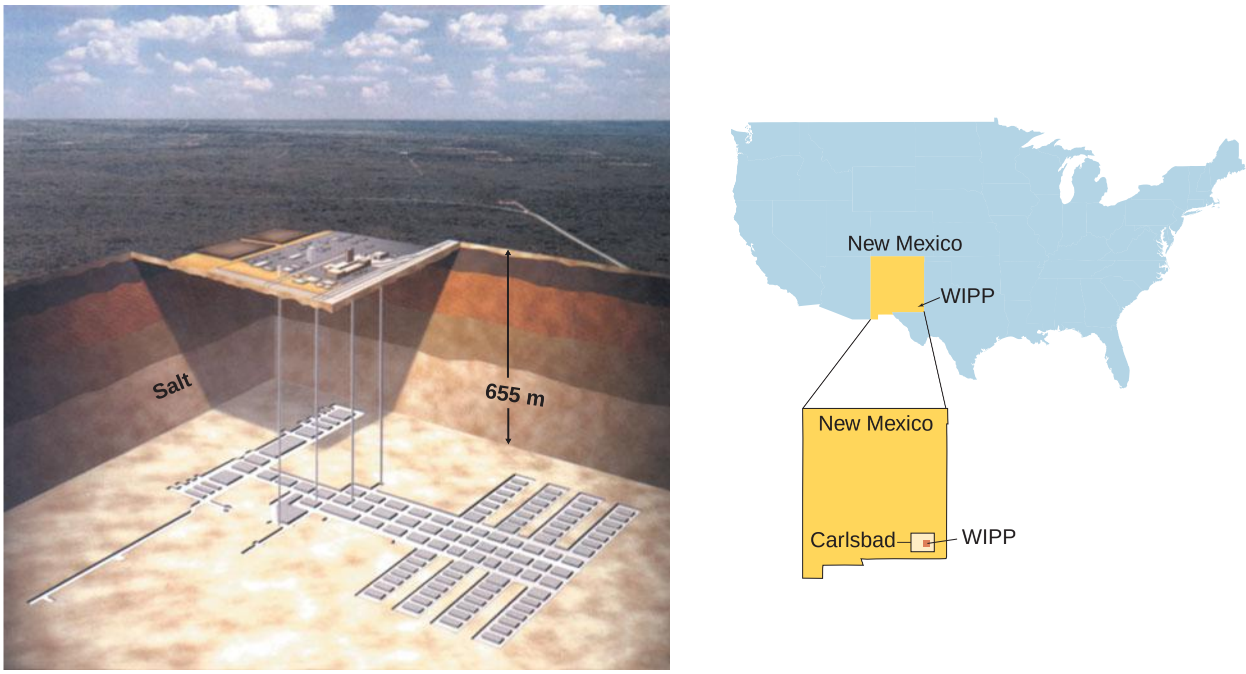


FIGURE 17.15 Waste isolation pilot plant (WIPP) in New Mexico for disposal of transuranic waste. (*Source*: U.S. Department of Energy, 1999.)

These storage arrangements are at best a temporary solution, and serious problems with radioactive waste have occurred where it is being stored. Although improvements in storage tanks and other facilities will help, eventually some sort of disposal program must be initiated. Some scientists believe the geologic environment can best provide safe containment of high-level radioactive waste. Others disagree and have criticized proposals for long-term underground disposal of high-level radioactive waste. A comprehensive geologic disposal development program should have the following objectives:[42]

- Identification of sites that meet broad geologic criteria, including ground stability and slow movement of groundwater with long flow paths to the surface.
- Intensive subsurface exploration of possible sites to positively determine geologic and hydrologic characteristics.
- Predictions of the behavior of potential sites based on present geologic and hydrologic situations and assumptions about future changes in climate, groundwater flow, erosion, ground movements, and other variables.
- Evaluation of risk associated with various predictions.
- Political decision making based on risks acceptable to society.

What Should the United States Do with Its Nuclear Wastes?

For decades in the United States, the focal point for debates over nuclear wastes has been the plan to bury them deep in the earth at Yucca Mountain, Nevada. But the Obama administration rejected that plan, and Secretary of Energy Steven Chu has set up a blue ribbon panel to consider the alternatives. At present, there are 70,000 tons of radioactive wastes from nuclear power plants, and federally authorized temporary storage facilities for these are said to be full. That is to say, there is no government-sanctioned and locally approved place to put any more nuclear wastes. Yet they continue to build up.

Why was the Yucca Mountain repository so controversial, and why has it finally been canceled, or at least put on hold? The Nuclear Waste-Policy Act of 1982 initiated a high-level nuclear-waste-disposal program. The Department of Energy was given the responsibility to investigate several potential sites and make a recommendation. The 1982 act was amended in 1987; the amendment, along with the Energy Power Act of 1992, specified that high-level waste was to be disposed of underground in a deep, geologic waste repository. It also specified that the Yucca Mountain site in Nevada was to be the only site evaluated. Costs to build the facility reached $77 billion, but no nuclear wastes have ever been sent there.[43]

Evaluation of the safety and utility of a new waste repository would have to consider factors such as the following:

- The probability and consequences of volcanic eruptions.
- Earthquake hazard.
- Estimation of changes in the storage environment over long periods.
- Estimation of how long the waste may be contained and the types and rates of radiation that may escape from deteriorated waste containers.
- How heat generated by the waste may affect moisture in and around the repository and the design of the repository.
- Characterization of groundwater flow near the repository.
- Identification and understanding of major geochemical processes that control the transport of radioactive materials.

One of the problems is just transporting the present amount of nuclear waste from power plants to any repository. According to previous U.S. government plans, beginning in 2010 some 70,000 tons of highly radioactive nuclear waste were going to be moved across the country to Yucca Mountain, Nevada, by truck and train, one to six trainloads or truck convoys every day for 24 years. These train and truck convoys would have to be heavily guarded against terrorism and protected as much as possible against accidents.

Extensive scientific evaluations of the Yucca Mountain site have been carried out.[44] Use of this site remains controversial and is generating considerable resistance from the state and people of Nevada as well as from scientists not confident of the plan. Some of the scientific questions at Yucca Mountain have concerned natural processes and hazards that might allow radioactive materials to escape, such as surface erosion, groundwater movement, earthquakes, and volcanic eruptions. In 2002, Congress voted to submit a license of application for Yucca Mountain to the Nuclear Regulatory Commission.

A major question about the disposal of high-level radioactive waste is this: How credible are extremely long-range geologic predictions—those covering several thousand to a few *million* years?[45] Unfortunately, there is no easy answer to this question because geologic processes vary over both time and space. Climates change over long periods, as do areas of erosion, deposition, and groundwater activity. For example, large earthquakes even thousands of kilometers from a site may permanently change groundwater levels. The earthquake record for most of the United States extends back only a few hundred years; therefore, estimates of future earthquake activity are tenuous at best.

The bottom line is that geologists can suggest sites that have been relatively stable in the geologic past, but they cannot absolutely guarantee future stability. This means that policymakers (not geologists) need to evaluate the uncertainty of predictions in light of pressing political, economic, and social concerns.[46] In the end, the geologic environment may be deemed suitable for safe containment of high-level radioactive waste, but care must be taken to ensure that the best possible decisions are made on this important and controversial issue.

17.7 The Future of Nuclear Energy

The United States would need 1,000 new nuclear power plants of the same design and efficiency as existing nuclear plants to completely replace fossil fuels. The International Atomic Energy Agency, which promotes nuclear energy, says a total of just 4.7 million tons of "identified" conventional uranium stock can be mined economically. If we switched from fossil fuels to nuclear today, that uranium would run out in four years. Even the most optimistic estimate of the quantity of uranium ore would last only 29 years.[47]

Nevertheless, nuclear energy as a power source for electricity is now being seriously evaluated. Its advocates argue that nuclear power is good for the environment because (1) it does not contribute to potential global warming through release of carbon dioxide (see Chapter 20) and (2) it does not cause the kinds of air pollution or emit precursors (sulfates and nitrates) that cause acid rain (see Chapter 21). They also argue that developing breeder reactors for commercial use would greatly increase the amount of fuel available for nuclear plants, that nuclear power plants are safer than other means of generating power, and that we should build many more nuclear power plants in the future. Their argument assumes that if we standardize nuclear reactors and make them safer and smaller, nuclear power could provide much of our electricity in the future,[48] although the possibility of accidents and the disposal of spent fuel remain concerns.

The argument against nuclear power is based on political and economic considerations as well as scientific uncertainty about safety issues. Opponents emphasize, as we pointed out earlier, that more than half the U.S. population lives within 75 miles of one of the nation's 104 nuclear power plants. They also argue, correctly, that converting from coal-burning plants to nuclear power plants for the purpose of reducing carbon dioxide emissions would require an enormous investment in nuclear power to make a real impact. Furthermore, they say, given that safer nuclear reactors are only just being developed, there will be a time lag, so nuclear power is unlikely to have a real impact on environmental problems—such as air pollution, acid rain, and potential global warming—before at least the year 2050.

Furthermore, uranium ore to fuel conventional nuclear reactors is limited. The International Nuclear Energy Association estimates that at the 2004 rate of use, there would be 85 years of uranium fuel from known reserves, but if nations attempt to build many new power plants in the next decade, known reserves of uranium ore would be used up much more quickly.[49] Nuclear power can thus be a long-term energy source only through the development of breeder reactors.

Another argument against nuclear power is that some nations may use it as a path to nuclear weapons. Reprocessing used nuclear fuel from a power plant produces plutonium that can be used to make nuclear bombs. There is concern that rogue nations with nuclear power could divert plutonium to make weapons, or may sell plutonium to others, even terrorists, who would make nuclear weapons.[50]

Until 2001, proponents of nuclear energy were losing ground. Nearly all energy scenarios were based on the expectation that nuclear power would grow slowly or perhaps even decline in coming years. Since the Chernobyl accident, many European countries have been reevaluating the use of nuclear power, and in most instances the number of nuclear power plants being built has significantly declined. Germany, which gets about one-third of its electricity from nuclear power, has decided to shut down all nuclear power plants in the next 25 years as they become obsolete.

There is also a problem with present nuclear technology: Today's light-water reactors use uranium very inefficiently; only about 1% of it generates electricity, and the other 99% ends up as waste heat and radiation. Therefore, our present reactors are part of the nuclear-waste problem and not a long-term solution to the energy problem.

One design philosophy that has emerged in recent decades in the nuclear industry is to build less complex, smaller reactors that are safer. Large nuclear power plants, which produce about 1,000 MW of electricity, require an extensive set of pumps and backup equipment to ensure that adequate cooling is available to the reactor. Smaller reactors can be designed with cooling systems that work by gravity and thus are less vulnerable to pump failure caused by power loss. Such cooling systems are said to have *passive stability*, and the reactors are said to be *passively safe*. Another approach is the use of helium gas to cool reactors that have specially designed fuel capsules capable of withstanding temperatures as high as 1,800°C (about 3,300°F). The idea is to design the fuel assembly so that it can't hold enough fuel to reach this temperature and thus can't experience a core meltdown.

One way for nuclear power to be sustainable for at least hundreds of years would be to use a process known as *breeding*. **Breeder reactors** are designed to produce new nuclear fuel by transforming waste or lower-grade uranium into fissionable material. Although proponents of nuclear energy suggest that breeder reactors are the future of nuclear power, only a few are known to be operating anywhere in the world. Bringing breeder reactors online to produce safe nuclear power will take planning, research, and advanced reactor development. Also, fuel for the breeder reactors will have to be recycled because reactor fuel must be replaced every few years. What is needed is a new type of breeder reactor comprising an entire system that includes reactor, fuel cycle (especially fuel recycling and reprocessing), and less production of waste. Such a reactor appears possible but will require redefining our national energy policy and turning energy production in new directions. It remains to be seen whether this will happen.

Possible New Kinds of Nuclear Power Plants

New Kinds of Fission Reactors

Several new designs for conventional nonbreeder fission nuclear power plants are in development and the object of widespread discussion. Among these are the Advanced Boiling Water Reactor, the High Temperature Gas Reactor, and the Pebble Reactor.[51, 52] None are yet installed or operating anywhere in the world. The general goals of these designs are to increase safety, energy efficiency, and ease of operation. Some are designed to shut down automatically if there is any failure in the cooling system, rather than require the action of an operator. Although proponents of nuclear power believe these will offer major advances, it will be years, perhaps decades, until even one of each kind achieves commercial operation, so planning for the future cannot depend on them.

Fusion Reactors

In contrast to fission, which involves splitting heavy nuclei (such as uranium), fusion involves combining the nuclei of light elements (such as hydrogen) to form heavier ones (such as helium). As fusion occurs, heat energy is released. Nuclear fusion is the source of energy in our sun and other stars.

In a hypothetical fusion reactor, two isotopes of hydrogen—deuterium and tritium—are injected into the reactor chamber, where the necessary conditions for fusion are maintained. Products of the deuterium–tritium (DT) fusion include helium, producing 20% of the energy released, and neutrons, producing 80%.

Several conditions are necessary for fusion to take place. First, the temperature must be extremely high (approximately 100 million degrees Celsius for DT fusion). Second, the density of the fuel elements must be sufficiently high. At the temperature necessary for fusion, nearly all atoms are stripped of their electrons, forming a *plasma*—an electrically neutral material consisting of positively charged nuclei, ions, and negatively charged electrons. Third, the plasma must be confined long enough to ensure that the energy released by the fusion reactions exceeds the energy supplied to maintain the plasma.

The potential energy available when and if fusion reactor power plants are developed is nearly inexhaustible. One gram of DT fuel (from a water and lithium fuel supply) has the energy equivalent of 45 barrels of oil. Deuterium can be extracted economically from ocean water, and tritium can be produced in a reaction with lithium in a fusion reactor. Lithium can be extracted economically from abundant mineral supplies.

Many problems remain to be solved before nuclear fusion can be used on a large scale. Research is still in the first stage, which involves basic physics, testing of possible fuels (mostly DT), and magnetic confinement of plasma.

CRITICAL THINKING ISSUE

Should the United States Increase or Decrease the Number of Nuclear Power Plants?

There are two contradictory political movements regarding nuclear power plants in the United States. The federal government has supported an increase in the number of plants. The G. W. Bush administration did, and the Obama administration has allocated $18.5 for new "next-generation" nuclear power plants. But in February 2010, the Vermont Senate voted to prevent relicensing of the Yankee Power Plant, the state's only nuclear plant, after its current license expires in 2012. In 2009 the power plant leaked radioactive tritium into groundwater, and the plant's owners have been accused of misleading state regulators about underground pipes that carry cooling water at the plant.[53] Also, as you saw in this chapter's opening case study, there are major political pressures at the state, county, and local level to prevent the relicensing of Indian Point Power Plant near New York City.

Critical Thinking Questions

1. Refer to the map of nuclear power plants in the United States (Figure 17.4) and to other material in this chapter. Taking into account safety and the problem of transporting large amounts of electricity long distances, choose three locations that you consider appropriate for new nuclear power plants. Or, if you believe there should be none, present your argument for that conclusion. (Be as specific as possible about the locations—include the state and, if possible, name the nearest city.) In answering this question, you can take into account information from other chapters you have read.
2. Should new nuclear power plants be licensed now and built as soon as possible using existing and proven designs? Or would you propose putting off any new nuclear power plants until one of the safer and more efficient designs has been proved—let's say, two decades from now?
3. Which do you believe is the greater environmental problem facing the United States: global warming or the dangers of nuclear power plants? Explain your answer.

SUMMARY

- Nuclear fission is the process of splitting an atomic nucleus into smaller fragments. As fission occurs, energy is released. The major components of a fission reactor are the core, control rods, coolant, and reactor vessel.
- Nuclear radiation occurs when a radioisotope spontaneously undergoes radioactive decay and changes into another isotope.
- The three major types of nuclear radiation are alpha, beta, and gamma.
- Each radioisotope has its own characteristic emissions. Different types of radiation have different toxicities; and in terms of the health of humans and other organisms, it is important to know the type of radiation emitted and the half-life.
- The nuclear fuel cycle consists of mining and processing uranium, generating nuclear power through controlled fission, reprocessing spent fuel, disposing of nuclear waste, and decommissioning power plants. Each part of the cycle is associated with characteristic processes, all with different potential environmental problems.
- The present burner reactors (mostly light-water reactors) use uranium-235 as a fuel. Uranium is a nonrenewable resource mined from the Earth. If many more burner reactors were constructed, we would face fuel shortages. Nuclear energy based on burning uranium-235 in light-water reactors is thus not sustainable. For nuclear energy to be sustainable, safe, and economical, we will need to develop breeder reactors.
- Radioisotopes affect the environment in two major ways: by emitting radiation that affects other materials, and by entering ecological food chains.
- Major environmental pathways by which radiation reaches people include uptake by fish ingested by people, uptake by crops ingested by people, inhalation from air, and exposure to nuclear waste and the natural environment.
- The dose response for radiation is fairly well established. We know the dose–response for higher exposures, when illness or death occurs. However, there are vigorous debates about the health effects of low-level exposure to radiation and what relationships exist between exposure and cancer. Most scientists believe that radiation can cause cancer. But, Ironically, radiation can be used to kill cancer cells, as in radiotherapy treatments.
- We have learned from accidents at nuclear power plants that it is difficult to plan for the human factor. People make mistakes. We have also learned that we are not as prepared for accidents as we would like to think. Some believe that people are not ready for the responsibility of nuclear power. Others believe that we can design much safer power plants where serious accidents are impossible.
- Transuranic nuclear waste is now being disposed of in salt beds—the first disposal of radioactive waste in the geologic environment in the United States.
- There is a consensus that high-level nuclear waste may be safely disposed of in the geologic environment. The problem has been to locate a site that is safe and not objectionable to the people who make the decisions and to those who live in the region.
- Nuclear power is again being seriously evaluated as an alternative to fossil fuels. On the one hand, it has advantages: It emits no carbon dioxide, will not contribute to global warming or cause acid rain, and can be used to produce alternative fuels such as hydrogen. On the other hand, people are uncomfortable with nuclear power because of waste-disposal problems and possible accidents.

REEXAMINING THEMES AND ISSUES

Human Population

As the human population has increased, so has demand for electrical power. In response, a number of countries have turned to nuclear energy. The California energy crisis has caused many people in the United States to rethink the value of nuclear energy. Though relatively rare, accidents at nuclear power plants such as Chernobyl have exposed people to increased radiation, and there is considerable debate over potential adverse effects of that radiation. The fact remains that as the world population increases, and if the number of nuclear power plants increases, the total number of people exposed to a potential release of toxic radiation will increase as well.

Sustainability

Some argue that sustainable energy will require a return to nuclear energy because it doesn't contribute to a variety of environmental problems related to burning fossil fuels. However, for nuclear energy to significantly contribute to sustainable energy development, we cannot depend on burner reactors that will quickly use Earth's uranium resources; rather, development of safer breeder reactors will be necessary.

Global Perspective

Use of nuclear energy fits into our global management of the entire spectrum of energy sources. In addition, testing of nuclear weapons has spread radioactive isotopes around the entire planet, as have nuclear accidents. Radioactive isotopes that enter rivers and other waterways may eventually enter the oceans of the world, where oceanic circulation may further disperse and spread them.

Urban World

Development of nuclear energy is a product of our technology and our urban world. In some respects, it is near the pinnacle of our accomplishments in terms of technology.

People and Nature

Nuclear reactions are the source of heat for our sun and are fundamental processes of the universe. Nuclear fusion has produced the heavier elements of the universe. Our use of nuclear reactions in reactors to produce useful energy is a connection to a basic form of energy in nature. However, abuse of nuclear reactions in weapons could damage or even destroy nature on Earth.

Science and Values

We have a good deal of knowledge about nuclear energy and nuclear processes. Still, people remain suspicious and in some cases frightened by nuclear power—in part because of the value we place on a quality environment and our perception that nuclear radiation is toxic to that environment. As a result, the future of nuclear energy will depend in part on how much risk is acceptable to society. It will also depend on research and development to produce much safer nuclear reactors.

KEY TERMS

breeder reactors **363**
burner reactors **349**
fission **348**
fusion **348**
high-level radioactive waste **361**
low-level radioactive waste **360**
meltdown **348**
nuclear energy **348**
nuclear fuel cycle **353**
nuclear reactors **348**
radioactive decay **350**
radioisotope **350**
transuranic waste **361**

STUDY QUESTIONS

1. If exposure to radiation is a natural phenomenon, why are we worried about it?
2. What is a radioisotope, and why is knowing its half-life important?
3. What is the normal background radiation that people receive? Why is it variable?
4. What are the possible relationships between exposure to radiation and adverse health effects?
5. What processes in our environment may result in radioactive substances reaching people?
6. Suppose it is recommended that high-level nuclear waste be disposed of in the geologic environment of the region in which you live. How would you go about evaluating potential sites?
7. Are there good environmental reasons to develop and build new nuclear power plants? Discuss both sides of the issue.

FURTHER READING

Botkin, D.B., ***Powering the Future: A Scientist's Guide to Energy Independence*** (Indianapolis: Pearson FT Press, 2010).

Hore Lacy, Ian, ***Nuclear Energy in the 21st Century*** (New York: Academic Press, 2006). A pro-nuclear power plant book.

World Nuclear Association, "Waste Management in the Nuclear Fuel Cycle." www.world nuclear.org/info/inf04.html. A major international organization's review of this problem.

CHAPTER 18

Water Supply, Use, and Management

Great blue heron and young in Wakodahatchee Wetlands near Palm Beach, Florida.

LEARNING OBJECTIVES

Although water is one of the most abundant resources on Earth, water management involves many important issues and problems. After reading this chapter, you should understand . . .

- Why water is one of the major resource issues of the 21st century;
- What a water budget is, and why it is useful in analyzing water-supply problems and potential solutions;
- What groundwater is, and what environmental problems are associated with its use;
- How water can be conserved at home, in industry, and in agriculture;
- Why sustainable water management will become more difficult as the demand for water increases;
- The concepts of virtual water and a water footprint and their link to water management and conservation;
- The environmental impacts of water projects such as dams;
- What a wetland is, how wetlands function, and why they are important;
- Why we are facing a growing global water shortage linked to our food supply.

CASE STUDY

Palm Beach County, Florida: Water Use, Conservation, and Reuse

The southeastern United States–experienced one of the worst droughts on record from 2006 to 2008. Although March of 2008 brought significant rainfall to south Florida, it was not sufficient to end the shortage that had built up over several years. Hurricane Fran brought another 15–30 cm (6–12 in.) to south Florida in August 2008, relieving drought conditions. Water shortages during the drought in Palm Beach County led to water restrictions and water rules. For example, lawns could be watered and cars washed only once a week on a Saturday or Sunday, depending on whether your home address was an odd or even number.

Even with such rules, there were water-use problems because people use very different amounts of water. Palm Beach County and its famous resort city of Palm Beach have some large estates that use huge quantities of water. During one year of the ongoing drought, one estate of about 14 acres (6 hectares) reportedly used an average of 57,000 gallons per day—about as much as a modest single-family home in Palm Beach County uses in an entire year. Some landowners continue to use very large amounts of water during a drought, while others choose to conserve water and let their lawns go brown.[1]

Although that drought has ended, it highlighted the need to plan for projected greater shortages in the future. To this end, Florida has turned to water-conservation projects, including the use of reclaimed and purified water from wastewater-treatment plants. Florida has several hundred water-recycling projects, making it a national leader in water reuse, and Palm Beach County is a leader in south Florida. Water-conservation measures include installing low-flow showers and toilets in homes, businesses, and public buildings; limiting lawn watering and car washing; and promoting landscaping that uses less water.

The county has reclaimed approximately 9 million gallons of water per day, distributing it to parks, golf courses, and homes by way of separate water pipes painted purple (the color for reclaimed water). In addition, over 1 million gallons a day of highly treated wastewater are sent to Wakodahatchee Wetlands (see opening photograph), constructed (human-made) wetlands of approximately 25 hectares. In the Seminole language, *wakodahatchee* means "created water." The wetlands function as giant filters where wetland plants and soil use and reduce the concentration of nitrogen and phosphorus in the water and thus further treat the water. A second, larger wetland in Palm Beach County, the Green Cay Wetlands, constructed from about 50 hectares of farmland, receives over 1 million gallons of treated wastewater per day. Both are contributing to the fresh water resource base of south Florida.

Using reclaimed water has some significant benefits: (1) people who use it for private lawns or golf courses save money because the reclaimed water is less expensive; (2) reclaimed water used on lawns, golf courses, and parks has traces of nitrogen and phosphorus, which are types of fertilizer; (3) reclaimed water leaves more fresh drinking water available to the rest of the community; and (4) constructed wetlands that accept treated wastewater help the natural environment by creating wildlife habitat as well as green space in which people can walk, bird-watch, and generally enjoy a more natural setting (see Figure 18.1).[2]

Water is a critical, limited, resource in many regions on Earth. As a result, water is one of the major resource issues of the 21st century. This chapter discusses our water resources in terms of supply, use, management, and sustainability. It also addresses important environmental concerns related to water: wetlands, dams and reservoirs, channelization, and flooding.

FIGURE 18.1 Boardwalk for viewing the Wakodahatchee Wetlands near Palm Beach, Florida.

18.1 Water

To understand water as a necessity, as a resource, and as a factor in the pollution problem, we must understand its characteristics, its role in the biosphere, and its role in sustaining life. Water is a unique liquid; without it, life as we know it is impossible. Consider the following:

- Compared with most other common liquids, water has a high capacity to absorb and store heat. Its capacity to hold heat has important climatic significance. Solar energy warms the oceans, storing huge amounts of heat. The heat can be transferred to the atmosphere, developing hurricanes and other storms. The heat in warm oceanic currents, such as the Gulf Stream, warms Great Britain and Western Europe, making these areas much more hospitable for humans than would otherwise be possible at such high latitudes.
- Water is the universal solvent. Because many natural waters are slightly acidic, they can dissolve a great variety of compounds, ranging from simple salts to minerals, including sodium chloride (common table salt) and calcium carbonate (calcite) in limestone rock. Water also reacts with complex organic compounds, including many amino acids found in the human body.
- Compared with other common liquids, water has a high surface tension, a property that is extremely important in many physical and biological processes that involve moving water through, or storing water in, small openings or pore spaces.
- Water is the only common compound whose solid form is lighter than its liquid form. (It expands by about 8% when it freezes, becoming less dense.) That is why ice floats. If ice were heavier than liquid water, it would sink to the bottom of the oceans, lakes, and rivers. If water froze from the bottom up, shallow seas, lakes, and rivers would freeze solid. All life in the water would die because cells of living organisms are mostly water, and as water freezes and expands, cell membranes and walls rupture. If ice were heavier than water, the biosphere would be vastly different from what it is, and life, if it existed at all, would be greatly altered[3].
- Sunlight penetrates water to variable depths, permitting photosynthetic organisms to live below the surface.

A Brief Global Perspective

The water-supply problem, in brief, is that we are facing a growing global water shortage that is linked to our food supply. We will return to this important concept at the end of the chapter, following a discussion of water use, supply, and management.

A review of the global hydrologic cycle, introduced in Chapter 6, is important here. The main process in the cycle is the global transfer of water from the atmosphere to the land and oceans and back to the atmosphere (Figure 18.2). Table 18.1 lists the relative amounts of water in the major storage compartments of the cycle. Notice that more than 97% of Earth's water is in the oceans; the next-largest storage compartment, the ice caps and glaciers, accounts for another 2%. Together, these sources account for more than 99% of the total water, and both are generally unsuitable for human use because of salinity (seawater) and location (ice caps and glaciers). Only about 0.001% of the total water on Earth is in the atmosphere at any one time. However, this relatively small amount of water in the global water cycle, with an average atmosphere residence time of only about nine days, produces all our freshwater resources through the process of precipitation.

Table 18.1 THE WORLD'S WATER SUPPLY (SELECTED EXAMPLES)

LOCATION	SURFACE AREA (KM^2)	WATER VOLUME (KM^3)	PERCENTAGE OF TOTAL WATER	ESTIMATED AVERAGE RESIDENCE TIME OF WATER
Oceans	361,000,000	1,230,000,000	97.2	Thousands of years
Atmosphere	510,000,000	12,700	0.001	9 days
Rivers and streams	–	1,200	0.0001	2 weeks
Groundwater (shallow to depth of 0.8 km)	130,000,000	4,000,000	0.31	Hundreds to many thousands of years
Lakes (freshwater)	855,000	123,000	0.01	Tens of years
Ice caps and glaciers	28,200,000	28,600,000	2.15	Tens of thousands of years and longer

Source: U.S. Geological Survey

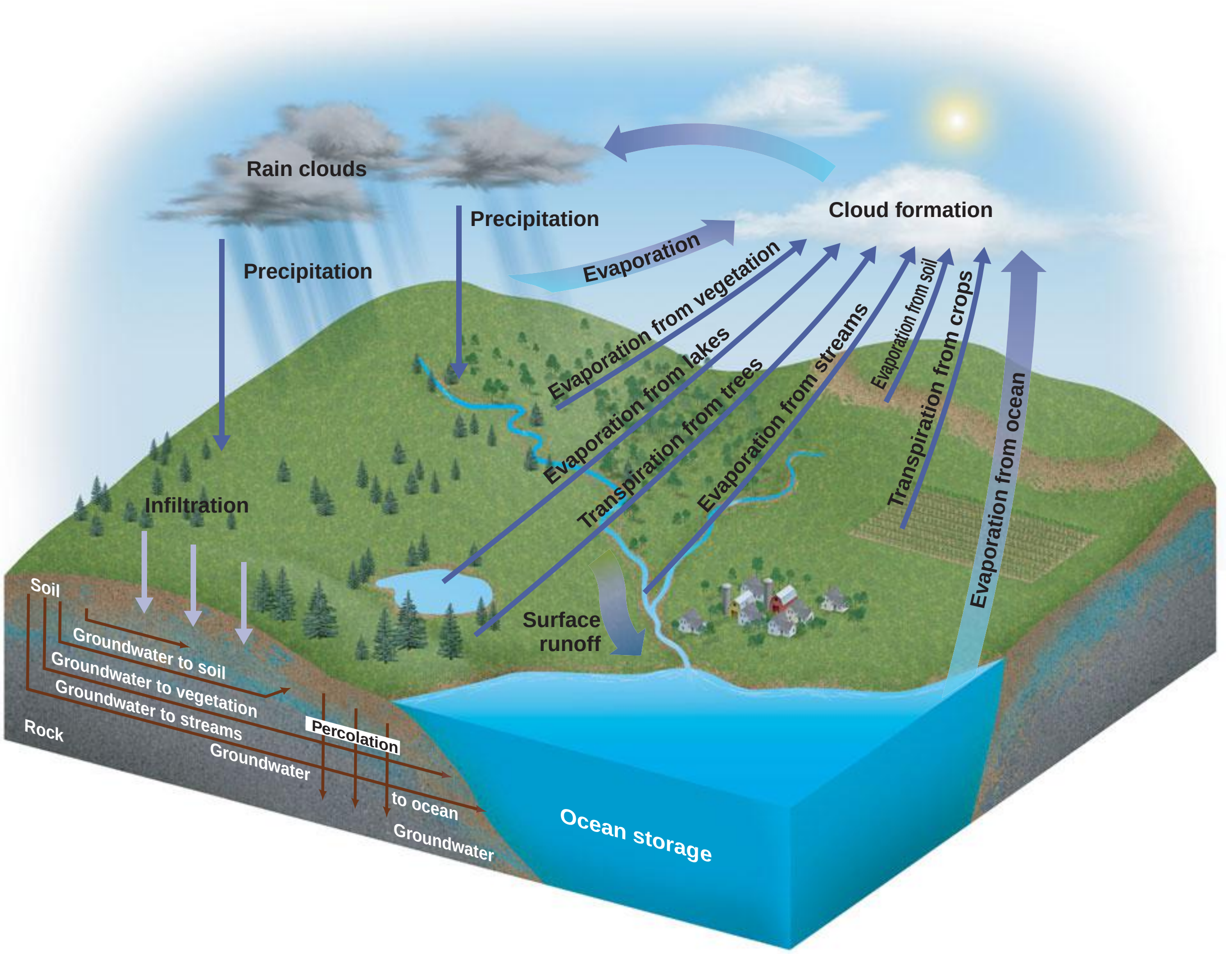


FIGURE 18.2 The hydrologic cycle, showing important processes and transfer of water. (*Source:* Modified from Council on Environment Quality and Department of State, *The Global 2000 Report to the President*, vol. 2 [Washington, DC].)

Water can be found in either liquid, solid, or gaseous form at a number of locations at or near Earth's surface. Depending on the specific location, the water's residence time may vary from a few days to many thousands of years (see Table 18.1). However, as mentioned, more than 99% of Earth's water in its natural state is unavailable or unsuitable for beneficial human use. Thus, the amount of water for which all the people, plants, and animals on Earth compete is much less than 1% of the total.

As the world's population and industrial production of goods increase, the use of water will also accelerate. The global per capita use of water in 1975 was about 700 m^3/year, or 2,000 gallons/day (185,000 gal/yr), and the total human use of water was about 3,850 km^3/year (about 10^{15} gal/yr). Today, world use of water is about 6,000 km^3/yr (about 1.58×10^{15} gal/yr), which is a significant fraction of the naturally available freshwater.

Compared with other resources, water is used in very large quantities. In recent years, the total mass (or weight) of water used on Earth per year has been approximately 1,000 times the world's total production of minerals, including petroleum, coal, metal ores, and nonmetals. Where it is abundant and readily available, water is generally a very inexpensive resource. In places where it is not abundant, such as the southwestern United States, the cost of water has been kept artificially low by government subsidies and programs.

Because the quantity and quality of water available at any particular time are highly variable, water shortages have occurred, and they will probably occur with increasing frequency, sometimes causing serious economic disruption and human suffering.[4] In the Middle East and northern Africa, scarce water has led to harsh exchanges and threats between countries and could even lead to war. The U.S. Water Resources Council estimates that water use in the United States by the year 2020 may exceed surface-water resources by 13%.[4] Therefore, an important question is, How can we best manage our water resources, use, and treatment to maintain adequate supplies?

Groundwater and Streams

Before moving on to issues of water supply and management, we introduce groundwater and surface water and the terms used in discussing them. You will need to be familiar with this terminology to understand many environmental issues, problems, and solutions.

The term **groundwater** usually refers to the water below the water table, where saturated conditions exist. The upper surface of the groundwater is called the *water table*.

Rain that falls on the land evaporates, runs off the surface, or moves below the surface and is transported underground. Locations where surface waters move into (infiltrate) the ground are known as *recharge zones*. Places where groundwater flows or seeps out at the surface, such as springs, are known as *discharge zones* or *discharge points*.

Water that moves into the ground from the surface first seeps through pore spaces (empty spaces between soil particles or rock fractures) in the soil and rock known as the *vadose zone*. This area is seldom saturated (not all pore spaces are filled with water). The water then enters the groundwater system, which is saturated (all of its pore spaces are filled with water).

An *aquifer* is an underground zone or body of earth material from which groundwater can be obtained (from a well) at a useful rate. Loose gravel and sand with lots of pore space between grains and rocks or many open fractures generally make good aquifers. Groundwater in aquifers usually moves slowly at rates of centimeters or meters per day. When water is pumped from an aquifer, the water table is depressed around the well, forming a cone of *depression*. Figure 18.3 shows the major features of a groundwater and surface-water system.

Streams may be classified as effluent or influent. In an **effluent stream**, the flow is maintained during the dry season by groundwater seepage into the stream channel from the subsurface. A stream that flows all year is called a *perennial stream*. Most perennial streams flow all year because they constantly receive groundwater to sustain flow. An **influent stream** is entirely above the water table and flows only in direct response to precipitation. Water from an influent stream seeps down into the subsurface. An influent stream is called an *ephemeral* stream because it doesn't flow all year.

A given stream may have reaches (unspecified lengths of stream) that are perennial and other reaches that are ephemeral. It may also have reaches, known as intermittent, that have a combination of influent and effluent flow varying with the time of year. For example, streams flowing from the mountains to the sea in Southern California often have reaches in the mountains that are perennial, supporting populations of trout or endangered southern steelhead, and lower intermittent reaches that transition to ephemeral reaches. At the coast, these streams may receive fresh or salty groundwater and tidal flow from the ocean to become a perennial lagoon.

Interactions between Surface Water and Groundwater

Surface water and groundwater interact in many ways and should be considered part of the same resource. Nearly all natural surface-water environments, such as rivers and lakes, as well as man-made water environments, such as reservoirs, have strong linkages with groundwater. For example, pumping groundwater from wells may reduce stream flow, lower lake levels, or change the quality of surface water. Reducing effluent stream flow by lowering

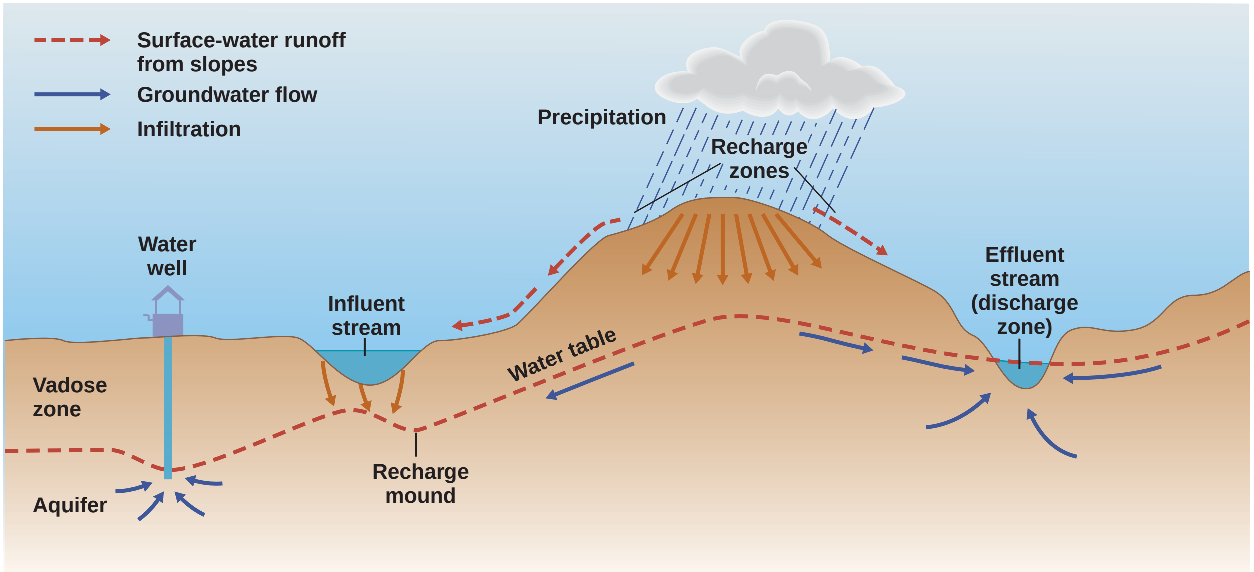


FIGURE 18.3 Groundwater and surface-water flow system.

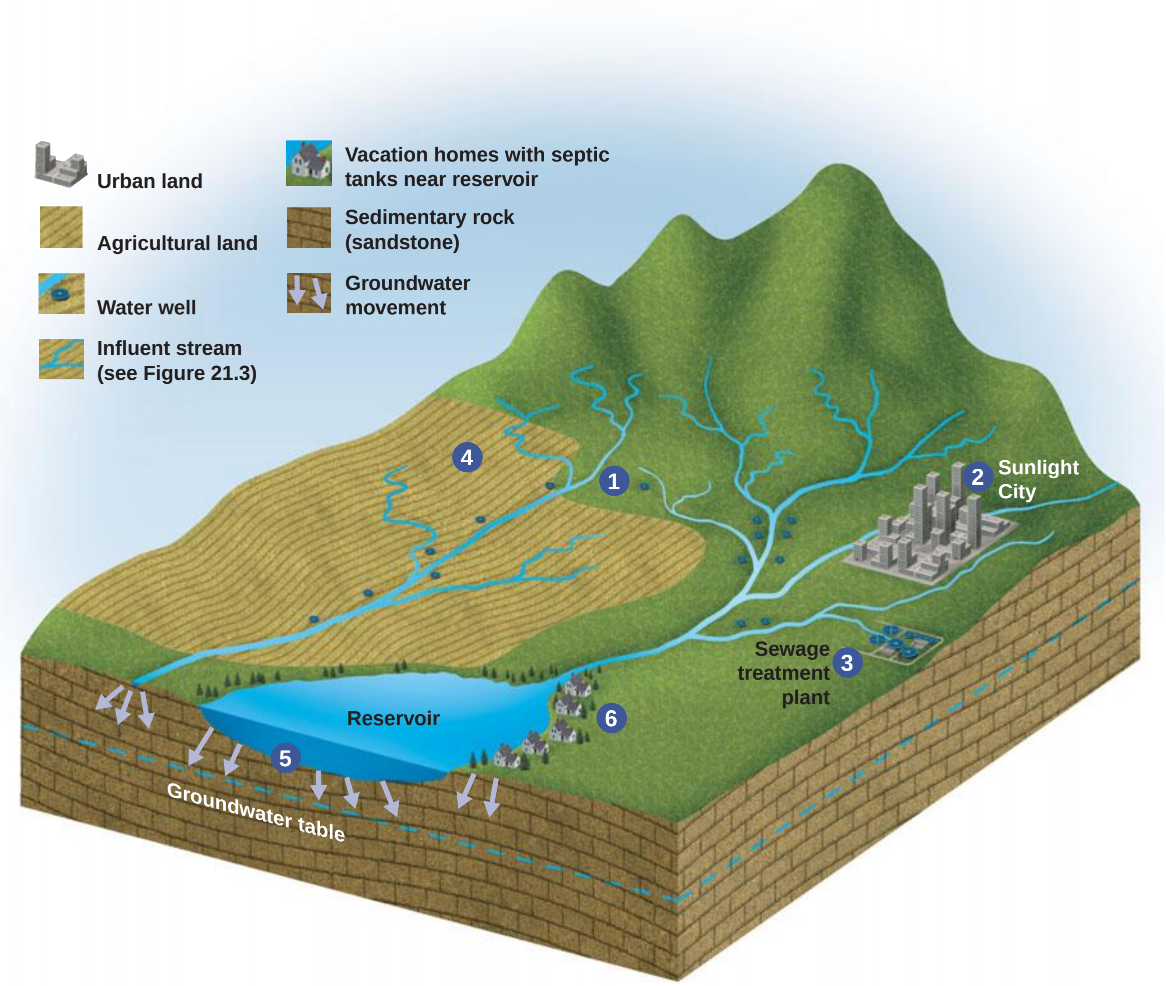


FIGURE 18.4 Idealized diagram illustrating some interactions between surface water and groundwater for a city in a semiarid environment with adjacent agricultural land and reservoir. (1) Water pumped from wells lowers the groundwater level. (2) Urbanization increases runoff to streams. (3) Sewage treatment discharges nutrient-rich waters into stream, groundwater, and reservoir. (4) Agriculture uses irrigation waters from wells, and runoff to stream from fields contains nutrients from fertilizers. (5) Water from the reservoir is seeping down to the groundwater. (6) Water from septic systems for homes is seeping down through the soil to the groundwater.

the groundwater level may change a perennial stream into an intermittent influent stream. Similarly, withdrawing surface water by diverting it from streams and rivers can deplete groundwater or change its quality. Diverting surface waters that recharge groundwaters may increase concentrations of dissolved chemicals in the groundwater because dissolved chemicals in the groundwater will no longer be diluted by infiltrated surface water. Finally, pollution of groundwater may result in polluted surface water, and vice versa.[5]

Selected interactions between surface water and groundwater in a semiarid urban and agricultural environment are shown in Figure 18.4. Urban and agricultural runoff increases the volume of water in the reservoir. Pumping groundwater for agricultural and urban uses lowers the groundwater level. The quality of surface water and groundwater is reduced by urban and agricultural runoff, which adds nutrients from fertilizers, oil from roads, and nutrients from treated wastewaters to streams and groundwater.

18.2 Water Supply: A U.S. Example

The water supply at any particular point on the land surface depends on several factors in the hydrologic cycle, including the rates of precipitation, evaporation, transpiration (water in vapor form that directly enters the atmosphere from plants through pores in leaves and stems), stream flow, and subsurface flow. A concept useful in understanding water supply is the **water budget**, a model that balances the inputs, outputs, and storage of water in a system. Simple annual water budgets (precipitation – evaporation = runoff) for North America and other continents are shown in Table 18.2. The total average annual water yield (runoff) from Earth's rivers is approximately 47,000 km^3 (1.2 $\times$ 10^{16} gal), but its distribution is far from uniform (see Table 18.2). Some

Table 18.2 ANNUAL WATER BUDGETS FOR THE CONTINENTS[a]

CONTINENTAL	PRECIPITATION mm/yr	PRECIPITATION km^3	EVAPORATION mm/yr	EVAPORATION km^3	RUNOFF km^3/yr
North America	756	18,300	418	10,000	8,180
South America	1,600	28,400	910	16,200	12,200
Europe	790	8,290	507	5,320	2,970
Asia	740	32,200	416	18,100	14,100
Africa	740	22,300	587	17,700	4,600
Australia and Oceania	791	7,080	511	4,570	2,510
Antarctica	165	2,310	0	0	2,310
Earth (entire land area)	800	119,000	485	72,000	47,000[b]

[a] Precipitation – evaporation = runoff.

[b] Surface runoff is 44,800; groundwater runoff is 2,200.

Source: I. A. Shiklomanov, "World Fresh Water Resources," in P. H. Gleick, ed., *Water in Crisis* (New York: Oxford University Press, 1993), pp. 3–12.

runoff occurs in relatively uninhabited regions, such as Antarctica, which produces about 5% of Earth's total runoff. South America, which includes the relatively uninhabited Amazon basin, provides about 25% of Earth's total runoff. Total runoff in North America is about two-thirds that of South America. Unfortunately, much of the North American runoff occurs in sparsely settled or uninhabited regions, particularly in the northern parts of Canada and Alaska.

The daily water budget for the contiguous United States is shown in Figure 18.5. The amount of water vapor passing over the United States every day is approximately 152,000 million m^3 (40 trillion gal), and approximately 10% of this falls as precipitation—rain, snow, hail, or sleet. Approximately 66% of the precipitation evaporates quickly or is transpired by vegetation. The remaining 34% enters the surface water or groundwater storage systems, flows to the oceans or across the nation's boundaries, is

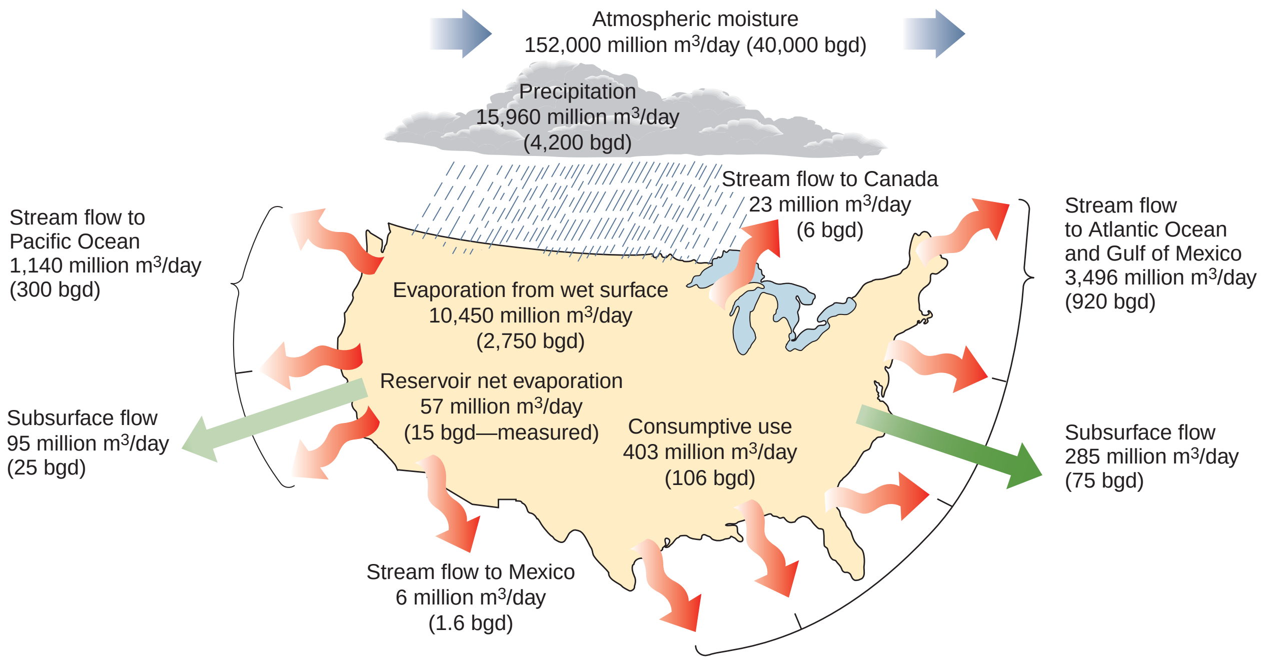


FIGURE 18.5 Water budget for the United States (bgd = billion gallons per day). (*Source:* Water Resources Council, *The Nation's Water Resources 1975–2000* [Washington, DC: Water Resources Council, 1978].)

used by people, or evaporates from reservoirs. Owing to natural variations in precipitation that cause either floods or droughts, only a portion of this water can be developed for intensive uses (only about 50% is considered available 95% of the time).[4]

Precipitation and Runoff Patterns

To put all this information in perspective, consider just the water in the Missouri River. In an average year, enough water flows down the Missouri River to cover 25 million acres a foot deep—8.4 trillion gallons. The average water use in the United States is about 100 gallons a day per person—very high compared to the rest of the world. People in Europe use about half that amount, and in some regions, such as sub-Saharan Africa, people make do with 5 gallons a day. At 100 gallons use a day, the Missouri's flow is enough to provide water for domestic and public use in the United States for about 230 million people. With a little water conservation and reduction in per capita use, the Missouri could provide enough water for all the people in the United States, so great is its flow. Not that people would actually use the Missouri's water that way, but you can stand on the shore of the Missouri, where the river flows under a major highway bridge, and get an idea of just how much water it would take to supply all those people.

In developing water budgets for water resources management, it is useful to consider annual precipitation and runoff patterns. Potential problems with water supply can be predicted in areas where average precipitation and runoff are relatively low, such as the arid and semiarid parts of the southwestern and Great Plains regions of the United States. Surface-water supply can never be as high as the average annual runoff because not all runoff can be successfully stored, due to evaporative losses from river channels, ponds, lakes, and reservoirs. Water shortages are common in areas that have naturally low precipitation and runoff, coupled with strong evaporation. In such areas, rigorous conservation practices are necessary to help ensure an adequate supply of water.[4]

Droughts

Because of large annual and regional variations in stream flow, even areas with high precipitation and runoff may periodically suffer from droughts. For example, recent dry years in the western United States produced serious water shortages. Fortunately for the more humid eastern United States, stream flow there tends to vary less than in other regions, and drought is less likely.[5] Nevertheless, summertime droughts in the southeastern United States in the early 21st century are causing hardships and billions of dollars of damage from Georgia to Florida (see opening case study).

Groundwater Use and Problems

Nearly half the people in the United States use groundwater as a primary source of drinking water. It accounts for approximately 20% of all water used. Fortunately, the total amount of groundwater available in the United States is enormous. In the contiguous United States, the amount of shallow groundwater within 0.8 km (about 0.5 mi) of the surface is estimated at 125,000 to 224,000 km^3 (3.3×10^{16} to 5.9×10^{16} gal). To put this in perspective, the lower estimate of the amount of shallow groundwater is about equal to the total discharge of the Mississippi River during the last 200 years. However, the high cost of pumping limits the total amount of groundwater that can be economically recovered.[4]

In many parts of the country, groundwater withdrawal from wells exceeds natural inflow. In such cases of **overdraft**, we can think of water as a nonrenewable resource that is being *mined*. This can lead to a variety of problems, including damage to river ecosystems and land subsidence. Groundwater overdraft is a serious problem in the Texas–Oklahoma–High Plains area (which includes much of Kansas and Nebraska and parts of other states), as well as in California, Arizona, Nevada, New Mexico, and isolated areas of Louisiana, Mississippi, Arkansas, and the South Atlantic region.

In the Texas–Oklahoma–High Plains area, the overdraft amount per year is approximately equal to the natural flow of the Colorado River for the same period.[4] The Ogallala Aquifer (also called the High Plains Aquifer), which is composed of water-bearing sands and gravels that underlie an area of about 400,000 km^2 from South Dakota into Texas, is the main groundwater resource in this area. Although the aquifer holds a tremendous amount of groundwater, it is being used in some areas at a rate up to 20 times higher than the rate at which it is being naturally replaced. As a result, the water table in many parts of the aquifer has declined in recent years (Figure 18.6), causing yields from wells to decrease and energy costs for pumping the water to rise. The most severe water-depletion problems in the Ogallala Aquifer today are in locations where irrigation was first used in the 1940s. There is concern that eventually a significant portion of land now being irrigated will be returned to dryland farming as the resource is used up.

Some towns and cities in the High Plains are also starting to have water-supply problems. Along the Platte River in northern Kansas there is still plenty of water, and groundwater levels are high (Figure 18.6). Farther south, in southwest Kansas and the panhandle in western Texas, where water levels have declined the most, supplies may last only another decade or so. In Ulysses, Kansas (population 6,000), and Lubbock, Texas (population 200,000), the situation is already getting serious. South of Ulysses, Lower Cimarron Springs, which was a famous water hole along a dry part of

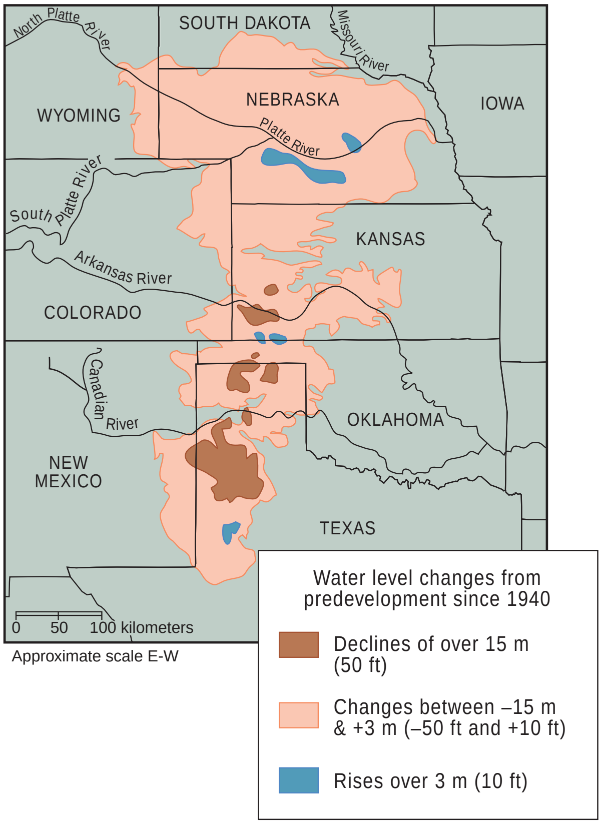


FIGURE 18.6 Groundwater-level changes as a result of pumping in the Texas–Oklahoma–High Plains region. (*Source:* U.S. Geological Survey.)

the Santa Fe Trail, dried up decades ago due to pumping groundwater. It was a symptom of what was coming. Both Ulysses and Lubbock are now facing water shortages and will need to spend millions of dollars to find alternative sources.

Desalination as a Water Source

Seawater is about 3.5% salt; that means each cubic meter of seawater contains about 40 kg (88 lb) of salt. **Desalination**, a technology for removing salt from water, is being used at several hundred plants around the world to produce water with reduced salt. To be used as a freshwater resource, the salt content must be reduced to about 0.05%. Large desalination plants produce 20,000–30,000m^3 (about 5–8 million gal) of water per day. Today, about 15,000 desalination plants in over 100 countries are in operation, and improving technology is significantly lowering the cost of desalination.

Even so, desalinated water costs several times as much as traditional water supplies in the United States. Desalinated water has a *place value*, which means that the price rises quickly with the transport distance and the cost of moving water from the plant. Because the various processes that remove the salt require large amounts of energy, the cost of the water is also tied to ever-increasing energy costs. For these reasons, desalination will remain an expensive process, used only when alternative water sources are not available.

Desalination also has environmental impacts. Discharge of very salty water from a desalination plant into another body of water, such as a bay, may locally increase salinity and kill some plants and animals. The discharge from desalination plants may also cause wide fluctuations in the salt content of local environments, which may damage ecosystems.

18.3 Water Use

In discussing water use, it is important to distinguish between off-stream and in-stream uses. **Off-stream use** refers to water removed from its source (such as a river or reservoir) for use. Much of this water is returned to the source after use; for example, the water used to cool industrial processes may go to cooling ponds and then be discharged to a river, lake, or reservoir. **Consumptive use** is an off-stream use in which water is consumed by plants and animals or used in industrial processes. The water enters human tissue or products or evaporates during use and is not returned to its source.[4]

In-stream use includes the use of rivers for navigation, hydroelectric power generation, fish and wildlife habitats, and recreation. These multiple uses usually create controversy because each requires different conditions. For example, fish and wildlife require certain water levels and flow rates for maximum biological productivity. These levels and rates will differ from those needed for hydroelectric power generation, which requires large fluctuations in discharges to match power needs. Similarly, in-stream uses of water for fish and wildlife will likely conflict with requirements for shipping and boating. Figure 18.7 demonstrates some of these conflicting demands on a graph that shows optimal discharge for various uses

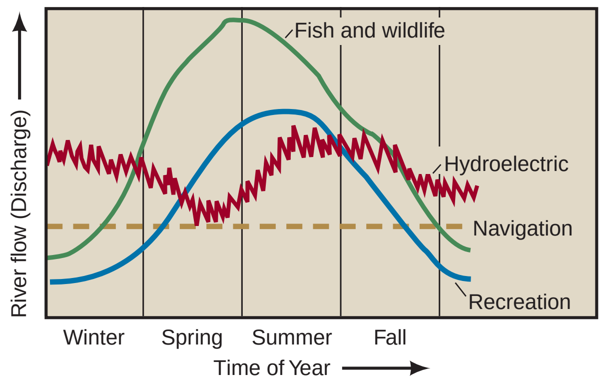


FIGURE 18.7 In-stream water uses and optimal discharge (volume of water flowing per second) for each use. Discharge is the amount of water passing by a particular location and is measured in cubic meters per second. Obviously, all these needs cannot be met simultaneously.

throughout the year. In-stream water use for navigation is optimal at a constant fairly high discharge. Some fish, however, prefer higher flows in the spring for spawning.

One problem for off-stream use is how much water can be removed from a stream or river without damaging the stream's ecosystem. This is an issue in the Pacific Northwest, where fish, such as steelhead trout and salmon, are on the decline partly because diversions for agricultural, urban, and other uses have reduced stream flow to the point where fish habitats are damaged.

The Aral Sea in Kazakhstan and Uzbekistan provides a wake-up call regarding the environmental damage that can be caused by diverting water for agriculture. Diverting water from the two rivers that flow into the Aral Sea has transformed one of the largest bodies of inland water in the world from a vibrant ecosystem into a dying sea. The present shoreline is surrounded by thousands of square kilometers of salt flats that formed as the sea's surface area shrank about 90% in the past 50 years (Figures 18.8 and 18.9). The volume of the sea was reduced by more than 50%, and the salt content increased to more than twice that of seawater, causing fish kills, including sturgeon, an important component of the economy. Dust raised by winds from the dry salt flats is producing a regional air-pollution problem, and the climate in the region has changed as the moderating effect of the sea has been reduced. Winters have grown colder and summers warmer. Fishing centers, such as Muynak in the south and Aralsk to the north that were once on the shore of the sea, are now many kilometers inland (Figure 18.10). Loss of fishing, along with a decline in tourism, has damaged the local economy.

A restoration of the small northern port of the Aral Sea is ongoing. A low, long dam was constructed across the lakebed just south of where the Syr Darya River enters the lake (see Figure 18.8). Conservation of water and the construction of the dam are producing dramatic improvement to the northern port of the lake, and some fishing is returning there. The future of the lake has improved, but great concern remains.[6]

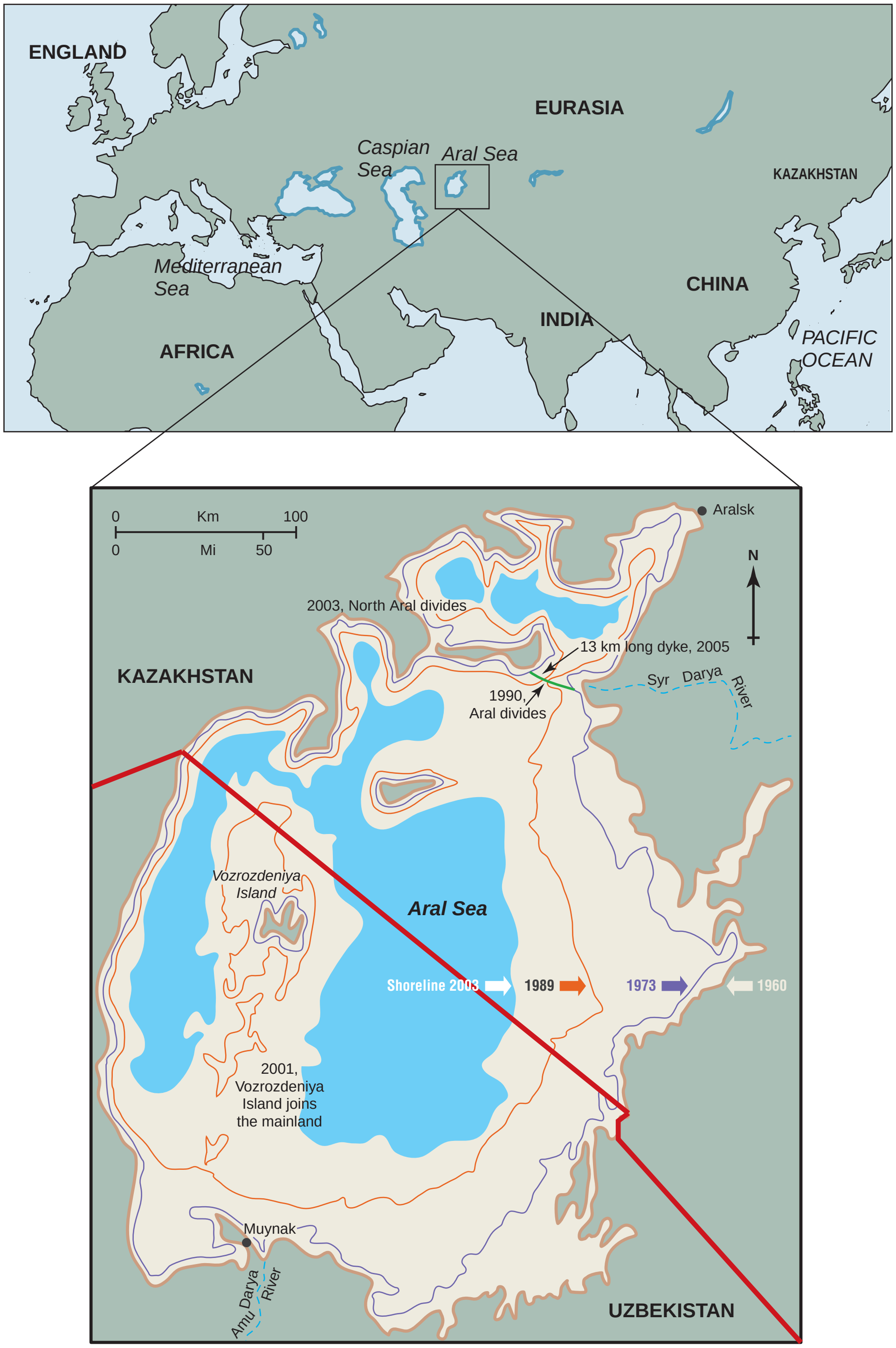


FIGURE 18.8 The Aral Sea from 1960 to 2003. A strong dike (dam), 13 km long, was constructed in 2005, and the northern lake increased in area by 18% and in depth by 2 km by 2007. (Modified after *unimaps.com 2004.*)

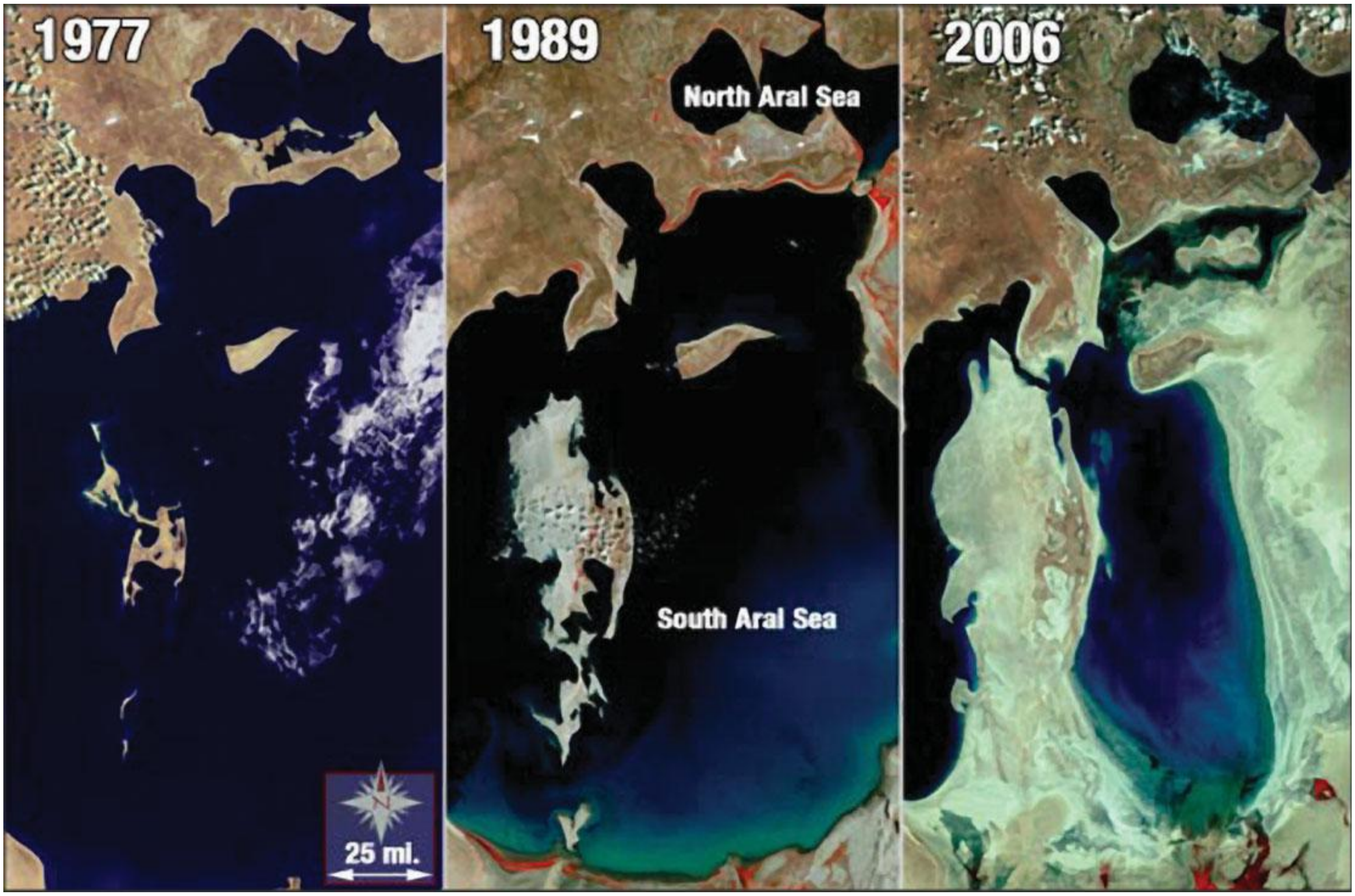


FIGURE 18.9 Three images of the Aral Sea from 1977 to 2006. By 2006, the sea had been reduced to about 10% of its original size. Wetlands around the sea were reduced by 85%; fish species declined 80%, and birds 50%.

FIGURE 18.10 Ships grounded in the dry seabed as the fishing industry collapsed.

Transport of Water

In many parts of the world, demands are being made on rivers to supply water to agricultural and urban areas. This is not a new trend—ancient civilizations, including the Romans and Native Americans, constructed canals and aqueducts to transport water from distant rivers to where it was needed. In our modern civilization, as in the past, water is often moved long distances from areas with abundant rainfall or snow to areas of high use (usually agricultural areas). For instance, in California, two-thirds of the state's runoff occurs north of San Francisco, where there is a surplus of water. However, two-thirds of the water use in California occurs south of San Francisco, where there is a deficit. In recent years, canals of the California Water Project have moved great quantities of water from the northern to the southern part of the state, mostly for agricultural uses, but increasingly for urban uses as well.

On the opposite coast, New York City has imported water from nearby areas for more than 100 years. Water use and supply in New York City show a repeating pattern. Originally, local groundwater, streams, and the

Hudson River itself were used. However, as the population increased and the land was paved over, surface waters were diverted to the sea rather than percolating into the soil to replenish groundwater. Furthermore, what water did infiltrate the soil was polluted by urban runoff. Water needs in New York exceeded local supply, and in 1842 the first large dam was built.

As the city rapidly expanded from Manhattan to Long Island, water needs increased. The shallow aquifers of Long Island were at first a source of drinking water, but this water was used faster than the infiltration of rainfall could replenish it. At the same time, the groundwater became contaminated with urban and agricultural pollutants and from saltwater seeping in underground from the ocean. (The pollution of Long Island groundwater is explored in more depth in the next chapter.) Further expansion of the population created the same pattern: initial use of groundwater; pollution, salinization, and overuse of the resource. A larger dam was built in 1900 about 30 miles north of New York City, at Croton-on-Hudson, and later on new, larger dams farther and farther upstate, in forested areas.

From a broader perspective, the cost of obtaining water for large urban centers from far-off sources, along with competition for available water from other sources and users, will eventually place an upper limit on the water supply of New York City. As shortages develop, stronger conservation measures are implemented, and the cost of water increases. As with other resources, as the water supply shrinks and demand for water rises, so does its price. If the price goes high enough, costlier sources may be developed—for example, pumping from deeper wells or desalinating.

Some Trends in Water Use

Trends in freshwater withdrawals and human population for the United States from 1950 to 2005 (the most recent data available) are shown in Figure 18.11. You can see that during that period, withdrawal of surface water far exceeded withdrawal of groundwater. In addition, withdrawals of both surface water for human uses and groundwater increased between 1950 and 1980, reaching a total maximum of approximately 375,000 million gal/day. However, after 1980, water withdrawals decreased and leveled off. It is encouraging that water withdrawals decreased after 1980 while the U.S. population continued to increase. This suggests that we have improved our water management and water conservation.[7]

Trends in freshwater withdrawals by water-use categories for the United States from 1950 to 2005 (most recent data available) are shown in Figure 18.12. Examination of this graph suggests the following:

1. The major uses of water were for irrigation and the thermoelectric industry. Excluding thermoelectric use, agriculture accounted for 65% of total withdrawals in 2005.
2. The use of water for irrigation by agriculture increased about 68% from 1950 to 1980. It decreased and leveled off from about 1985 to 2005, due in part to better irrigation efficiency, crop type, and higher energy costs.
3. Water use by the thermoelectric industry decreased slightly, beginning in 1980, and has stabilized since 1985 due to recirculating water for cooling in closed-loop systems. During the same period, electrical generation from power plants increased by more than 10 times.

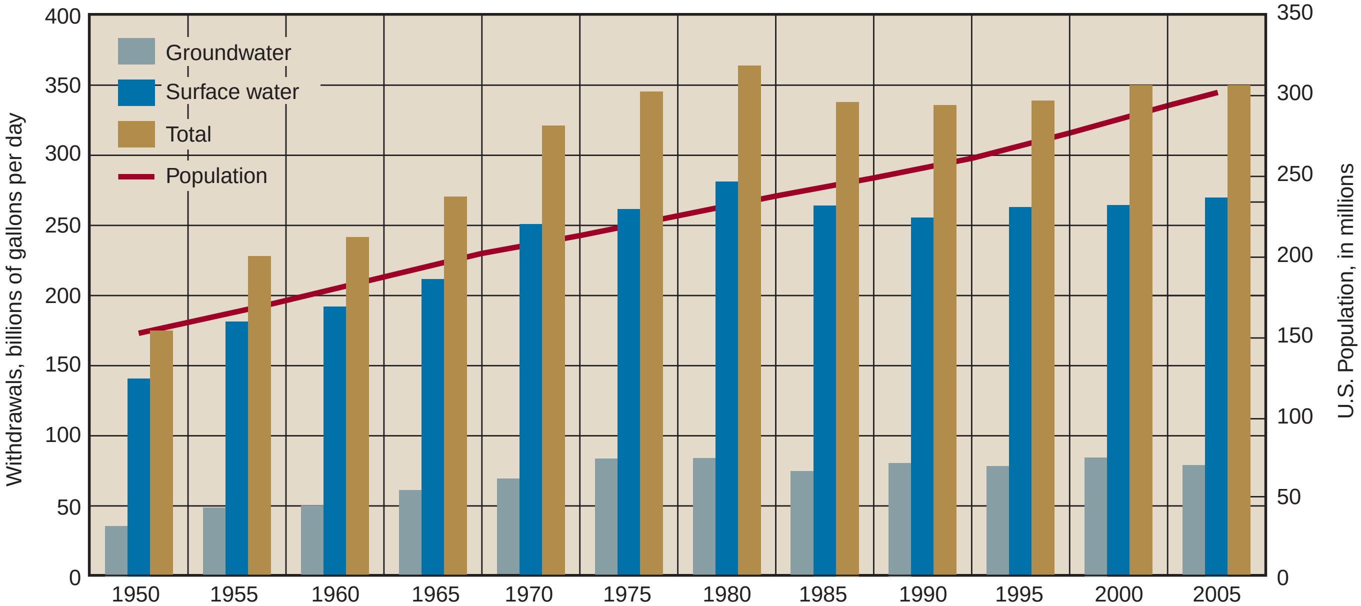


FIGURE 18.11 Trends in U.S. fresh groundwater and surface-water withdrawals and human population, 1950–2005. (*Source*: Kenny, J.F. et al., 2005. *Estimated Use of Water in the United States in 2005*. U.S. Geological Survey Circular 1344, 2010).

4. Use of water for public and rural supplies continued to increase through the period 1950– 2005, presumably due to the increase in human population.[7, 8]

18.4 Water Conservation

Water conservation is the careful use and protection of water resources. It involves both the quantity of water used and its quality. Conservation is an important component of sustainable water use. Because the field of water conservation is changing rapidly, it is expected that a number of innovations will reduce the total withdrawals of water for various purposes, even though consumption will continue to increase.[4]

Agricultural Use

Improved irrigation (Figure 18.13) could reduce agricultural withdrawals by 20 to 30%. Because agriculture is the biggest water user, this would be a huge savings. Suggestions for agricultural conservation include the following:

- Price agricultural water to encourage conservation (subsidizing water encourages overuse).
- Use lined or covered canals that reduce seepage and evaporation.
- Use computer monitoring and schedule release of water for maximum efficiency.
- Integrate the use of surface water and groundwater to more effectively use the total resource. That is, irrigate with surplus surface water when it is abundant, and also use surplus surface water to recharge groundwater aquifers, using specially designed infiltration ponds or injection wells. When surface water is in short supply, use more groundwater.
- Irrigate when evaporation is minimal, such as at night or in the early morning.
- Use improved irrigation systems, such as sprinklers or drip irrigation, that apply water to crops more effectively.
- Improve land preparation for water application—that is, improve the soil so that more water sinks in and less runs off. Where applicable, use mulch to help retain water around plants.
- Encourage the development of crops that require less water or are more salt-tolerant, so that less periodic flooding of irrigated land is necessary to remove accumulated salts in the soil.

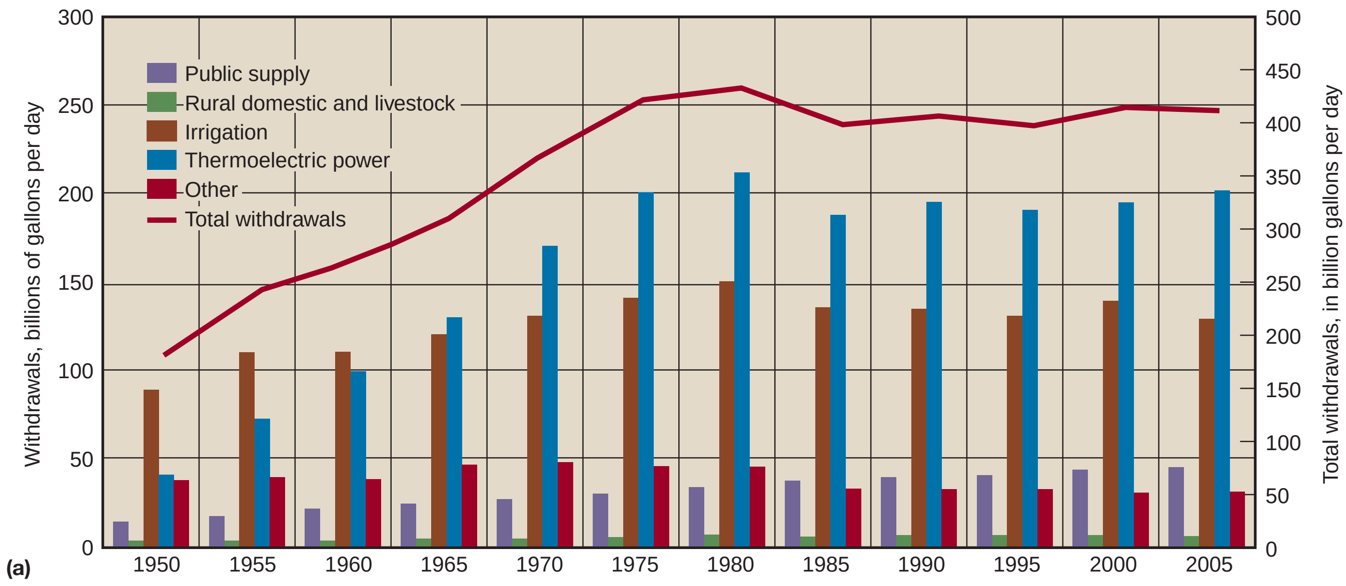


FIGURE 18.12 **(a)** Trends in total U.S. water withdrawals by water-use category (1950–2005). (*Source*: Kenny J. F. et al., 2010, *Estimated Use of Water in the United States in 2005.* U.S. Geological Survey Circular 1344); **(b)** U.S. water use in 2005 (by percent).


Public supply, 11 percent
Richard L. Marella, USGS
Public supply water intake, Bay County, Florida
Irrigation, 31 percent
Jeff Vanuga, USDA NRCS
Gated-pipe flood irrigation, Fremont County, Wyoming
Aquaculture, less than 2 percent
Courtesy of Clear Springs Foods, Inc.
World's largest trout farm, Buhl, Idaho
Mining, 1 percent
Nancy L. Barber, USGS
Spodumene pegmatite mine, Kings Mountain, North Carolina
Domestic, 1 percent
Alan M. Cressler, USGS
Domestic well, Early County, Georgia
Livestock, less than 1 percent
Jeff Vanuga, USDA NRCS
Livestock watering, Rio Arriba County, New Mexico
Industrial, 4 percent
Alan M. Cressler, USGS
Paper mill, Savannah, Georgia
Thermoelectric power, 49 percent
Alan M. Cressler, USGS
Cooling towers, Burke County, Georgia

(b)

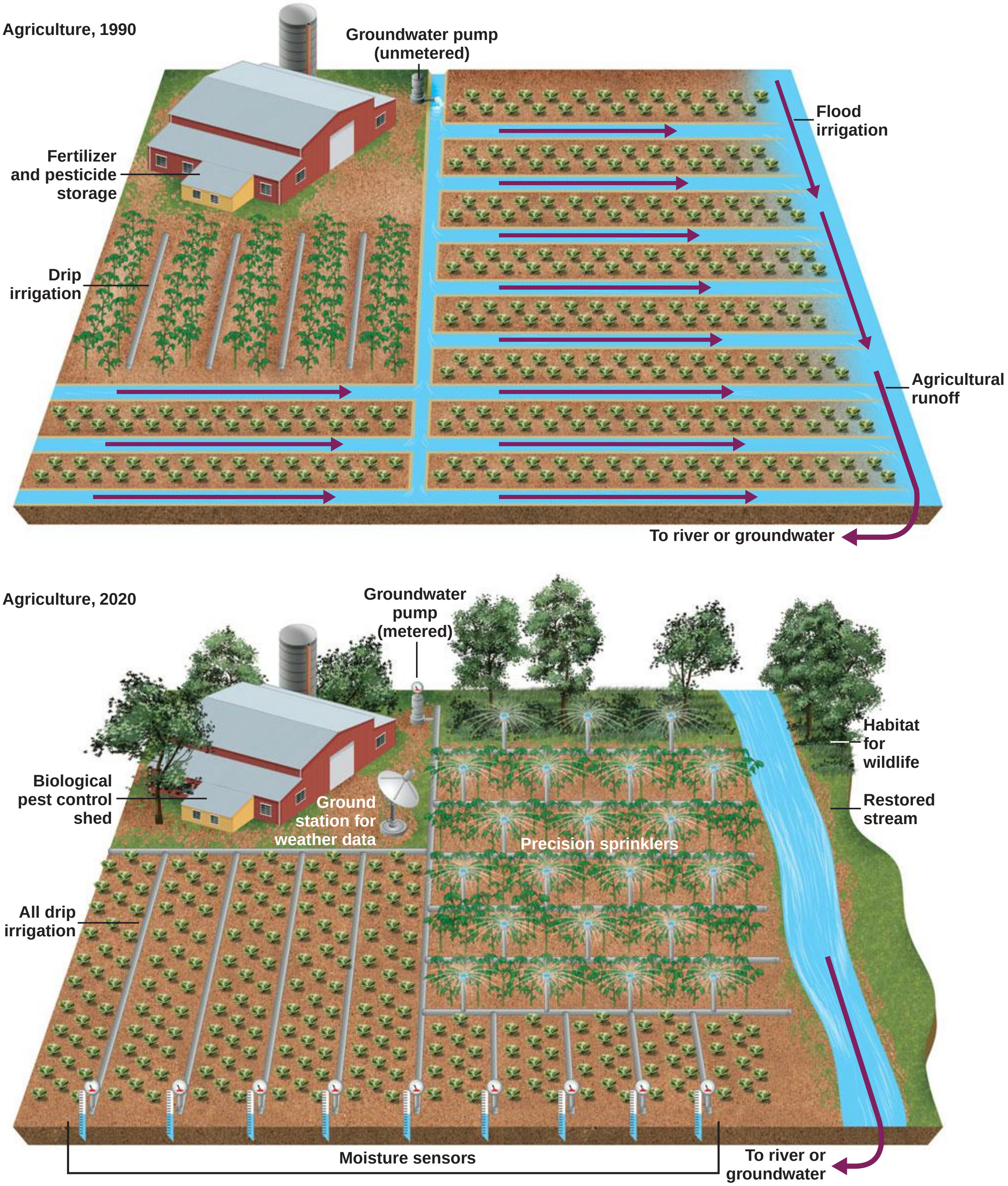


FIGURE 18.13 Comparison of agricultural practices in 1990 with what they might be by 2020. The improvements call for a variety of agricultural procedures, including biological pest control, more efficient irrigation, and restoration of water resources and wildlife habitat. (*Source:* P.H. Gleick, P. Loh, S.V. Gomez, and J. Morrison, *California Water 2020, a Sustainable Vision* [Oakland, CA: Pacific Institute for Studies in Development, Environment, and Security, 1995].)

Public Supply and Domestic Use

Domestic use of water accounts for only about 12% of total national water withdrawals. However, because public supply water use is concentrated in urban areas, it may pose major local problems in areas where water is periodically or often in short supply. The population of the United States continues to grow, and many urban areas in the United States are experiencing or will experience the impact of population growth on water supply. For example:

- Southern California, in particular San Diego and Los Angeles, is growing rapidly, and its water needs are quickly exceeding local supplies. As a result, the city of San Diego has negotiated with farmers to the east, in the Imperial Valley, to purchase water for urban areas. The city is also building desalination plants and considering raising the height of dams so more water can be stored for urban uses. Southern California has long imported water from the Sierra Nevada to the north. If climate change brings less snow and more rain, that supply may become more variable because snow melts slowly and thus serves as a water source for a longer time than rain, which quickly runs off. In the expectation of more rain than snow, plans for what is called the Inland Feeder Project include a series of large-diameter tunnels to quickly deliver large volumes of water from northern California to Southern California during periods of rapid runoff. They will be used to fill local reservoirs and groundwater basins, providing water during dry periods and emergencies.
- In Denver, city officials, fearing future water shortages, are proposing strict conservation measures that include limits on water use for landscaping and the amount of grass that can be planted around new homes.
- Chicago, one of the fastest-growing urban areas in the United States and located on the shore of Lake Michigan, one of the largest sources of freshwater in the world, reports groundwater-depletion problems. Water shortages in outlying urban areas may become apparent by 2020.
- Tampa, Florida, fearing shortages of freshwater because of its continuing growth, began operating a desalination plant in 2003 that produces approximately 25 million gallons of water daily.
- Atlanta, Georgia, another fast-growing urban area in the United States, expects increased demand on its water supplies as a result and is exploring ways to meet that demand.
- New York City, which imports water from the upstate Catskill Mountains, periodically has water shortages during droughts. The city placed water restrictions on its more than 9 million citizens in 2002.

What is clear from these examples is that while there is no shortage of water in the United States or the world, there are local and regional shortages, particularly in large, growing urban areas in the semiarid western and southwestern United States.[9]

Most water in homes is used in the bathroom and for washing laundry and dishes. Domestic water use can be substantially reduced at a relatively small cost by the following measures:

- In semiarid regions, replace lawns with decorative gravel and native plants.
- Use more efficient bathroom fixtures, such as low-flow toilets that use 1.6 gallons or less per flush rather than the standard 5 gallons, and low-flow showerheads that still deliver sufficient water.
- Flush only when really necessary.
- Turn off water when not absolutely needed for washing, brushing teeth, shaving, and so on.
- Fix all leaks quickly. Dripping pipes, faucets, toilets, or garden hoses waste water. A small drip can waste several liters per day; multiply this by millions of homes with a leak, and a large volume of water is lost.
- Purchase dishwashers and laundry machines that minimize water use.
- Take a long bath rather than a long shower.
- Don't hose sidewalks and driveways; sweep them.
- Consider using gray water (from showers, bathtubs, sinks, and washing machines) to water vegetation. The gray water from laundry machines is easiest to use, as it can be easily diverted before entering a drain.
- Water lawns and plants in the early morning, late afternoon, or at night to reduce evaporation.
- Use drip irrigation and place water-holding mulch around garden plants.
- Plant drought-resistant vegetation that requires less water.
- Learn how to read the water meter to monitor for unobserved leaks and record your conservation successes.
- Use reclaimed water (see opening case study).

In addition, local water districts should encourage water pricing policies that make water use more expensive for those who exceed some baseline amount determined by the number of people in a home and the size of the property.

Industry and Manufacturing Use

Water conservation by industry can be improved. For instance, water use for steam generation of electricity could be reduced 25 to 30% by using cooling towers that require less or no water (as has often been done in the United States). Manufacturing and industry could curb water use by increasing in-plant treatment and recycling water and by developing new equipment and processes that require less water.[4]

18.5 Sustainability and Water Management

Because water is essential to sustain life and maintain ecological systems necessary for human survival, it plays important roles in ecosystem support, economic development, cultural values, and community well-being. Managing water use for sustainability is thus important in many ways.

Sustainable Water Use

From a supply and management perspective, **sustainable water use** can be defined as use of water resources in a way that allows society to develop and flourish in an indefinite future without degrading the various components of the hydrologic cycle or the ecological systems that depend on it. Some general criteria for water-use sustainability are as follows.[10]

- Develop enough water resources to maintain human health and well-being.
- Provide sufficient water resources to guarantee the health and maintenance of ecosystems.
- Ensure basic standards of water quality for the various users of water resources.
- Ensure that people do not damage or reduce the long-term renewability of water resources.
- Promote the use of water-efficient technology and practice.
- Gradually eliminate water-pricing policies that subsidize inefficient use of water.

Groundwater Sustainability

The concept of sustainability, by definition, implies a long-term perspective. With groundwater resources, effective management for sustainability requires an even longer time frame than for other renewable resources. Surface waters, for example, may be replaced over a relatively short time, whereas replacement of groundwater may take place slowly over many years. The effects of pumping groundwater faster than it is being replenished—drying up of springs, weaker stream flow—may not be noticed until years after pumping begins. The long-term approach to sustainability with respect to groundwater is basically not to take out more than is going in; to keep monitoring input and adjusting output accordingly.[11]

Water Management

Maintaining a water supply is a complex issue that will become more difficult as demand for water increases in the coming years. The problem will be especially challenging in the southwestern United States and other semiarid and arid parts of the world where water is in short supply or soon will be. Options for minimizing problems include finding alternative water supplies and managing existing supplies better. In some areas, finding new supplies is so unlikely that people are seriously considering some literally far-fetched water sources, such as towing icebergs to coastal regions where freshwater is needed. It seems apparent that water will become much more expensive in the future; and if the price is right, many innovative programs are possible.

A number of municipalities are using the *variable-water-source approach*. The city of Santa Barbara, California, for example, has developed a variable-water-source approach that uses several interrelated measures to meet present and future demand. Details of the plan (shown in Figure 18.14) include importing state water, developing new sources, using reclaimed water, and instituting a permanent conservation program. In addition, there is a desalination plant near the ocean and a wastewater-treatment plant (see Figure 18.14) that is in long-term storage but could be brought online if needed. In essence, this seaside community has developed a master water plan.

A Master Plan for Water Management

Luna Leopold, a famous U.S. hydrologist, suggests that a new philosophy of water management is needed, one based on geologic, geographic, and climatic factors, as well as on the traditional economic, social, and political factors. He argues that the management of water resources cannot be successful as long as it is perceived only from an economic and political standpoint.

The essence of Leopold's water-management philosophy is that surface water and groundwater are both subject to natural flux with time. In wet years, there is plenty of surface water, and the near-surface groundwater is replenished. But we must have in place, and ready to

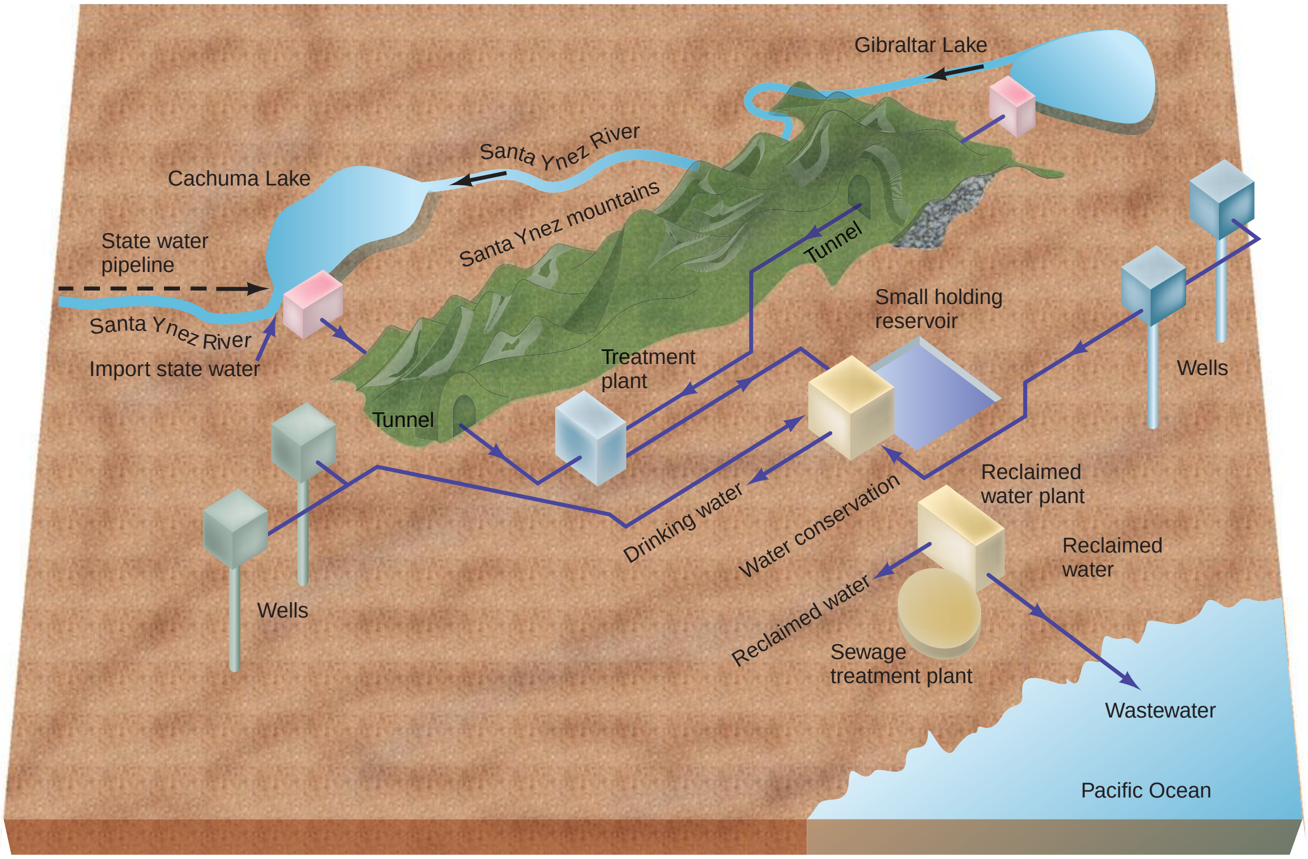


FIGURE 18.14 Schematic drawing of a variable source model (present and future) for water supply for the city of Santa Barbara, California. (*Source:* Santa Barbara City Council, data from 2009.)

use, specific plans to supply water on an emergency basis to minimize hardships in dry years, which we must expect even though we can't accurately predict them.

For example, subsurface waters in various locations in the western United States are too deep to be economically pumped from wells, or else are of marginal quality. These waters may be isolated from the present hydrologic cycle and therefore not subject to natural recharge, but might be used when the need is great if wells have been drilled and connected to existing water lines so as to be ready when the need arises.

Another possible emergency plan might involve the treatment of wastewater. Its reuse on a regular basis is expensive, but advance planning to reuse treated wastewater during emergencies is a wise decision.

Finally, we should develop plans to use surface water when available, and not be afraid to use groundwater as needed in dry years. During wet years, natural recharge as well as artificial recharge (pumping excess surface water into the ground) will replenish the groundwater. This water-management plan recognizes that excesses and deficiencies in water are natural and can be planned for.[12]

Water Management and the Environment

Many agricultural and urban areas depend on water delivered from nearby (and in some cases not-so-nearby) sources. Delivering the water requires a system for water storage and routing by way of canals and aqueducts from reservoirs. As a result, dams are built, wetlands may be modified, and rivers may be channelized to help control flooding—all of which usually generates a good deal of controversy.

The days of developing large projects in the United States without environmental and public review have passed. Resolving water-development issues now involves input from a variety of government and public groups, which may have very different needs and concerns. These range from agricultural groups that see water development as critical for their livelihood to groups primarily concerned with wildlife and wilderness preservation. It is a positive sign that the various parties with interests in water issues are encouraged—and in some cases required—to meet and communicate their desires and concerns. Below we discuss some of these concerns: wetlands, dams, channelization, and flooding.

Virtual Water

When we think of water resources, we generally think of drainage basins or groundwater reservoirs. An emerging concept is that we can also think about water resources on a global scale in terms of what is known as **virtual water**: the amount of water necessary to produce a product, such as an automobile, or a crop such as rice.[13-15] The virtual water content is measured at the place where the product is produced or the crop grown. It is called "virtual" because the water content in the product or crop is very small compared with the amount of water used to produce it.[14]

The amount of virtual water necessary for crops and animals is surprisingly large and variable. A few years ago, the question of how much water is required to produce a cup of coffee was asked. The answer is not trivial. Coffee is an important crop for many countries and the major social drink in much of the world. Many a romance has been initiated with the question "Would you like a cup of coffee?"

How much water is necessary to produce a cup of coffee requires knowing how much water is necessary to produce the coffee berries (that contain the bean) and the roasted coffee. The question is complicated by the fact that water used to raise coffee varies from location to location, as does the yield of berries. Much of the water in coffee-growing areas is free; it comes from rain. However, that doesn't mean the water has no value. People are usually surprised to learn that it takes about 140 liters (40 gallons) of water to produce one cup of coffee. The amount of water that is needed to produce a ton of a crop varies from a low of about 175 m^3 for sugarcane to 1,300 m^3 for wheat, 3,400 m^3 for white rice, and 21,000 m^3 for roasted coffee. For the meat we eat, the amount per ton is 3,900 m^3 for chicken, 4,800 m^3 for pork, and 15,500 m^3 for beef.[14]

The United States produces food that is exported around the world. The concept of virtual water shows that people consuming imported U.S. crops in Western Europe directly affect the regional water resources of the United States. Similarly, our consumption of imported foods—such as cantaloupes grown in Mexico, or blueberries from Chile—affect the regional water supply and groundwater resources of the countries that grew and exported them.

The concept of virtual water is useful in water-resource planning from the local to global scale. A country with an arid climate and restricted water resources can choose between developing those resources for agriculture or for other water uses—for example, to support wetland ecosystems or a growing human population. Since the average global amount of water necessary to produce a ton of white rice is about 3,400 m^3 (nearly 900,000 gallons), growing rice in countries with abundant water resources makes sense. For countries with a more arid environment, it might be prudent to import rice and save local and regional water resources for other purposes. Jordan, for example, imports about 7 billion m^3 of virtual water per year by importing foods that requires a lot of water to produce. As a result, Jordan withdraws only about 1 billion m^3 of water per year from its own water resources. Egypt, on the other hand, has the Nile River and imports only about one-third as much water (virtual water) as it withdraws from its domestic supply. Egypt has a goal of water independence and is much less dependent on imported virtual water than is Jordan.[14]

Examination of global water resources and potential global water conservation is an important part of sustaining our water supply. For example, by trading virtual water, the international trade markets reduce agriculture's global water use by about 5%.[14] Figure 18.15 shows net virtual water budgets (balances) for major trades. The balance is determined by import minus export in km^3 of virtual water, where 1 km^3 is 10^9 (one billion) m^3. For example, when the United States and Canada export wheat and other products to Mexico and Eastern Europe, a lot of virtual water is exported, explaining the negative balance for the United States and Canada, both of which export more virtual water than they import. On the other hand, countries that import a lot of food and other products have a positive balance because their imports of virtual water exceed their exports.

The concept of virtual water has three major uses to society and the world: [16]

- It promotes efficient use of water from a local to global scale. Trading virtual water can conserve global water resources by producing products that require a lot of water in places where water is abundant and can be efficiently used. When those products are exported to places where water is scarce or difficult to use efficiently, water is conserved and real water savings are realized.
- It offers countries and regions an opportunity to enjoy greater water security. Virtual water can be thought of as an alternative, additional water supply that, from a political point of view, can increase security and help solve geopolitical problems between nations.
- It helps us to understand relationships between water-consumption patterns and their environmental, economic, and political impacts. Knowing the virtual water content of the products we produce and where and how they are produced increases our awareness of water demand and ways to realize water savings.

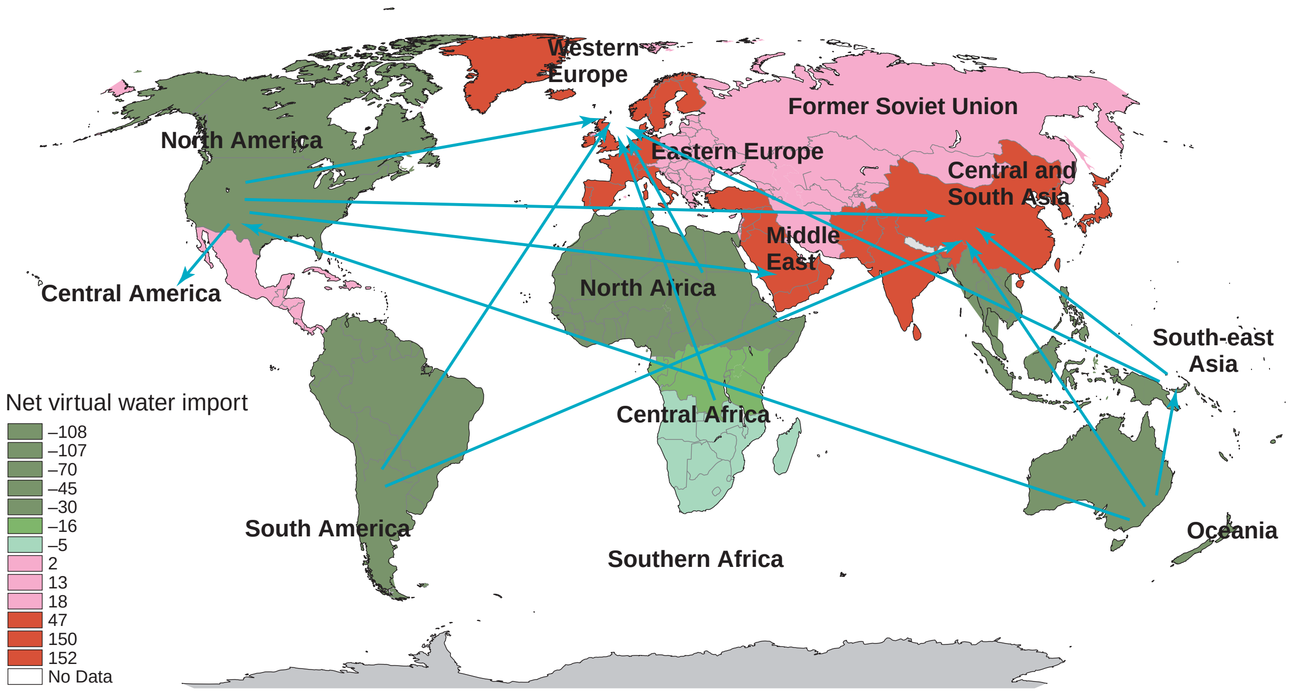


FIGURE 18.15 Virtual-water balances and transfers (6m^3 of water). 1 Gm^3 is 1 billion cubic meters. (*Source:* A.Y. Hoekstra, ed., 2003, Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series 12. IHE Delft. The Netherlands.)

Water Footprint

The water footprint is the total volume of freshwater used to produce the products and services used by an individual, community, country, or region. The footprint is generally expressed as the volume of water used per year and is divided into three components:[14]

- *Green water*, defined as precipitation that contributes to water stored in soils. This is the water consumed by crops (consumptive use) that evaporates or transpires from plants we cultivate.
- *Blue water*, defined as surface and groundwater. This is used to produce our goods and services (consumptive use).
- *Gray water,* defined as water polluted by the production of goods and services and rendered not available for other uses. The volume of gray water use has been estimated by calculating the amount of water required to dilute pollutants to the point that the water quality is acceptable and consistent with water quality standards.

The concept of virtual water, when linked to the water footprint, provides new tools to better manage water resources sustainably. An objective is to work toward water conservation and ultimately water self-sufficiency.

18.6 Wetlands

Wetlands is a comprehensive term for landforms such as salt marshes, swamps, bogs, prairie potholes, and vernal pools (shallow depressions that seasonally hold water). Their common feature is that they are wet at least part of the year and, as a result, have a particular type of vegetation and soil. Figure 18.16 shows several types of wetlands.

Wetlands may be defined as areas inundated by water or saturated to a depth of a few centimeters for at least a few days per year. Three major characteristics in identifying wetlands are hydrology, or wetness; type of vegetation; and type of soil. Of these, hydrology is often the most difficult to define because some freshwater wetlands may be wet for only a few days a year. The duration of inundation or saturation must be sufficient for the development of wetland soils, which are characterized by poor drainage and lack of oxygen, and for the growth of specially adapted vegetation.

Natural Service Functions of Wetlands

Wetland ecosystems may serve a variety of natural service functions for other ecosystems and for people, including the following:

- Freshwater wetlands are a natural sponge for water. During high river flow, they store water, reducing downstream flooding. Following a flood, they slowly release the stored water, nourishing low flows.
- Many freshwater wetlands are important as areas of groundwater recharge (water seeps into the ground from a prairie pothole, for instance) or discharge (water seeps out of the ground in a marsh fed by springs).
- Wetlands are one of the primary nursery grounds for fish, shellfish, aquatic birds, and other animals. It has been estimated that as many as 45% of endangered animals and 26% of endangered plants either live in wetlands or depend on them for their continued existence.[17]
- Wetlands are natural filters that help purify water; plants in wetlands trap sediment and toxins.
- Wetlands are often highly productive and are places where many nutrients and chemicals are naturally cycled.
- Coastal wetlands buffer inland areas from storms and high waves.
- Wetlands are an important storage site for organic carbon; carbon is stored in living plants, animals, and rich organic soils.
- Wetlands are aesthetically pleasing to people.

Freshwater wetlands are threatened in many areas. An estimated 1% of the nation's total wetlands are lost every two years, and freshwater wetlands account for 95% of this loss. Wetlands such as prairie potholes in the midwestern United States and vernal pools in Southern California are particularly vulnerable because their hydrology is poorly understood and establishing their wetland status is more difficult.[18] Over the past 200 years, over 50% of the wetlands in the United States have disappeared because they have been diked or drained for agriculture or filled for urban or industrial development. Perhaps as much as 90% of the freshwater wetlands have disappeared.

Although most coastal marshes are now protected in the United States, the extensive salt marshes at many of the nation's major estuaries, where rivers entering the ocean widen and are influenced by tides, have been modified or lost. These include deltas and estuaries of major rivers,

(a)

(b)

(c)

FIGURE 18.16 Several types of wetlands: **(a)** aerial view of part of the Florida Everglades at a coastal site; **(b)** cypress swamp water surface covered with a floating mat of duckweed, northeast Texas; and **(c)** aerial view of farmlands encroaching on prairie potholes, North Dakota.

such as the Mississippi, Potomac, Susquehanna (Chesapeake Bay), Delaware, and Hudson.[19] The San Francisco Bay estuary, considered the estuary most modified by human activity in the United States today, has lost nearly all its marshlands to leveeing and filling (Figure 18.17).[19] Modifications result not only from filling and diking but also from loss of water. The freshwater inflow has been reduced by more than 50%, dramatically changing the hydrology of the bay in terms of flow characteristics and water quality. As a result of the modifications, the plants and animals in the bay have changed as habitats for fish and wildfowl have been eliminated.[19]

The delta of the Mississippi River includes some of the major coastal wetlands of the United States and the world. Historically, coastal wetlands of southern Louisiana were maintained by the flooding of the Mississippi River, which delivered water, mineral sediments, and nutrients to the coastal environment. The mineral sediments contributed to the vertical accretion (building up) of wetlands. The nutrients enhanced growth of wetland plants, whose coarse, organic components (leaves, stems, roots) also accreted. These accretion processes counter processes that naturally submerge the wetlands, including a slow rise in sea level and subsidence (sinking) due to compaction. If the rates of submergence of wetlands exceed the rates of accretion, then the area of open water increases, and the wetlands are reduced.

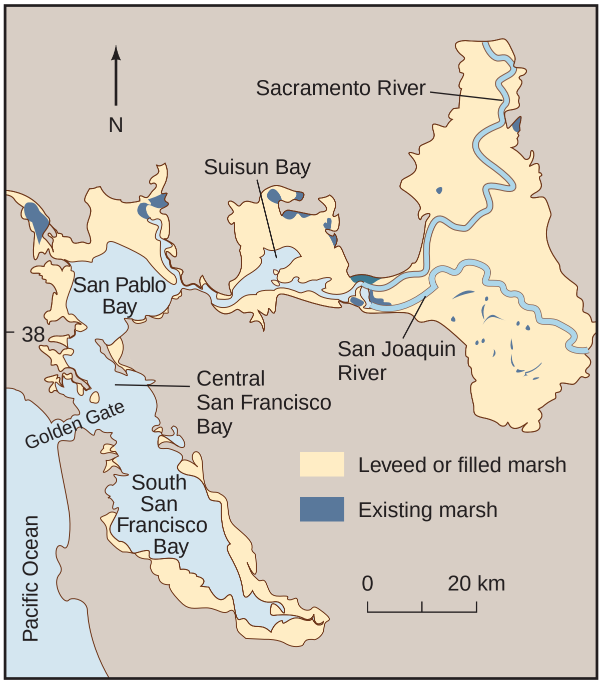


FIGURE 18.17 Loss of marshlands in the San Francisco Bay estuary from about 1850 to the present. (*Sources:* T.J. Conomos, ed., *San Francisco, the Urbanized Estuary* [San Francisco: American Association for the Advancement of Science, 1979]; F.H. Nichols, J.E. Cloern, S.N. Luoma, and D.H. Peterson, "The Modification of an Estuary," *Science* 231 [1986]: 567—573. Copyright 1986 by the American Association for the Advancement of Science.)

Today, levees line the lower Mississippi River, confining the river and directing floodwaters, mineral sediments, and nutrients into the Gulf of Mexico, rather than into the coastal wetlands. Deprived of water, sediments, and nutrients, in a coastal environment where the sea level is rising, the coastal wetlands are being lost. The global sea level is rising 1 to 2 mm/yr as a result of processes that began at the end of the last ice age: the melting of glaciers and expansion of ocean waters as they warm. Regional and local subsidence in the Mississippi delta region combines with the global rise in sea level to produce a relative sea-level rise of about 12 mm/yr. To keep the coastal wetlands from declining, the rate of vertical accretion would thus need to be about 13 mm/yr. Currently, natural vertical accretion is only about 5 to 8 mm/yr.[20]

Most people agree that wetlands are valuable and productive for fish and wildlife. But wetlands are also valued as potential lands for agriculture, mineral exploitation, and building sites. Wetland management is drastically in need of new incentives for private landowners (who own the majority of several types of wetlands in the United States) to preserve wetlands rather than fill them in and develop the land.[18] Management strategies must also include careful planning to maintain the water quantity and quality necessary for wetlands to flourish or at least survive. Unfortunately, although laws govern the filling and draining of wetlands, no national wetland policy for the United States is in place. Debate continues as to what constitutes a wetland and how property owners should be compensated for preserving wetlands.[17, 21]

Restoration of Wetlands

A related management issue is wetlands restoration. A number of projects have attempted to restore wetlands, with varied success. The most important factor to be considered in most freshwater marsh restoration projects is the availability of water. If water is present, wetland soils and vegetation will likely develop. The restoration of salt marshes is more difficult because of the complex interactions among the hydrology, sediment supply, and vegetation that allow salt marshes to develop. Careful studies of relationships between the movement of sediment and the flow of water in salt marshes is providing information crucial to restoration, which makes successful reestablishment of salt marsh vegetation more likely. The restoration of wetlands has become an important topic in the United States because of the mitigation requirement related to environmental impact analysis, as set forth in the National Environmental Policy Act of 1969. According to this requirement, if wetlands are destroyed or damaged by a particular project, the developer must obtain or create additional wetlands at another site to compensate.[17] Unfortunately, the state of the art of restoration is not adequate to ensure that specific restoration projects will be successful.[22]

Constructing wetlands for the purpose of cleaning up agricultural runoff is an idea being implemented in areas with extensive agricultural runoff. Wetlands have a natural ability to remove excess nutrients, break down pollutants, and cleanse water. A series of wetlands are being created in Florida to remove nutrients (especially phosphorus) from agricultural runoff and thus help restore the Everglades to more natural functioning. The Everglades are a huge wetland ecosystem that functions as a wide, shallow river flowing south through southern Florida to the ocean. Fertilizers applied to farm fields north of the Everglades make their way directly into the Everglades by way of agricultural runoff, disrupting the ecosystem. (Phosphorus enrichment causes undesired changes in water quality and aquatic vegetation; see the discussion of eutrophication in the next chapter.) The man-made wetlands are designed to intercept and hold the nutrients so that they do not enter and damage the Everglades.[23]

In southern Louisiana, restoration of coastal wetlands includes the application of treated wastewater, which adds nutrients, nitrogen, and phosphorous to accelerate plant growth. As plants grow, organic debris (stems, leaves, and so forth) builds up on the bottom and causes the wetland to grow vertically. This growth helps offset a relative rise in sea level, maintaining and restoring the wetland.[20]

18.7 Dams and the Environment

Dams and their reservoirs generally are designed to be multifunctional. People who propose the construction of dams and reservoirs point out that they may be used for recreational activities and for generating electricity, as well as providing flood control and ensuring a more stable water supply. However, it is often difficult to reconcile these various uses at a given site. For example, water demands for agriculture might be high during the summer, resulting in a drawdown of the reservoir and leaving extensive mudflats or an exposed bank area subject to erosion (Figure 18.18). Recreational users find the low water level and the mudflats aesthetically displeasing. Also, high demand for water may cause quick changes in lake levels, which could interfere with wildlife (particularly fish) by damaging or limiting spawning opportunities. Another consideration is that dams and reservoirs tend to give a false sense of security to those living below them. Dams may fail. Flooding may originate from tributary rivers that enter the main river below a dam, and dams cannot be guaranteed to protect people against floods larger than those for which they have been designed.

FIGURE 18.18 Erosion along the shoreline of a reservoir in central California following release of water, exposing bare banks.

The environmental effects of dams are considerable and include the following:

- Loss of land, cultural resources, and biological resources in the reservoir area.
- Potential serious flood hazard, should larger dams and reservoirs fail.
- Storage behind the dam of sediment that would otherwise move downstream to coastal areas, where it would supply sand to beaches. The trapped sediment also reduces water storage capacity, limiting the life of the reservoir.
- Downstream changes in hydrology and in sediment transport that change the entire river environment and the organisms that live there.
- Fragmentation of ecosystems above and below a dam.
- Restricted movement upstream and downstream of organic material, nutrients, and aquatic organisms.

For a variety of reasons—including displacement of people, loss of land, loss of wildlife, and permanent, adverse changes to river ecology and hydrology—many people today are vehemently opposed to turning remaining rivers into a series of reservoirs with dams. In the United States, several dams have been removed, and the removal of others is being considered because of the environmental damage they are causing. In contrast, China recently constructed the world's largest dam. Three Gorges Dam, on the Yangtze River (Figure 18.19), has drowned cities, farm fields, important archaeological sites, and highly scenic gorges and has displaced approximately 2 million people from their homes. In the river, rare freshwater dolphins called *Baiji* (by legend the reincarnated 3rd-century

FIGURE 18.19 Three Gorges on the Yangtze River is a landscape of high scenic value. Shown here is the Wu Gorge, near Wushan, one of the gorges flooded by the water in the reservoir.

Chinese princess who symbolizes peace, prosperity, and love) are functionally extinct. A few may still exist, but scientists believe recovery is not possible. On land, habitats were fragmented and isolated as mountaintops became islands in the reservoir.

The dam, which is approximately 185 m high and more than 1.6 km wide, produces a reservoir nearly 600 km long. Raw sewage and industrial pollutants that are discharged into the river are deposited in the reservoir, and there is concern that the reservoir will become seriously polluted. Since the reservoir has been filling for several years, the banks are becoming saturated, increasing the landslide hazard. Large ships make matters worse by generating waves that increase shoreline erosion and cause the rock slopes and shoreline homes to vibrate and shake. Some older homes are thought to be unsafe due to the landslide hazard that has evidently increased since the reservoir began filling. In addition, the Yangtze River has a high sediment load, and it is feared that damage to deepwater shipping harbors will eventually occur at the upstream end of the reservoir, where sediments now being deposited are producing shallower water.

The dam may also give people living downstream a false sense of security. Should the dam fail, downstream cities, such as Wushan, with a population of several million people, might be submerged, with catastrophic loss of life.[24] The dam may also encourage further development in flood-prone areas, which will be damaged or lost if the dam and reservoir are unable to hold back floods in the future. If this happens, loss of property and life from flooding may be greater than if the dam had not been built. Contributing to this problem is the dam's location in a seismically active region where earthquakes and large landslides have been common in the past.

A positive attribute of the giant dam and reservoir is the capacity to produce about 18,000 MW of electricity, the equivalent of about 18 large coal-burning power plants. As pointed out in earlier discussions, pollution from coal burning is a serious problem in China. Some of the dam's opponents have pointed out, however, that a series of dams on tributaries to the Yangtze River could have produced similar electric power without causing environmental damage to the main river.[25]

The Glen Canyon Dam on the Colorado River was completed in 1963. From a hydrologic viewpoint, the Colorado River has been changed by the dam. The river has been tamed. The higher flows have been reduced, the average flow has increased, and the flow changes often because of fluctuating needs to generate electrical power. Changing the hydrology of the river has also changed other aspects, including the rapids, the distribution of sediments that form sandbars (called beaches by rafters; Figure 18.20), and the vegetation near the water's edge.[26]

FIGURE 18.20 A sandbar in the Colorado River below Glen Canyon Dam in the Grand Canyon. Releases of relatively large flows in recent years are designed to help maintain the sandbar.

The sandbars, valuable wildlife habitats, shrank in size and number following construction of the dam because sediment that would have moved downstream to nourish them was trapped in the reservoir. All these changes affect the Grand Canyon, which is downstream from the dam. In an effort to restore part of the sand flow and maintain sandbars, releases from the dam are periodically increased to more closely match natural pre-dam flows.[27, 28] The higher flows have helped maintain sandbars by mobilizing sand, but cannot be expected to restore the river to pre-dam conditions.

There is little doubt that if our present water-use practices continue, we will need additional dams and reservoirs, and some existing dams will be heightened to increase water storage. However, there are few acceptable sites for new dams, and conflicts over the construction of additional dams and reservoirs are bound to occur. Water developers may view a canyon dam site as a resource for water storage, whereas others may view that canyon as a wilderness area and recreation site for future generations. The conflict is common because good dam sites are often sites of high-quality scenic landscape.

Dams also have an economic aspect: They are expensive to build and operate, and they are often constructed with federal tax dollars in the western United States, where they provide inexpensive subsidized water for agriculture. This has been a point of concern to some taxpayers in the eastern United States, who do not have the benefit of federally subsidized water. Perhaps a different pricing structure for water would encourage conservation, and fewer new dams and reservoirs would be needed.

Removal of Dams

Many dams in the United States have outlived their original purposes or design lives. These are generally small structures that now are viewed as a detriment to the ecological community of the river. The dams fragment river ecosystems by producing an upstream-of-dam environment and a downstream environment. Often, the structure blocks upstream migration of threatened or endangered fish species (for example, salmon in the Pacific Northwest). The perceived solution is to remove the dam and restore the river's more natural hydrology and ecological functions. However, removal must be carefully planned and executed to ensure that the removal doesn't itself cause ecological problems, such as sudden release of an unacceptable amount of sediment to the river or contaminated sediment.[29]

A large number of U.S. dams (mostly small ones) have been removed or are in the planning stages for removal. The Edwards Dam near Augusta, Maine, was removed in 1999, opening about 29 km (18 mi) of river habitat to migrating fish, including Atlantic salmon, striped bass, shad, alewives, and Atlantic sturgeon. The Kennebec River came back to life as millions of fish migrated upstream for the first time in 160 years.[30]

The Marmot Dam on the Sandy River in northwest Oregon was removed in 2007 (Figure 18.21). The dam was 15 m (45 ft) high, 50 m (150 ft) wide, and was filled with 750,000 cubic meters of sand and gravel. The removal was a scientific experiment and provided useful information for future removal projects. Salmon again swim up the river and spawn. People are kayaking in stretches where the river hadn't been run by a boat in almost 100 years.[31]

The Elwha and Glines Canyon dams, constructed in the early 18th century on the Elwha River in Washington State's Puget Sound, are scheduled for removal beginning in 2012. The largest of the two is the Glines Canyon Dam, which is about 70 m (210 ft) high (the highest dam ever removed). The Elwha headwater is in Olympic National Park, and prior to the dams' construction it supported large salmon and steelhead runs. Denied access to almost their entire spawning habitat, fish populations there have declined greatly. Large runs of fish had also brought nutrients from the ocean to the river and landscape. Bears, birds, and other animals used to eat the salmon and transfer nutrients to the forest ecosystem. Without the salmon, both wildlife and forest suffer. The dams also keep sediment from reaching the sea. Denied sediment, beaches at the river's mouth have eroded, causing the loss of clam beds. The dams will be removed in stages to minimize downstream impacts from the release of sediment. With the dams removed, the river will flow freely for the first time in a century, and it is hoped that the ecosystem will recover and the fish will return in greater numbers.[32]

The Matilija Dam, completed by California's Ventura County in 1948, is about 190 m (620 ft) wide and 60 m (200 ft) high. The structure is in poor condition, with leaking, cracked concrete and a reservoir nearly filled with sediment. The dam serves no useful purpose and blocks endangered southern steelhead trout from their historical spawning grounds. The sediment trapped behind the dam also reduces the natural nourishment of sand on beaches and increases coastal erosion.

The removal process began with much fanfare in October 2000, when a 27 m (90 ft) section was removed from the top of the dam. The entire removal process may take years, after scientists have determined how to safely remove the sediment stored behind the dam. If released quickly, it could damage the downstream river environment, filling pools and killing river organisms such as fish, frogs, and salamanders. If the sediment can be slowly released in a more natural manner, the downstream damage can be minimized.

FIGURE 18.21 The concrete Marmot Dam before **(a)** and during **(b)** removal in 2007.

The cost of the dam in 1948 was about $300,000. The cost to remove the dam and sediment will be more than ten times that amount.

The perception of dams as permanent edifices, similar to the pyramids of Egypt, has clearly changed. What is learned from studying the removal of the Edwards Dam in Maine, the Marmot Dam in Oregon, and the Matilija Dam in California will be useful in planning other dam-removal projects. The studies will also provide important case histories to evaluate ecological restoration of rivers after removal of dams. In sum, removing dams is simple in concept, but involves complex problems relating to sediment and water. It provides an opportunity to restore ecosystems, but with that opportunity comes responsibility.[31]

18.8 Global Water Shortage Linked to Food Supply

As a capstone to this chapter, we present the hypothesis that we are facing a growing water shortage linked to our food supply. This is potentially a very serious problem. In the past few years, we have begun to realize that isolated water shortages are apparently indicators of a global pattern.[33] At numerous locations on Earth, both surface water and groundwater are being stressed and depleted:

- Groundwater in the United States, China, India, Pakistan, Mexico, and many other countries is being mined (used faster than it is being renewed) and is therefore being depleted.
- Large bodies of water—for example, the Aral Sea—are drying up (see earlier Figures 18.8–10).
- Large rivers, including the Colorado in the United States and the Yellow in China, do not deliver any water to the ocean in some seasons or years. Others, such as the Nile in Africa, have had their flow to the ocean greatly reduced.

Water demand during the past half-century has tripled as the human population more than doubled. In the next half-century, the human population is expected to grow by another 2 to 3 billion. There is growing concern that there won't be enough water to grow the food to feed the 8–9 billion people expected to be inhabiting the planet by the year 2050. Therefore, a food shortage linked to water resources seems a real possibility. The problem is that our increasing use of groundwater and surface water for irrigation has allowed for increased food production—mostly crops such as rice, corn, and soybeans. These same water resources are being depleted, and as water shortages for an agricultural region occur, food shortages may follow. Water is also linked to energy because irrigation water is often pumped from groundwater. As the cost of energy rises, so does the cost of food and the difficulty of purchasing food, especially in poor countries. This scenario in 2007-2008 resulted in a number of food riots in over 30 countries including Haiti, Mexico and west Bengal.

The way to avoid food shortages caused by water-resource depletion is clear: We need to control human population growth and conserve and sustain water resources. In this chapter, we have outlined a number of ways to conserve, manage, and sustain water. The good news is that a solution is possible—but it will take time, and we need to be proactive, taking steps now before significant food shortages develop. For all the reasons discussed, one of the most important and potentially serious resource issues of the 21st century is water supply and management.

CRITICAL THINKING ISSUE

What Is Your Water Footprint?

The concept of an environmental footprint has been developed in recent years to become a part of environmental science. The footprint, as it has evolved, is a quantitative measure of how our use of natural resources is affecting the environment. There are three main environmental footprints:

- The ecological footprint is a measure of the biologically productive space, measured in hectares, that an individual, community, or country uses.
- The carbon footprint is a measure of the amount of greenhouse gases produced and emitted into the atmosphere by the activities of an individual, group of people, or nation.
- The water footprint is a measure of water use by an individual, community, or country, measured in cubic meters of water per year.

Here, we are concerned with the water footprint, which measures direct water use by people and as such involves virtual water. The water footprint is somewhat different from the other two footprints in that water is a variable resource in terms of where it is found on Earth and its availability.

Water is the most abundant fluid in the crust of the Earth, and we use lots of it for drinking and washing our clothes, dishes, and ourselves. However, even more water is used in producing the goods and the services that our society wishes. The water footprint of an individual, group of people, or even a country is defined as the total volume of freshwater, in cubic meters, used per year to produce the goods or services that the individual, group, or country uses.[34]

The water footprint is closely related to our society's consumption of crops, goods, and services. As such, it is also a measure of environmental stress. The basic assumption is that there is a finite amount of water, and the more we use, the less is available for ecosystems and other purposes. Also, the more water we use for industrial processes, the likelier we are to use more of our other resources, such as energy and materials. The general idea with the water footprint is that by examining it we can better understand how we actually use water, which could lead to better water management and conservation. The water footprint includes both direct and indirect uses of water. Of the two, the indirect or virtual water is often much larger than the amount of water directly consumed (taken up in tissue)—for example, for personal consumption or growing crops.

Calculating the water footprint is a quantitative exercise based on gathering extensive data about how much water is used for agriculture, industry, and other activities. Based on water-use data and analysis, average amounts of water use can be estimated, and these data are used to generate an individual's water footprint. To estimate your personal water footprint, you can go to a water-footprint calculator, such as that on the Web site *waterfootprint.org*. In this Critical Thinking exercise, go to that Web site and use the water-footprint calculator for two scenarios: (1) the quick individual water footprint; and (2) the extended individual water footprint. For income, put in the amount of money you spend per year for your college education, plus whatever other money you earn. The quick individual water-footprint calculation involves very few variables, whereas the extended calculator includes a number of variables relating to how you eat and your personal lifestyle.

After you have calculated your personal water footprint, try some experiments by substituting at least three or four other countries for the country in which you live. These countries

Table 18.3 WATER FOOTPRINTS FOR SELECTED COUNTRIES (ARRANGED FROM LOWEST TO HIGHEST WATER FOOTPRINT PER PERSON)

COUNTRY	APPROXIMATE POPULATION (MILLIONS)[a]	TOTAL WATER FOOTPRINT (GM^3/YR)[b]	WATER FOOTPRINT PER PERSON (M^3/YR)	GROSS DOMESTIC PRODUCT PER PERSON (1,000S US$)[c]
Afghanistan	26	17.3	660	0.4
China	1258	883.4	702	3
South Africa	42	39.5	931	6
India	1007	987.4	980	1
Egypt	63	69.5	1097	2
Japan	127	146.1	1153	37
United Kingdom	59	73.1	1245	44
Mexico	97	140.2	1441	10
Switzerland	7	12.1	1682	67
France	59	110.2	1875	46
Spain	40	94.0	2325	35
USA	280	696	2483	47

[a] Population (approx.) in 2000

[b] $1 Gm^3 = 1$ billion cubic meters

[c] Gross domestic product (GDP) per person in 2008. International Monetary Fund 2008. *Source:* National Water Footprints: Statistics. Accessed August 25, 2009 at www.waterfootprint.org.

should range from some that are wealthier than the United States (such as Switzerland) and some that are poorer (such as China). By "rich" and "poor," we are not referring to absolutes of happiness or any other measure, but only the median income for an individual (see Table 18.3).

Critical Thinking Questions

1. How well do you think the variables in the extended individual footprint characterize your water use?
2. Do you think the water footprint you calculated is a useful concept to better understand water resources?
3. In evaluating your individual water footprint living in the United States versus several other countries, what is actually controlling the footprint that you produced? Why is individual income or GDP per person apparently so important?
4. Has calculating your personal water footprint led you to a better understanding of some of the components of water use? What could you do to reduce your water footprint?

SUMMARY

- Water is a liquid with unique characteristics that have made life on Earth possible.
- Although it is one of the most abundant and important renewable resources on Earth, more than 99% of Earth's water is unavailable or unsuitable for beneficial human use because of its salinity or location.
- The pattern of water supply and use at any particular point on the land surface involves interactions and linkages among the biological, hydrological, and rock cycles. To evaluate a region's water resources and use patterns, a water budget is developed to define the natural variability and availability of water.
- It is expected that during the next several decades the total water withdrawn from streams and groundwater in the United States will decrease slightly, but that the consumptive use will increase because of greater demands from our growing population and industry.

- Water withdrawn from streams competes with instream needs, such as maintaining fish and wildlife habitats and navigation, and may therefore cause conflicts.
- Groundwater use has led to a variety of environmental problems, including loss of vegetation along watercourses, and land subsidence.
- Because agriculture is the biggest user of water, conservation of water in agriculture has the most significant effect on sustainable water use. However, it is also important to practice water conservation at the personal level in our homes and to price water in a way that encourages conservation and sustainability.
- There is a need for a new philosophy in water-resource management that considers sustainability and uses creative alternatives and variable sources. A master plan must include normal sources of surface water and groundwater, conservation programs, and use of reclaimed water.
- Development of water supplies and facilities to more efficiently move water may cause considerable environmental degradation; construction of dams and reservoirs should be considered carefully in light of potential environmental impacts.
- Removal of dams as a way to reconnect river ecosystems is becoming more common.
- The concepts of virtual water and the water footprint are becoming important in managing water resources at the regional to global level.
- Wetlands serve a variety of functions at the ecosystem level that benefit other ecosystems and people.
- We are facing a growing global water shortage linked to the food supply.
- Water supply and management is one of the major resource issues of the 21st century.

REEXAMINING THEMES AND ISSUES

Human Population

As the human population has increased, so has the demand for water resources. As a result, we must be more careful in managing Earth's water resources, particularly near urban centers.

Sustainability

Our planet's water resources are sustainable, provided we manage them properly and they are not overused, polluted, or wasted. This requires good water-management strategies. We believe that the move toward sustainable water use must begin now if we are to avoid conflicts in the future. Principles of water management presented in this chapter help delineate what needs to be done.

Global Perspective

The water cycle is one of the major global geochemical cycles. It is responsible for the transfer and storage of water on a global scale. Fortunately, the total abundance of water on Earth is not a problem. However, ensuring that it is available when and where it is needed in a sustainable way *is* a problem.

Urban World

Although urban areas consume only a small portion of the water resources used by people, it is in urban areas that shortages are often most apparent. Thus, the concepts of water management and water conservation are critical in urban areas.

People and Nature

To many people, water is an icon of nature. Waves crashing on a beach, water flowing in a river or over falls or shimmering in lakes have inspired poets and countless generations of people to connect with nature.

Science and Values

Conflicts result from varying values related to water resources. We value natural areas such as wetlands and free-running rivers, but we also want water resources and protection from hazards such as flooding. As a result, we must learn to align more effectively with nature to minimize natural hazards, maintain a high-quality water resource, and provide the water necessary for the ecosystems of our planet. The relatively high, controlled releases of the Colorado River discussed in this chapter are examples of new river-management practices that embody both scientific knowledge and social values—in this case, scientific understanding of river processes and the wish to sustain the Colorado as a vibrant, living river.

KEY TERMS

consumptive use **376**
desalination **376**
effluent stream **372**
groundwater **372**
influent stream **372**
in-stream use **376**
off-stream use **376**
overdraft **375**
sustainable water use **384**
virtual water **386**
water budget **373**
water conservation **380**
wetlands **387**

STUDY QUESTIONS

1. If water is one of our most abundant resources, why are we concerned about its availability in the future?
2. Which is more important from a national point of view, conservation of water use in agriculture or in urban areas? Why?
3. Distinguish between in-stream and off-stream uses of water. Why is in-stream use controversial?
4. What are some important environmental problems related to groundwater use?
5. How might your community better manage its water resources?
6. Discuss how the concept of virtual water is related to water conservation and management at the global level.
7. What are some of the major environmental impacts associated with the construction of dams? How might these be minimized?
8. What are the most important factors in planning to remove a dam?
9. How can we reduce or eliminate the growing global water shortage? Do you believe the shortage is related to our food supply? Why? Why not?
10. Why is water such an important resource issue?

FURTHER READING

Gleick. P.H, Global freshwater resources: Soft-path solutions for the 21st century, *Science* 302(2003):1524–1528.

Gleick, P.H., *The World's Water 2000–2001* (Washington, DC.: Island Press, 2000).

Hoekstra, A.Y., and A.K. Chapagain, *Globalization of Water* (Malden, MA: Blackwell Publishing, 2008).

James, W., and J. Neimczynowicz, eds., *Water, Development and the Environment* (Boca Raton, FL: CRC Press, 1992). Covers problems with water supplies imposed by a growing population, including urban runoff, pollution and water quality, and management of water resources.

La Riviere, J.W.M. Threats to the world's water, *Scientific American* 261, no. 3 (1989): 80–84. Summary of water supply and demand and threats to continued supply.

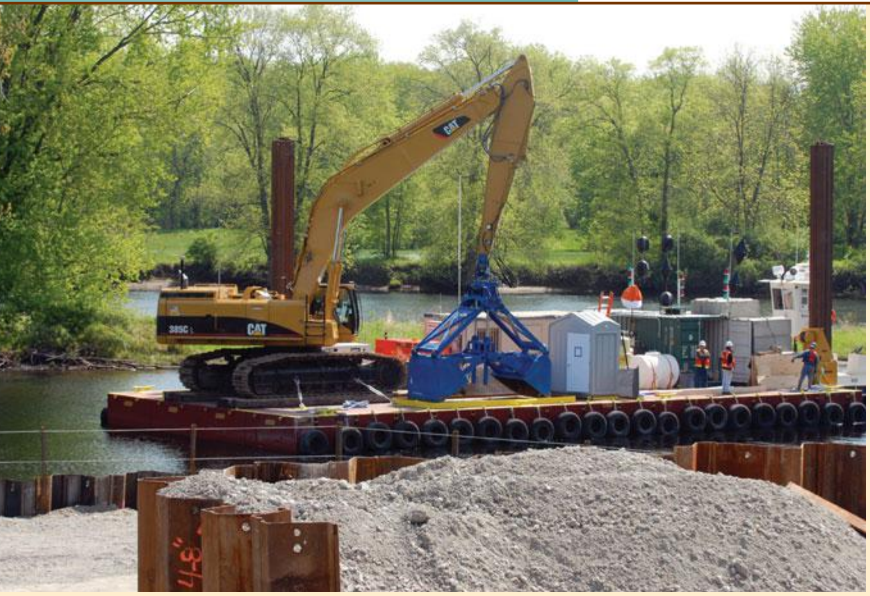
Spulber, N., and A. Sabbaghi, *Economics of Water Resources: From Regulation to Privatization* (London: Kluwer Academic, 1994). Discussions of water supply and demand, pollution and its ecological consequences, and water on the open market.

Twort, A.C., F.M. Law, F.W.Crowley, and D.D.Ratnayaka, *Water Supply,* 4th ed. (London: Edward Arnold, 1994). Good coverage of water topics from basic hydrology to water chemistry, and water use, management, and treatment.

Wheeler, B.D., S.C. Shaw, W.J. Fojt, and R.A.Robertson, *Restoration of Temperate Wetlands* (New York: Wiley, 1995). Discussions of wetland restoration around the world.

CHAPTER 19

Water Pollution and Treatment



Dredging began in 2009 to remove contaminant sediment from the Hudson River in New York.

LEARNING OBJECTIVES

Degradation of our surface-water and groundwater resources is a serious problem. Although all of its effects are not yet fully known, we can and should begin taking steps to treat water and to minimize pollution. After reading this chapter, you should understand . . .

- What constitutes water pollution and what the major categories of pollutants are;
- Why the lack of disease-free drinking water is the primary water-pollution problem in many locations around the world;
- How point and nonpoint sources of water pollution differ;
- What biochemical oxygen demand is, and why it is important;
- What eutrophication is, why it is an ecosystem effect, and how human activity can cause it;
- Why sediment pollution is a serious problem;
- What acid mine drainage is, and why it is a problem;
- How urban processes can cause shallow-aquifer pollution;
- What the various methods of wastewater treatment are, and why some are environmentally preferable to others;
- Which environmental laws protect water resources and ecosystems.

CASE STUDY

America's "First River": A Success Story

The Hudson River is sometimes referred to as America's first river. It is named after Henry Hudson, who sailed up the river from the Atlantic in 1609 looking for a route to Asia. Native Americans, however, called the river by a name meaning "flows in two directions." This is because, for much of its lower course, the river ebbs and flows with the ocean tides, flowing upstream, then downstream, and sometimes part of the river is flowing up while part is flowing down. The total length of the river from the Adirondack Mountains to the Atlantic Ocean is just over 480 kilometers, but it's the lower 160 kilometers that has gained the most attention. Before emptying into New York Harbor, the lower Hudson flows past New Jersey communities such as Fort Lee, Union City, and Hoboken on its western shore and Mt Vernon, Yonkers, and Manhattan Island on its eastern shore. Farther upstream, about 50 to 150 km from Manhattan, the river flows through the scenic Hudson River Highlands. The high hills that border the river have a core of ancient hard igneous and metamorphic rock that erosion has carved into beautiful scenery, such as Storm King Mountain.

The story of the Hudson River and the environment go back to the 1800s. The nation's first military academy, West Point, was established along the river in 1802, and during the War of 1812 industrial activity sprang up along the river. A foundry opened near West Point to manufacture such products as cannonballs, pipes, and railroad engines. The foundry closed after about 100 years, but other factories became established along the river, including the Anaconda Wire and Cable Company. That plant closed in 1974, leaving behind a legacy of toxic pollution that helped turn the Hudson River into an environmental battleground in the 20th century between people who revered the river and those deemed responsible for making it unsafe to swim in its waters and making the fish that lived in it unsafe to eat.[1] In one of the nation's earliest battles to eliminate water pollutants, activists and others in the early 1970s sued the company, which was fined about $200,000, a very large fine for pollution violations at that time.

Those who thought that from then on the river would be clean again for future generations were mistaken: From around 1950 to 1977, General Electric discharged (dumped) over a million pounds of polychlorinated biphenyls (PCBs) into the Hudson River from two manufacturing plants. PCBs are highly stable man-made chemical compounds produced by combining chlorine and biphenyl (an organic compound). Because they are good electrical insulators and were considered safe, PCBs were widely used to prevent fires in electric transformers and capacitors. GE operated the plants for decades. Then, in the early 1970s, the story of the catastrophe unfolding in the Hudson River became common knowledge. Commercial fishing for striped bass and other fish was banned in 1976, and fishermen blamed GE for destroying a fishing industry, a way of life, and a culture that had been going on for centuries in the river valley.

PCBs were found to cause liver disease and are a suspected carcinogen in humans and a known carcinogen in other animals. PCBs were found to be persistent in the environment and entered the food chain to damage the river ecosystem, especially fish and invertebrates. As a result, they were banned in the United States in 1977. During this period, environmentalism became important and federal water laws were passed, including the Clean Water Act of 1972. In that year the U.S. government started dealing with hazardous waste and passed the Resource Conservation and Recovery Act, followed a few years later by the Comprehensive Environmental Response Compensation and Liability Act of 1980, which established the so-called Superfund to clean up several hundred of the most hazardous sites in the country.

At the top of the list was the Hudson River, and in 1983 a roughly 300-kilometer reach of the river was classified as the largest and one of the most serious Superfund sites in the country. The new law also changed the way the federal government dealt with industries that polluted the environment. Companies became responsible for their previous pollution of Superfund sites and liable for cleanup.

Today, however, over 100 tons of PCBs are still in the Hudson River sediments, with concentrations thousands of times greater than what is considered safe. PCBs accumulate in food chains in a process known as bioaccumulation. For example, organisms in the sediment contain a concentration of PCBs that increases as these organisms are eaten by fish, and these concentrations may increase further when the fish are eaten by predators such as eagles or people. Health advisories were issued in the mid-1970s and these remain in place today, warning women and children not to eat fish from the Hudson River.

A battle raged on as to what should be done about the PCBs. The two major alternatives were either to dredge areas where PCB concentrations are particularly high or just let natural processes in the river clean up the PCBs. The second option assumed that the sources of PCBs have been nearly eliminated and that the river would naturally cleanse itself of approximately half of the PCBs in three or four years.[2,3] Those arguing for dredging said the pollution was far too great to leave the cleanup to natural processes, and that dredging would greatly shorten the time necessary for the river to clean itself. To dredge or not to dredge was a several-hundred-million-dollar question. General Electric spent millions in an attempt to avoid spending hundreds of millions to clean up the river by dredging. The company said dredging would just stir up the PCBs in the riverbed, moving them up into the water and thus into the food chain.

The issue was settled in 2001: General Electric would have to pay several hundred million dollars to clean up the river by dredging. The work on mapped PCB hotspots began in 2009, using barges to dredge the contaminated sediment from the river bottom and place it in hopper barges. From there it is sent to a processing facility, and then finally transported by train about 3,000 kilometers to a waste-disposal site in west Texas. The cleanup is expected to take until 2015, ending an era of water pollution and toxic legacy in the Hudson.

The lower Hudson River Valley is urbanizing. There are more parking lots and cars than ever before. There is concern that runoff from streets and parking lots and urban houses will lead to a new wave of urban pollution. On the other hand, more and more people are experiencing the Hudson River in very positive ways. Numerous river groups focus their time and effort on cleaning up the river and promoting activities such as boating, hiking, and bird-watching. Parks of all sizes are being established at scenic sites along the river, factories have been removed, making room for some of the new parks, and there is an attempt to join these together in a greenbelt that would stretch many miles up the river from Manhattan. Some of the river culture from times past is reappearing.

In sum, the future of the Hudson River seems secure as progress in its cleanup and preservation continues. Some say that modern environmentalism was born on the Hudson River, one of the few American rivers to be designated an American Heritage River. Many people made important personal sacrifices to their careers, reputations, and livelihoods to protect the river.

These people truly revered the Hudson River and were in the forefront of fighting to protect our natural environment. An organization known as Scenic Hudson led the fight to protect the river. It was joined in 1969 by Clearwater, which included the folksinger, activist, and environmentalist Pete Seeger. Clearwater built a sloop that took people up and down the river, educating them on environmental concerns, fighting to control and eliminate pollution, and encouraging river restoration. Both Scenic Hudson and Clearwater remain active today.

The story of PCB pollution is a powerful reminder that individuals and groups can make a difference in correcting past environmental errors and working toward sustainability.

19.1 Water Pollution

Water pollution refers to degradation of water quality. In defining pollution, we generally look at the intended use of the water, how far the water departs from the norm, its effects on public health, or its ecological impacts. From a public-health or ecological view, a pollutant is any biological, physical, or chemical substance that, in an identifiable excess, is known to be harmful to desirable living organisms. Water pollutants include heavy metals, sediment, certain radioactive isotopes, heat, fecal coliform bacteria, phosphorus, nitrogen, sodium, and other useful (even necessary) elements, as well as certain pathogenic bacteria and viruses. In some instances, a material may be considered a pollutant to a particular segment of the population, although it is not harmful to other segments. For example, excessive sodium as a salt is not generally harmful, but it may be harmful to people who must restrict salt intake for medical reasons.

Today, the world's primary water-pollution problem is a lack of clean, disease-free drinking water. In the past, epidemics (outbreaks) of waterborne diseases such as cholera have killed thousands of people in the United States. Fortunately, we have largely eliminated epidemics of such diseases in the United States by treating drinking water prior to consumption. This certainly is not the case worldwide, however. Every year, several billion people are exposed to waterborne diseases. For example, an epidemic of cholera occurred in South America in the early 1990s, and outbreaks of waterborne diseases continue to be a threat even in developed countries.

Many different processes and materials may pollute surface water or groundwater. Some of these are listed in Table 19.1. All segments of society—urban, rural, industrial, agricultural, and military—may contribute to the problem of water pollution. Most of it results from runoff and leaks or seepage of pollutants into surface water or groundwater. Pollutants are also transported by air and deposited in bodies of water.

Increasing population often results in the introduction of more pollutants into the environment as well as greater demands on finite water resources.[4] As a result, we can expect sources of drinking water in some locations to be degraded in the future.[5,6]

Table 19.1 SOME SOURCES AND PROCESSES OF WATER POLLUTION

SURFACE WATER	GROUNDWATER
Urban runoff (oil, chemicals, organic matter, etc.) (U, I, M) Agricultural runoff (oil, metals, fertilizers, pesticides, etc.) (A)	Leaks from waste-disposal sites (chemicals, radioactive materials, etc.) (I, M)
Accidental spills of chemicals including oil (U, R, I, A, M)	Leaks from buried tanks and pipes (gasoline, oil, etc.) (I, A, M)
Radioactive materials (often involving truck or train accidents) (I, M)	Seepage from agricultural activities (nitrates, heavy metals, pesticides, herbicides, etc.) (A)
Runoff (solvents, chemicals, etc.) from industrial sites (factories, refineries, mines, etc.) (I, M)	Saltwater intrusion into coastal aquifers (U, R, I, M) Seepage from cesspools and septic systems (R)
Leaks from surface storage tanks or pipelines (gasoline, oil, etc.) (I, A, M)	Seepage from acid-rich water from mines (I) Seepage from mine waste piles (I)
Sediment from a variety of sources, including agricultural lands and construction sites (U, R, I, A, M)	Seepage of pesticides, herbicide nutrients, and so on from urban areas (U)
Air fallout (particles, pesticides, metals, etc.) into rivers, lakes, oceans (U, R, I, A, M)	Seepage from accidental spills (e.g., train or truck accidents) (I, M)
	Inadvertent seepage of solvents and other chemicals including radioactive materials from industrial sites or small businesses (I, M)

Key: U = urban; R = rural; I = industrial; A = agricultural; M = military.

The U.S. Environmental Protection Agency has set thresholds limiting the allowable levels for some (but not all) drinking-water pollutants. Because it is difficult to determine the effects of exposure to low levels of pollutants, thresholds have been set for only a small fraction of the more than 700 identified drinking-water contaminants. If the pollutant exceeds an established threshold, then the water is unsatisfactory for a particular use. Table 19.2 lists selected pollutants included in the national drinking-water standards for the United States.

Water withdrawn from surface or groundwater sources is treated by filtering and chlorinating before distribution to urban users. Sometimes it is possible to use the natural environment to filter the water as a service function, saving treatment cost (see A Closer Look 19.1).

The following sections focus on several water pollutants to emphasize principles that apply to pollutants in general. (See Table 19.3 for categories and examples of water pollutants.) Before proceeding to our discussion of pollutants, however, we first consider biochemical oxygen demand and dissolved oxygen. Dissolved oxygen is not a pollutant but rather is needed for healthy aquatic ecosystems.

Table 19.2 NATIONAL DRINKING-WATER STANDARDS

CONTAMINANT	MAXIMUM CONTAMINANT LEVEL (MG/L)
Inorganics	
Arsenic	0.05
Cadmium	0.01
Lead	0.015 action level[a]
Mercury	0.002
Selenium	0.01
Organic chemicals	
Pesticides	
Endrin	0.0002
Lindane	0.004
Methoxychlor	0.1
Herbicides	
2,4-D	0.1
2,4,S-TP	0.01
Silvex	0.01
Volatile organic chemicals	
Benzene	0.005
Carbon tetrachloride	0.005
Trichloroethylene	0.005
Vinyl chloride	0.002
Microbiological organisms	
Fecal coliform bacteria	1 cell/100 ml

[a] Action level is related to the treatment of water to reduce lead to a safe level. There is no maximum contaminant level for lead.

Source: U.S. Environmental Protection Agency.

A CLOSER LOOK 19.1

What Is the Value of Clean Water to New York City?

The forest of the Catskill Mountains in upstate New York (Figure 19.1) provides water to about 9 million people in New York City. The total contributing area in the forest is about 5,000 km^2 (2,000 square miles), of which the city of New York owns less than 8%. The water from the Catskills has historically been of high quality and in fact was once regarded as one of the largest municipal water supplies in the United States that did not require extensive filtering. Of course, what we are talking about here is industrial filtration plants, where the water enters from reservoirs and groundwater and is then treated before being dispersed to users.

In the past, the water from the Catskills has been filtered very effectively by natural processes. When rain or melting snow drips from trees or melts on slopes in the spring, some of it infiltrates the soil and moves down into the rocks below as groundwater. Some emerges to feed streams that flow into reservoirs. During its journey, the water enters into a number of physical and chemical processes that naturally treat and filter the water. These natural-service functions that the Catskill forest ecosystem provides to the people of New York were taken for granted until about the 1990s, when it became apparent that the water supply was becoming vulnerable to pollution from uncontrolled development in the watershed.

A particular concern was runoff from buildings and streets, as well as seepage from septic systems that treat wastewater from homes and buildings, partly by allowing it to seep through soil.

The city is also concerned that drilling for natural gas, that uses water and contaminates the groundwater, could damage surface water resources (see Chapter 15). Drilling for natural gas in the watershed supplying New York City was virtual banned in 2010.

The Environmental Protection Agency has warned that unless the water quality improved, New York City would have to build a water treatment plant to filter the water. The cost of such a facility was estimated at $6–8 billion, with an annual operating expense of several hundred million dollars. As an alternative, New York City chose to attempt to improve the water quality at the source. The city built a sewage treatment plant upstate in the Catskill Mountains at a cost of about $2 billion. This seems very expensive but was about one-third the cost of building the treatment plant to filter water. Thus, the city chose to invest in the "natural capital" of the forest, hoping that it will continue its natural service function of providing clean water. It will probably take several decades to tell whether New York City's gamble will work in the long term.[4]

There have been unanticipated benefits from maintaining the Catskill Mountain forest ecosystem. These benefits come from recreational activities, particularly trout fishing, which is a multibillion-dollar enterprise in upstate New York. In addition to the trout fishermen are people wanting to experience the Catskill Mountains through hiking, winter sports, and wildlife observation, such as bird-watching.

You might wonder why the city has been successful in its initial attempt to maintain high-quality water when it owns only about 8% of the land the water comes from. The reason is that the city has offered farmers, homeowners, and other people living in the forest financial incentives to maintain high-quality water resources. Although the amount of money is not large, it is sufficient to provide a sense of stewardship among the landowners, and they are attempting to abide by guidelines that help protect water quality.

New York isn't the only U.S. city that has chosen to protect watersheds to produce clean, high-quality drinking water rather than constructing and maintaining expensive water treatment plants. Others include Boston, Massachusetts; Seattle, Washington; and Portland, Oregon.

The main point of this story is that we mustn't undervalue the power of natural ecosystems to provide a variety of important services, including improved water and air quality.[4]

FIGURE 19.1 The Catskill Mountains of upstate New York are an ecosystem and landscape that provide high-quality water to millions of people in New York City as a natural-service function.

Table 19.3 CATEGORIES OF WATER POLLUTANTS

POLLUTANT CATEGORY	EXAMPLES OF SOURCES	COMMENTS
Dead organic matter	Raw sewage, agricultural waste, urban garbage	Produces biochemical oxygen demand and diseases.
Pathogens	Human and animal excrement and urine	Examples: Recent cholera epidemics in South America and Africa; 1993 epidemic of cryptosporidiosis in Milwaukee, Wisconsin. See discussion of fecal coliform bacteria in Section 22.3.
Drugs	Urban wastewater, painkillers, birth control pills, antidepressants, antibiotics	Pharmaceuticals flushed through our sewage treatment plants are contaminating our rivers and groundwater. Hormone residues or hormone mimickers are thought to be causing genetic problems in aquatic animals.
Organic chemicals	Agricultural use of pesticides and herbicides (Chapter 11); industrial processes that produce dioxin (Chapter 10)	Potential to cause significant ecological damage and human health problems. Many of these chemicals pose hazardous-waste problems (Chapter 23).
Nutrients	Phosphorus and nitrogen from agricultural and urban land use (fertilizers) and wastewater from sewage treatment	Major cause of artificial eutrophication. Nitrates in groundwater and surface waters can cause pollution and damage to ecosystems and people.
Heavy metals	Agricultural, urban, and industrial use of mercury, lead, selenium, cadmium, and so on (Chapter 10)	Example: Mercury from industrial processes that is discharged into water (Chapter 10). Heavy metals can cause significant ecosystem damage and human health problems
Acids	Sulfuric acid (H_2SO_4) from coal and some metal mines; industrial processes that dispose of acids improperly	Acid mine drainage is a major water pollution problem in many coal mining areas, damaging ecosystems and spoiling water resources.
Sediment	Runoff from construction sites, agricultural runoff, and natural erosion	Reduces water quality and results in loss of soil resources.
Heat (thermal pollution)	Warm to hot water from power plants and other industrial facilities	Causes ecosystem disruption (Chapter 10).
Radioactivity	Contamination by nuclear power industry, military, and natural sources (Chapter 17)	Often related to storage of radioactive waste. Health effects vigorously debated (Chapters 10 and 17).

19.2 Biochemical Oxygen Demand (BOD)

Dead organic matter in streams decays. Bacteria carrying out this decay use oxygen. If there is enough bacterial activity, the oxygen in the water available to fish and other organisms can be reduced to the point where they may die. A stream with low oxygen content is a poor environment for fish and most other organisms. A stream with an inadequate oxygen level is considered polluted for organisms that require dissolved oxygen above the existing level.

The amount of oxygen required for biochemical decomposition processes is called the **biological** or **biochemical oxygen demand (BOD)**. BOD is commonly used in water-quality management (Figure 19.2a). It measures the amount of oxygen consumed by microorganisms as they break down organic matter within small water samples, which are analyzed in a laboratory. BOD is routinely measured at discharge points into surface water, such as at wastewater treatment plants. At treatment plants, the BOD of the incoming sewage water from sewer lines is measured, as is water from locations both upstream and downstream of the plant. This allows comparison of upstream, or background, BOD, with the BOD of the water being discharged by the plant.

Dead organic matter—which produces BOD—enters streams and rivers from natural sources (such as dead leaves from a forest) as well as from agricultural runoff and urban sewage. Approximately 33% of all BOD in streams results from agricultural activities. However, urban areas, particularly those with older, combined sewer systems (in which stormwater runoff and urban sewage share the same line), also considerably increase BOD in streams. This is because during times of high flow, when sewage treatment plants are unable to handle the total volume of water, raw sewage mixed with storm runoff overflows and is discharged untreated into streams and rivers.

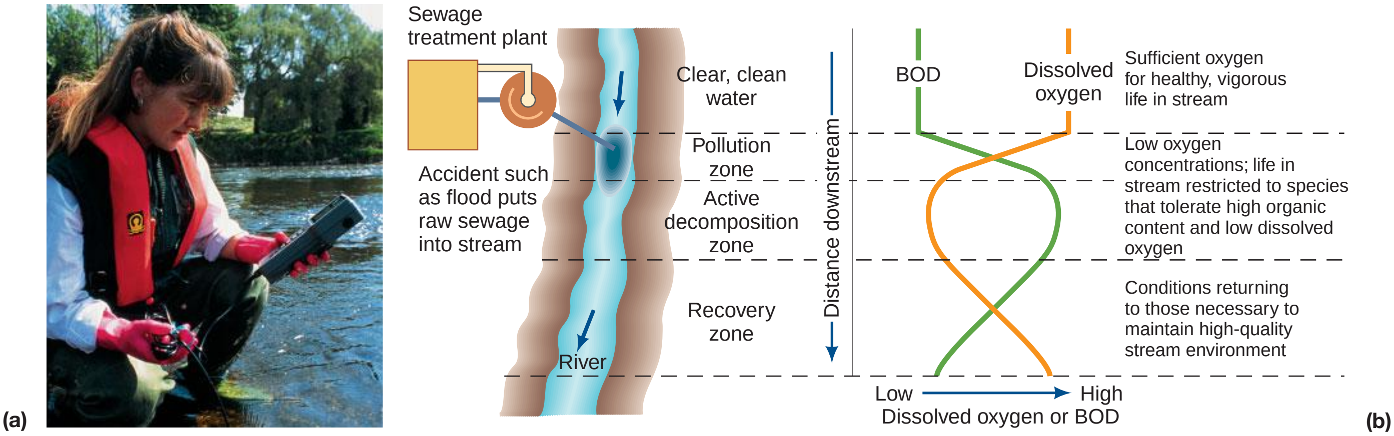


FIGURE 19.2 **(a)** Pollution-control officer measuring oxygen content of the River Severn near Shrewsbury, England. **(b)** The relationship between dissolved oxygen and biochemical oxygen demand (BOD) for a stream after the input of sewage.

When BOD is high, as suggested earlier, the *dissolved oxygen content* of the water may become too low to support life in the water. The U.S. Environmental Protection Agency defines the threshold for a water-pollution alert as a dissolved oxygen content of less than 5 mg/l of water. Figure 19.2b illustrates the effect of high BOD on dissolved oxygen content in a stream when raw sewage is introduced as a result of an accidental spill. Three zones are identified:

1. *A pollution zone*, where a high BOD exists. As waste decomposes, microorganisms use the oxygen, decreasing the dissolved oxygen content of the water.
2. *An active decomposition zone*, where the dissolved oxygen reaches a minimum owing to rapid biochemical decomposition by microorganisms as the organic waste is transported downstream.
3. *A recovery zone*, where dissolved oxygen increases and BOD is reduced because most of the oxygen-demanding organic waste from the input of sewage has decomposed and natural stream processes are replenishing the water's dissolved oxygen. For example, in quickly moving water, the water at the surface mixes with air, and oxygen enters the water.

All streams have some ability to degrade organic waste. Problems result when the stream is overloaded with oxygen-demanding waste, overpowering the stream's natural cleansing function.

19.3 Waterborne Disease

As mentioned earlier, the primary water-pollution problem in the world today is the lack of clean drinking water. Each year, particularly in less-developed countries, several billion people are exposed to waterborne diseases whose effects vary in severity from an upset stomach to death. As recently as the early 1990s, epidemics of cholera, a serious waterborne disease, caused widespread suffering and death in South America.

In the United States, we tend not to think much about waterborne illness. Although historically epidemics of waterborne disease killed thousands of people in U.S. cities, such as Chicago, public-health programs have largely eliminated such epidemics by treating drinking water to remove disease-carrying microorganisms and not allowing sewage to contaminate drinking-water supplies. As we will see, however, North America is not immune to **outbreaks**—or sudden occurrences—of waterborne disease.

Fecal Coliform Bacteria

Because it is difficult to monitor disease-carrying organisms directly, we use the count of **fecal coliform bacteria** as a standard measure and indicator of disease potential. The presence of fecal coliform bacteria in water indicates that fecal material from mammals or birds is present, so organisms that cause waterborne diseases may be present as well. Fecal coliform bacteria are usually (but not always) harmless bacteria that normally inhabit the intestines of all animals, including humans, and are present in all their waste. The EPA's threshold for swimming water is not more than 200 cells of fecal coliform bacteria per 100 ml of water; if fecal coliform is above the threshold level, the water is considered unfit for swimming (Figure 19.3). Water with *any* fecal coliform bacteria is unsuitable for drinking.

One type of fecal coliform bacteria, *Escherichia coli*, or *E. coli 0157*, has caused human illness and death. In the U.S., there are about 73,000 cases and 60 deaths per year from *E. coli 0157*. Outbreaks have resulted from eating contaminated meat (fecal transmission from humans and other animals) and drinking contaminated juices or water.[7-10] Table 19.4 lists some recent outbreaks of disease resulting from *E. coli 0157*.

FIGURE 19.3 This beach in Southern California is occasionally closed as a result of contamination by bacteria.

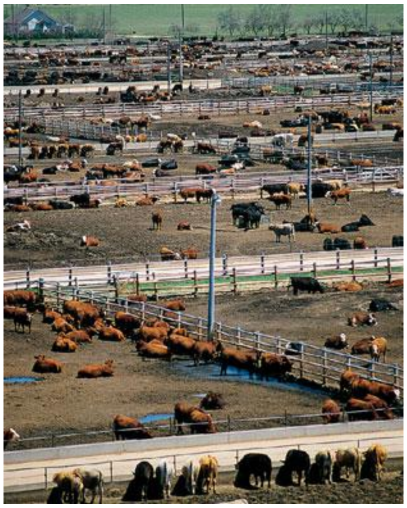


FIGURE 19.4 Cattle feedlot in Colorado. High numbers of cattle in small areas have the potential to pollute both surface water and groundwater because of runoff and infiltration of urine.

19.4 Nutrients

Two important nutrients that cause water-pollution problems are phosphorus and nitrogen, and both are released from sources related to land use. Stream waters on forested land have the lowest concentrations of phosphorus and nitrogen because forest vegetation efficiently removes phosphorus and nitrogen. In urban streams, concentrations of these nutrients are greater because of fertilizers, detergents, and products of sewage treatment plants. Often, however, the highest concentrations of phosphorus and nitrogen are found in agricultural areas, where the sources are fertilized farm fields and feedlots (Figure 19.4). Over 90% of all nitrogen added to the environment by human activity comes from agriculture.

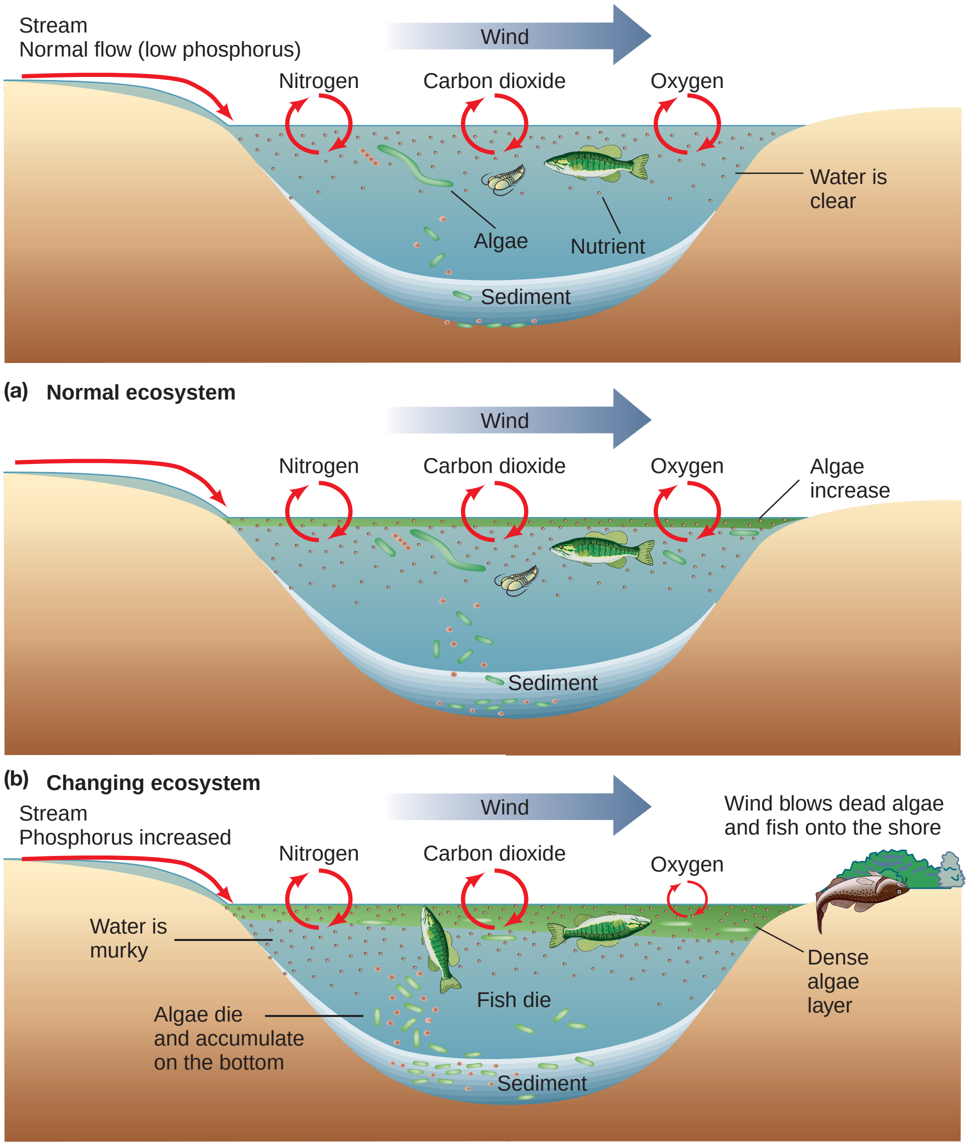
Eutrophication

Eutrophication is the process by which a body of water develops a high concentration of nutrients, such as nitrogen and phosphorus (in the forms of nitrates and phosphates). The nutrients increase the growth of aquatic plants in general, as well as production of photosynthetic blue-green bacteria and algae. Algae may form surface mats that shade the water and block light to algae below the surface, greatly reducing photosynthesis. The bacteria and algae die, and as they decompose, BOD increases, reducing the water's oxygen content, sometimes to the point where other organisms, such as fish, will die.[11, 12] They die not from phosphorus poisoning but from a chain of events that started with

Table 19.4 RECENT OUTBREAKS OF *E. COLI 0157* INFECTIONS[1]

YEAR	WHERE	SOURCE	COMMENT
1993	Washington State (fast-food restaurant)	Meat	5 children died; several hundred illnesses
1998	Georgia (water park)	Water in park pools	26 illnesses in children
1998	Town in Wyoming	Water supply	1 death
2000	Walkerton, Canada	Water supply	5 deaths
2006	23 states	Spinach	5 deaths; over 100 illnesses
2007	Hawaii (restaurant)	Lettuce	several illnesses (mostly tourists)
2009	Across the U.S.	Peanut butter	several deaths; several hundred illnesses
2009	29 states	Raw cookie dough	65 illnesses
2010	Several states, especially California, Colorado and N. Carolina	Raw eggs	at least 1,500 illnesses; 500 million eggs recalled

[a] *E. coli* 0157, a strain of *E. coli* bacteria, has been responsible for many human illnesses and deaths. *E. coli 0157* produces strong toxins in humans that may lead to bloody diarrhea, dehydration, kidney failure, and death.



(a) Normal ecosystem

(b) Changing ecosystem

(c) Degraded ecosystem

FIGURE 19.5 The eutrophication of a lake. **(a)** In an oligotrophic, or low-nutrient, lake, the abundance of green algae is low, the water clear. **(b)** Phosphorus is added to streams and enters the lake. Algae growth is stimulated, and a dense layer forms. **(c)** The algae layer becomes so dense that the algae at the bottom die. Bacteria feed on the dead algae and use up the oxygen. Finally, fish die from lack of oxygen.

the input of phosphorus and affected the whole ecosystem. The unpleasant effects result from the interactions among different species, the effects of the species on chemical elements in their environment, and the condition of the environment (the body of water and the air above it). This is what we call an **ecosystem effect**.

The process of eutrophication of a lake is shown in Figure 19.5. A lake that has a naturally high concentration of the chemical elements required for life is called a *eutrophic lake*. A lake with a relatively low concentration of chemical elements required by life is called an *oligotrophic lake*. The water in oligotrophic lakes is clear and pleasant for swimmers and boaters and has a relatively low abundance of life. Eutrophic lakes have an abundance of life, often with mats of algae and bacteria and murky, unpleasant water.

When eutrophication is accelerated by human processes that add nutrients to a body of water, we say that **cultural eutrophication** is occurring. Problems associated with the artificial eutrophication of bodies of water are not restricted to lakes (see A Closer Look 19.2). In recent years, concern has grown about the outflow of sewage from urban areas into tropical coastal waters and cultural eutrophication on coral reefs.[13, 14] For example, parts of the famous Great Barrier Reef of Australia, as well as some reefs that fringe the Hawaiian Islands, are being damaged by eutrophication.[15, 16] The damage to corals occurs as nutrient input stimulates algal growth on the reef, which smothers the coral.

The solution to artificial eutrophication is fairly straightforward and involves ensuring that high concentrations of nutrients from human sources do not enter lakes and other bodies of water. This can be accomplished by using phosphate-free detergents, controlling nitrogen-rich runoff from agricultural and urban lands, disposing of or reusing treated wastewater, and using more advanced water treatment methods, such as special filters and chemical treatments that remove more of the nutrients.

A CLOSER LOOK 19.2

Cultural Eutrophication in the Gulf of Mexico

Each summer, a so-called dead zone develops off the nearshore environment of the Gulf of Mexico, south of Louisiana. The zone varies in size from about 13,000 to 18,000 km^2 (5,000 to 7,000 mi^2), an area about the size of the small country of Kuwait or the state of New Jersey. Within the zone, bottom water generally has low concentrations of dissolved oxygen (less than 2 mg/l; a water-pollution alert occurs if the concentration of dissolved oxygen is less than 5 mg/l). Shrimp and fish can swim away from the zone, but bottom dwellers such as shellfish, crabs, and snails are killed. Nitrogen is believed to be the most significant cause of the dead zone (Figure 19.6).

The low concentration of oxygen occurs because the nitrogen causes cultural eutrophication. Algae bloom, and as the algae die and sink, their decomposition depletes the oxygen in the water. The source of nitrogen is believed to be in one of the richest, most productive agricultural regions of the world—the Mississippi River drainage basin.

The Mississippi River drains about 3 million km^2, which is about 40% of the land area of the lower 48 states. The use of nitrogen fertilizers in that area greatly increased beginning in the mid-20th century but leveled off in the 1980s and 1990s. The level of nitrogen in the river has also leveled off, suggesting that the dead zone may have reached its maximum size. This gives us time to study the cultural eutrophication problem carefully and make sound decisions to reduce or eliminate it.

We can partially reduce the amount of nitrogen (nitrates) reaching the Gulf of Mexico via the Mississippi River if we do the following:[12]

- Use fertilizers more effectively and efficiently.
- Restore and create river wetlands between farm fields and streams and rivers, particularly in areas known to contribute high amounts of nitrogen. The wetland plants use nitrogen, lowering the amount that enters the river.
- Implement nitrogen-reduction processes at wastewater treatment plants for towns, cities, and industrial facilities.
- Implement better flood control in the upper Mississippi River to confine floodwaters to floodplains, where nitrogen can be used by riparian vegetation.

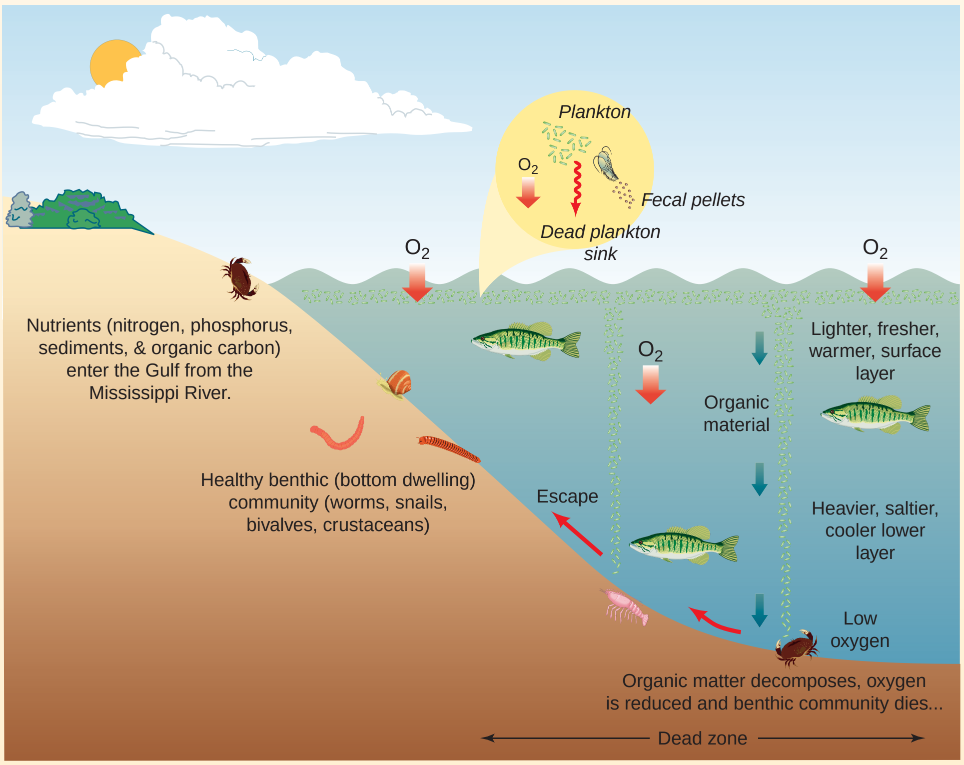


FIGURE 19.6 Idealized drawing showing some of the processes in the dead zone. Low oxygen from cultural eutrophication produces the dead zone. (*Source*: Modified after U.S. Environmental Protection Agency, www.epa.gov, accessed May, 30, 2005).

- Divert floodwater from the Mississippi to backwaters and coastal wetlands of the Mississippi River Delta. At present, levees in the delta push river waters directly into the gulf. Plants in coastal wetlands will use the nitrogen, reducing the concentration that reaches the Gulf of Mexico.

Better agricultural practices could reduce the amount of nitrogen reaching the Mississippi by up to 20%. But this would require reducing fertilizer use by about 20%, which farmers say would harm productivity. Still, restoring and creating river wetlands and riparian forests hold the promise of reducing nitrogen input to the river by up to 40%. This would require some combination of about 10 million hectares (24 million acres) of wetlands and forest, which is about 3.4% of the Mississippi River Basin.[11] That is a lot of land!

There is no easy solution to cultural eutrophication in the Gulf of Mexico. Clearly, however, we need to reduce the amount of nitrogen entering the Gulf. Also needed is a more detailed understanding of the nitrogen cycle within the Mississippi River basin and Delta. Gaining this understanding will require monitoring nitrogen and developing mathematical models of sources, sinks, and rates of nitrogen transfer. With an improved understanding of the nitrogen cycle, a management strategy to reduce or eliminate the dead zone can be put in place.

The dead zone in the Gulf of Mexico is not unique in the world. Other dead zones exist offshore of Europe, China, Australia, South America, and the northeastern United States. In all, about 150 dead zones in the oceans of the world have been observed. Most are much smaller than the zone in the Gulf of Mexico.

As with the Gulf, the other dead zones are due to oxygen depletion resulting from nitrogen, mostly from agricultural runoff. A few result from industrial pollution or runoff from urban areas, especially untreated sewage.

19.5 Oil

Oil discharged into surface water—usually in the ocean but also on land and in rivers—has caused major pollution problems. Several large oil spills from underwater oil drilling have occurred in recent years (for example the 2010 spill in the Gulf of Mexico, discussed in detail in Chapter 24). However, although spills make headlines, normal shipping activities probably release more oil over a period of years than is released by the occasional spill. The cumulative impacts of these releases are not well known.

Some of the best-known oil spills are caused by tanker accidents. On March 24, 1989, the supertanker *Exxon Valdez* ran aground on Bligh Reef south of Valdez in Prince William Sound, Alaska. Alaskan crude oil that had been delivered to the *Valdez* through the Trans-Alaska Pipeline poured out of the vessel's ruptured tanks at about 20,000 barrels per hour. The tanker was loaded with about 1.2 million barrels of oil, and about 250,000 barrels (11 million gal) entered the sound. The spill could have been larger than it was, but fortunately some of the oil in the tanker was offloaded (pumped out) into another vessel. Even so, the *Exxon Valdez* spill produced an environmental shock that resulted in passage of the Oil Pollution Act of 1990 and a renewed evaluation of cleanup technology.

The long-term effects of large oil spills are uncertain. We know that the effects can last several decades; toxic levels of oil have been identified in salt marshes 20 years after a spill.[17, 18]

19.6 Sediment

Sediment consisting of rock and mineral fragments—ranging from gravel particles greater than 2 mm in diameter to finer sand, silt, clay, and even finer colloidal particles—can produce a *sediment pollution* problem. In fact, by volume and mass, sediment is our greatest water pollutant. In many areas, it chokes streams; fills lakes, reservoirs, ponds, canals, drainage ditches, and harbors; buries vegetation; and generally creates a nuisance that is difficult to remove. Sediment pollution is a twofold problem: It results from erosion, which depletes a land resource (soil) at its site of origin (Figure 19.7), and it reduces the quality of the water resource it enters.[19]

Many human activities affect the pattern, amount, and intensity of surface water runoff, erosion, and sedimentation. Streams in naturally forested or wooded areas may be nearly stable, with relatively little excessive erosion or sedimentation. However, converting forested land to agriculture generally increases the runoff and sediment yield or erosion of the land. Applying soil-conservation procedures to farmland can minimize but not eliminate soil loss. The change from agricultural, forested, or rural land to highly urbanized land has even more dramatic effects. But although the construction phase of urbanization can produce large quantities of sediment, sediment production and soil erosion can be minimized by on-site erosion control.[20]

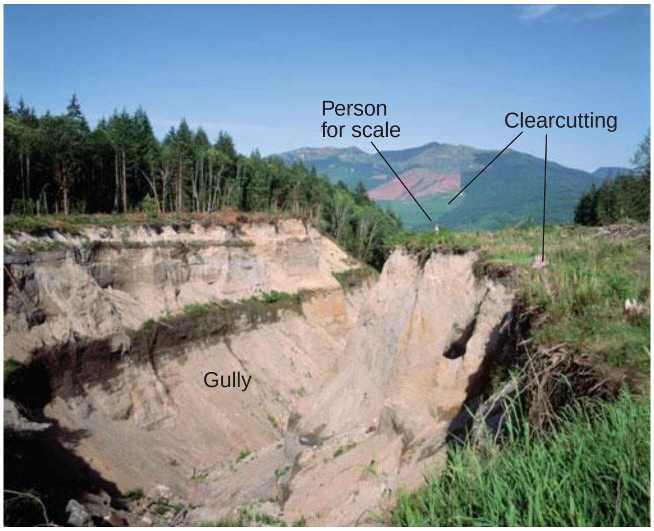


FIGURE 19.7 Massive erosion has produced this large, canyon-size gully, near Rockport Washington (see person in white, looks like a dot, at the top of gully). Note area of clearcutting (timber harvesting on right) and on mountain in background. Clearcutting is a practice that may result in accelerated soil erosion.

19.7 Acid Mine Drainage

Acid mine drainage is water with a high concentration of sulfuric acid (H_2SO_4) that drains from mines—mostly coal mines but also metal mines (copper, lead, and zinc). Coal and the rocks containing coal are often associated with a mineral known as fool's gold or pyrite (FeS_2), which is iron sulfide. When the pyrite, which may be finely disseminated in the rock and coal, comes into contact with oxygen and water, it weathers. A product of the chemical weathering is sulfuric acid. In addition, pyrite is associated with metallic sulfide deposits, which, when weathered, also produce sulfuric acid. The acid is produced when surface water or shallow groundwater runs through or moves into and out of mines or tailings (Figure 19.8). If the acidic water runs off to a natural stream, pond, or lake, significant pollution and ecological damage may result. The acidic water is toxic to the plants and animals of an aquatic ecosystem; it damages biological productivity, and fish and other aquatic life may die. Acidic water can also seep into and pollute groundwater.

Acid mine drainage is produced by complex geochemical and microbial reactions. The general equation is as follows:

$$4\,FeS_2 + 15\,O_2 + 14\,H_2O \rightarrow 4\,Fe(OH)_3 + 8\,H_2SO_4$$

Pyrite + Oxygen + Water → Ferric Hydroxide + Sulfuric Acid

Acid mine drainage is a significant water-pollution problem in Wyoming, Indiana, Illinois, Kentucky, Tennessee, Missouri, Kansas, and Oklahoma, and is probably the most significant water-pollution problem in West Virginia, Maryland, Pennsylvania, Ohio, and Colorado. The total impact is significant because thousands of kilometers of streams have been damaged.

Even abandoned mines can cause serious problems. Subsurface mining for sulfide deposits containing lead and zinc began in the tristate area of Kansas, Oklahoma, and Missouri in the late 19th century and ended in some areas in the 1960s. When the mines were operating, they were kept dry by pumping out the groundwater that seeped in. However, since the mining ended, some of them have flooded and overflowed into nearby creeks, polluting the creeks with acidic water. The problem was so severe in the Tar Creek area of Oklahoma that it was at one time designated by the U.S. Environmental Protection Agency as the nation's worst hazardous-waste site.

One solution being used in Tar Creek and other areas is passive treatment methods that use naturally occurring chemical and/or biological reactions in controlled environments to treat acid mine drainage. The simplest and least expensive method is to divert acidic water to an open limestone channel, where it reacts with crushed limestone and the acid is neutralized. A general reaction that neutralizes the acid is

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2$$

Sulfuric Acid + Calcium Carbonate (crushed limestone) → Calcium Sulfate + Water + Carbon Dioxide

Another solution is to divert the acidic water to a bioreactor (an elongated trough) containing sulfate-reducing bacteria and a bacteria nutrient to encourage bacterial growth. The sulfate-reducing bacteria are held in cells that have a honeycomb structure, forcing the acidic water to follow a tortuous path through the bacteria-laden cells of the reactor. Complex biochemical reactions between the acidic

FIGURE 19.8 Aerial view of an acid mine drainage holding pond adjacent to an iron mine (located in the mountains of southwestern Colorado).

water and bacteria in the reactor produce metal sulfides and in the process reduce the sulfuric acid content of the water. Both methods result in cleaner water with a lower concentration of acid being released into the environment.

19.8 Surface-Water Pollution

Pollution of surface water occurs when too much of an undesirable or harmful substance flows into a body of water, exceeding that body of water's natural ability to remove it, dilute it to a harmless concentration, or convert it to a harmless form.

Water pollutants, like other pollutants, are categorized as being emitted from point or nonpoint sources (see Chapter 10). **Point sources** are distinct and confined, such as pipes from industrial and municipal sites that empty into streams or rivers (Figure 19.9). 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. As mentioned earlier, such systems combine stormwater flow with municipal wastewater. During heavy rains, urban storm runoff may exceed the capacity of the sewer system, causing it to overflow and deliver pollutants to nearby surface waters.

FIGURE 19.9 This pipe is a point source of chemical pollution from an industrial site entering a river in England.

Nonpoint sources, such as runoff, are diffused and intermittent and are influenced by factors such as land use, climate, hydrology, topography, native vegetation, and geology. Common urban nonpoint sources include runoff from streets or fields; such runoff contains all sorts of pollutants, from heavy metals to chemicals and sediment. Rural sources of nonpoint pollution are generally associated with agriculture, mining, or forestry. Nonpoint sources are difficult to monitor and control.

Reducing Surface-Water Pollution

From an environmental view, two approaches to dealing with surface-water pollution are (1) to reduce the sources and (2) to treat the water to remove pollutants or convert them to forms that can be disposed of safely. Which option is used depends on the specific circumstances of the pollution problem. Reduction at the source is the environmentally preferable way of dealing with pollutants. For example, air-cooling towers, rather than water-cooling towers, may be used to dispose of waste heat from power plants, thereby avoiding thermal pollution of water. The second method—water treatment—is used for a variety of pollution problems. Water treatments include chlorination to kill microorganisms such as harmful bacteria, and filtering to remove heavy metals.

There is a growing list of success stories in the treatment of water pollution. One of the most notable is the cleanup of the Thames River in Great Britain. For centuries, London's sewage had been dumped into that river, and there were few fish to be found downstream in the estuary. In recent decades, however, improved water treatment has led to the return of a number of species of fish, some not seen in the river for centuries.

Many large cities in the United States—such as Boston, Miami, Cleveland, Detroit, Chicago, Portland, and Los Angeles—grew on the banks of rivers, but the rivers were often nearly destroyed by pollution and concrete. Today, there are grassroots movements all around the country dedicated to restoring urban rivers and adjacent lands as greenbelts, parks, and other environmentally sensitive developments. For example, the Cuyahoga River in Cleveland, Ohio, was so polluted by 1969 that sparks from a train ignited oil-soaked wood in the river, setting the surface of the river on fire! The burning of an American river became a symbol for a growing environmental consciousness. The Cuyahoga River today is cleaner and no longer flammable—from Cleveland to Akron, it is a beautiful greenbelt (Figure 19.10). The greenbelt changed part of the river from a sewer into a valuable public resource and focal point for economic and environmental renewal.[21] However, in downtown Cleveland and Akron, the river remains an industrial stream, and parts remain polluted.

FIGURE 19.10 The Cuyahoga River (lower left) flows toward Cleveland, Ohio, and the Erie Canal (lower right) is in the Cuyahoga National Park. The skyline is that of industrial Cleveland.

Two of the newer techniques are nanotechnology and urban-runoff naturalization. **Nanotechnology** uses extremely small material particles (10^{-9}m size, about 100,000 times thinner than human hair) designed for a number of purposes. Some nano particles can capture heavy metals such as lead, mercury, and arsenic from water. The nano particles have a tremendous surface area to volume. One cubic centimeter of particles has a surface area exceeding a football field and can take up over 50% of its weight in heavy metals.[22]

FIGURE 19.12 Bioswales collect runoff from Manzaneta Village Dormitory Complex at the University of California, Santa Barbara. **(a)** Plants in bioswales **(b)** help filter water and remove nutrients, reducing cultural eutrophication.

Urban-runoff naturalization is an emerging bioengineering technology to treat urban runoff before it reaches streams, lakes, or the ocean. One method is to create a "closed-loop" local landscape that does not allow runoff to leave a property. Plants may be located as "rain gardens" below downspouts, and parking-lot drainage is directed to plants instead of the street (Figure 19.11).[23] Runoff from five large building complexes such as Manzaneta Village at the University of California, Santa Barbara, can be directed to engineered wetlands (bioswales) where wetland plants remove contaminants before water is discharged into the campus lagoon and then the ocean. Removing nutrients has helped reduce cultural eutrophication of the lagoon (Figure 19.12).

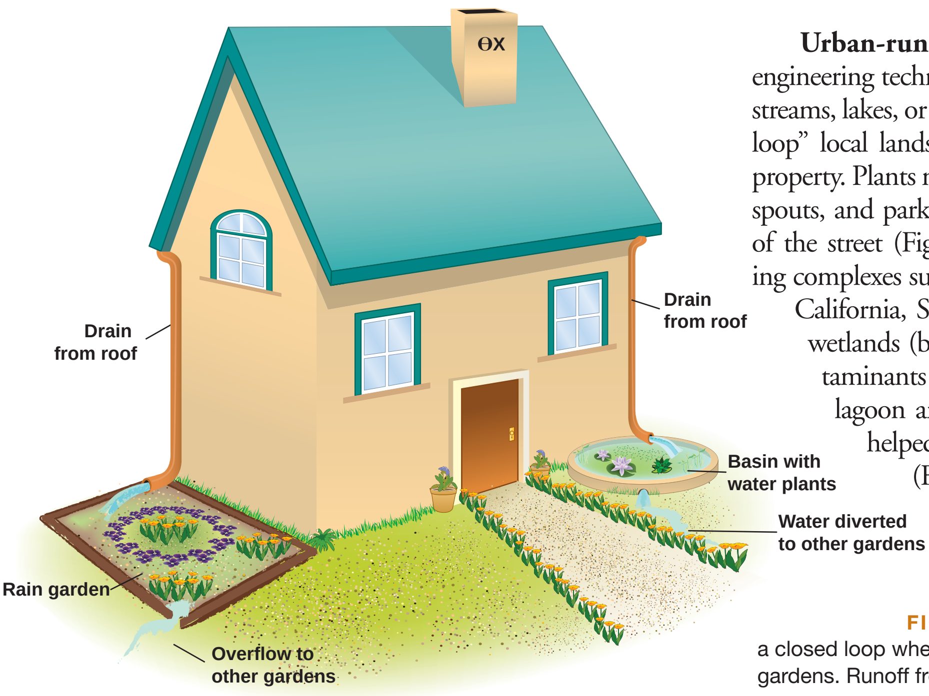


FIGURE 19.11 Water from roof runoff is part of a closed loop where water remains on the site and is used in rain gardens. Runoff from parking areas is diverted to other gardens.

19.9 Groundwater Pollution

Approximately half of all people in the United States today depend on groundwater as their source of drinking water. (Water for domestic use in the United States is discussed in A Closer Look 19.3.) People have long believed that groundwater is, in general, pure and safe to drink. In fact, however, groundwater can be easily polluted by any one of several sources (see Table 19.1), and the pollutants, though very toxic, may be difficult to recognize. (Groundwater processes were discussed in Section 19.1, and you may wish to review them.)

In the United States today, only a small portion of the groundwater is known to be seriously contaminated. However, as mentioned earlier, the problem may become worse as human population pressure on water resources increases. Our realization of the extent of the problem is growing as the testing of groundwater becomes more common. For example, Atlantic City and Miami are two eastern cities threatened by polluted groundwater that is slowly migrating toward their wells.

It is estimated that 75% of the 175,000 known waste-disposal sites in the United States may be spewing plumes of hazardous chemicals that are migrating into groundwater resources. Because many of the chemicals are toxic or are suspected carcinogens, it appears that we have inadvertently been conducting a large-scale experiment on how people are affected by chronic low-level exposure to potentially harmful chemicals. The final results of the experiment will not be known for many years.[24]

The hazard presented by a particular groundwater pollutant depends on several factors, including the concentration or toxicity of the pollutant in the environment and the degree of exposure of people or other organisms to the pollutants.[25] (See the section on risk assessment in Chapter 10.)

Principles of Groundwater Pollution: An Example

Some general principles of groundwater pollution are illustrated by an example. Pollution from leaking underground gasoline tanks belonging to automobile service stations is a widespread environmental problem that no one thought very much about until only a few years ago. Underground tanks are now strictly regulated. Many thousands of old, leaking tanks have been removed, and the surrounding soil and groundwater have been treated to remove the gasoline. Cleanup can be a very expensive process, involving removal and disposal of soil (as a hazardous waste) and treatment of the water using a process known as vapor extraction (Figure 19.13). Treatment may also be accomplished underground by microorganisms that consume the gasoline. This is known as **bioremediation** and is much less expensive than removal, disposal, and vapor extraction.

Pollution from leaking buried gasoline tanks emphasizes some important points about groundwater pollutants:

- Some pollutants, such as gasoline, are lighter than water and thus float on the groundwater.
- Some pollutants have multiple phases: liquid, vapor, and dissolved. Dissolved phases chemically combine with the groundwater (e.g., salt dissolves into water).

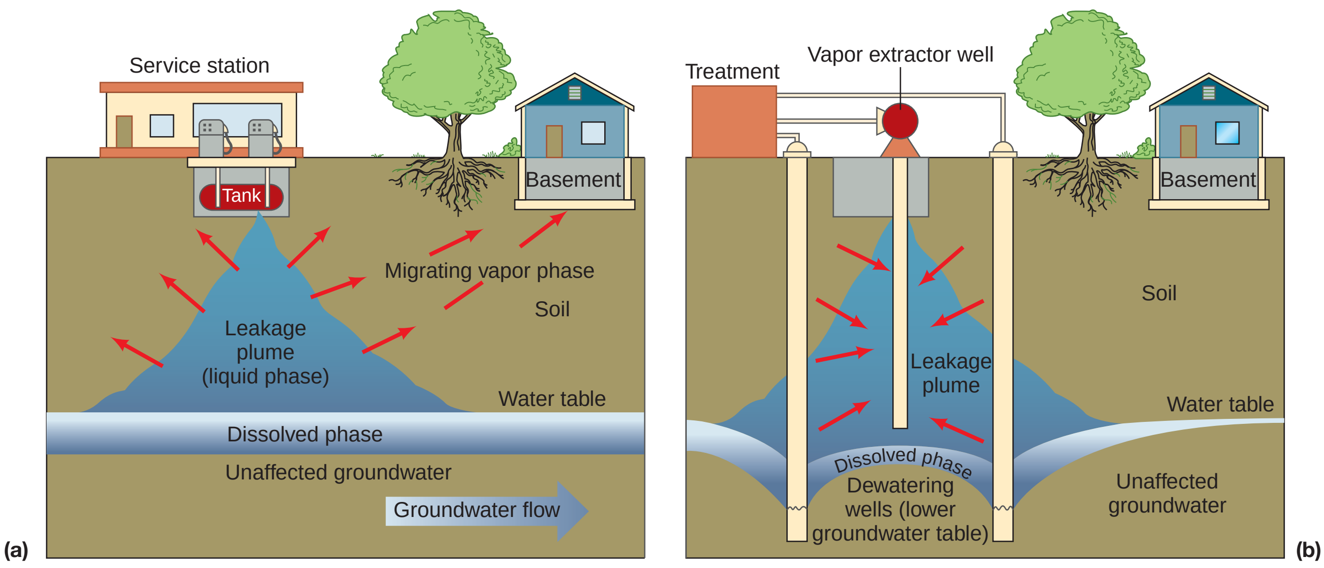


FIGURE 19.13 Diagram illustrating **(a)** a leak from a buried gasoline tank and **(b)** possible remediation using a vapor extractor system. Notice that the liquid gasoline and the vapor from the gasoline are above the water table; a small amount dissolves into the water. All three phases of the pollutant (liquid, vapor, and dissolved) float on the denser groundwater. The extraction well takes advantage of this situation. The function of the dewatering wells is to pull the pollutants in where the extraction is most effective. (*Source*: Courtesy of the University of California Santa Barbara Vadose Zone Laboratory and David Springer.)

- Some pollutants are heavier than water and sink or move downward through groundwater. Examples of sinkers include some particulates and cleaning solvents. Pollutants that sink may become concentrated deep in groundwater aquifers.
- The method used to treat or eliminate a water pollutant must take into account the physical and chemical properties of the pollutant and how these interact with surface water or groundwater. For example, the extraction well for removing gasoline from a groundwater resource (Figure 19.13) takes advantage of the fact that gasoline floats on water.
- Because cleanup or treatment of water pollutants in groundwater is very expensive, and because undetected or untreated pollutants may cause environmental damage, the emphasis should be on preventing pollutants from entering groundwater in the first place.

Groundwater pollution differs in several ways from surface-water pollution. Groundwater often lacks oxygen, a situation that kills aerobic types of microorganisms (which require oxygen-rich environments) but may provide a happy home for anaerobic varieties (which live in oxygen-deficient environments). The breakdown of pollutants that occurs in the soil and in material a meter or so below the surface does not occur readily in groundwater. Furthermore, the channels through which groundwater moves are often very small and variable. Thus, the rate of movement is low in most cases, and the opportunity for dispersion and dilution of pollutants is limited.

Long Island, New York

Another example—that of Long Island, New York—illustrates several groundwater pollution problems and how they affect people's water supply. Two counties on Long Island, New York (Nassau and Suffolk), with a population of several million people, depend entirely on groundwater. Two major problems with the groundwater in Nassau County are intrusion of saltwater and shallow-aquifer contamination.[27] Saltwater intrusion, where subsurface salty water migrates to wells being pumped, is a problem in many coastal areas of the world. The general movement of groundwater under natural conditions for Nassau County is illustrated in Figure 19.14. Salty groundwater is restricted from migrating inland by the large wedge of freshwater moving beneath the island.

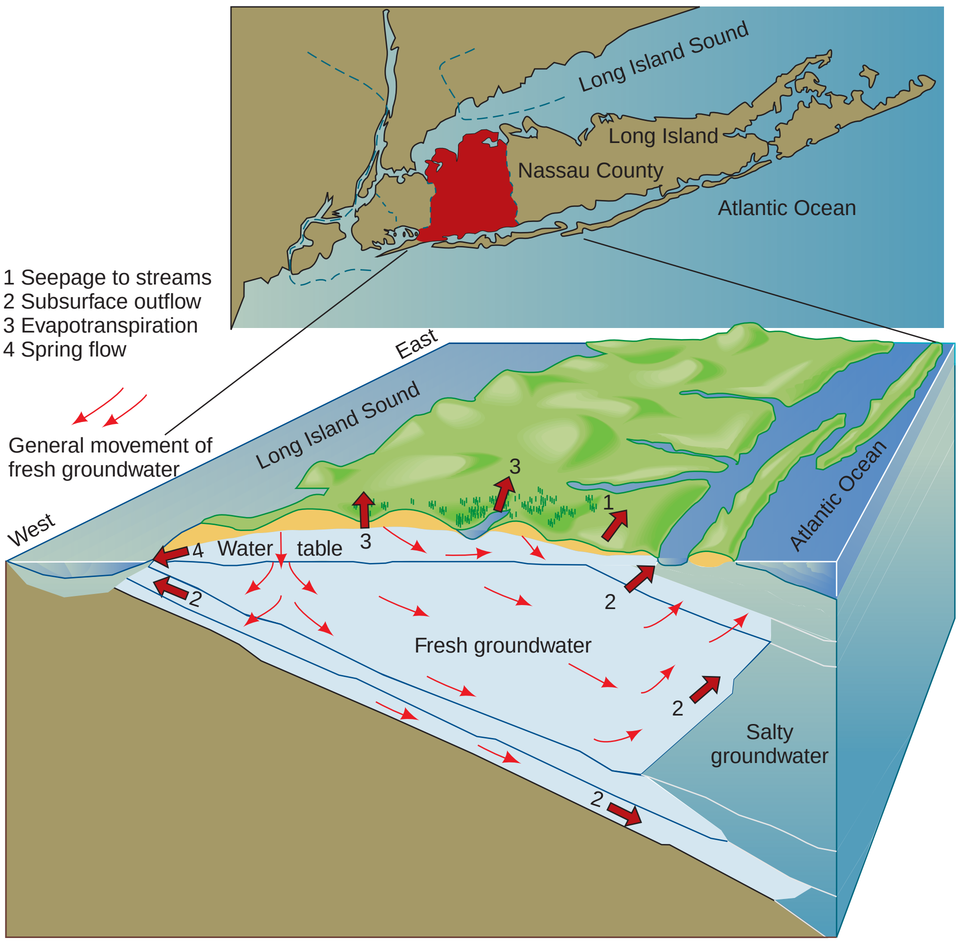


FIGURE 19.14 The general movement of fresh groundwater for Nassau County, Long Island. (*Source*: G.L. Foxworth, Nassau County, Long Island, New York, "Water Problems in Humid County," in G.D. Robinson and A.M. Spieke, eds., *Nature to Be Commanded*, U.S. Geological Survey Professional Paper 950, 1978, pp. 55–68.)

A CLOSER LOOK 19.3

Water for Domestic Use: How Safe Is It?

Water for domestic use in the United States is drawn from surface waters and groundwater. Although some groundwater sources are high quality and need little or no treatment, most are treated to conform to national drinking water standards (revisit Table 19.2).

Before treatment, water is usually stored in reservoirs or special ponds. Storage allows for solids, such as fine sediment and organic matter, to settle out, improving the clarity of water. The water is then run through a water plant, where it is filtered and chlorinated before it is distributed to individual homes. Once in people's homes, it may be further treated. For example, many people run their tap water through readily available charcoal filters before using it for drinking and cooking.

A growing number of people prefer not to drink tap water and instead drink bottled water. As a result, bottled water has become a multibillion-dollar industry. A lot of bottled water is filtered tap water delivered in plastic containers, and health questions have arisen regarding toxins leaching from the plastic, especially if bottles are left in the sun. Hot plastics can leach many more chemicals into the water than cool plastic. In any case, the plastic bottles should be used only once, then recycled.[26]

Some people prefer not to drink water that contains chlorine or that runs through metal pipes. Furthermore, water supplies vary in clarity, hardness (concentration of calcium and magnesium), and taste; and the water available locally may not be to some people's liking. A common complaint about tap water is a chlorine taste, which may be detectable at chlorine concentrations as low as 0.2–0.4 mg/l. People may also fear contamination by minute concentrations of pollutants.

The drinking water in the United States is among the safest in the world. There is no doubt that treating water with chlorine has nearly eliminated waterborne diseases, such as typhoid and cholera, which previously caused widespread suffering and death in the developed world and still do in many parts of the world. However, we need to know much more about the long-term effects of exposure to low concentrations of toxins in our drinking water. How safe is the water in the United States? It's much safer than it was 100 years ago, but low-level contamination (below what is thought dangerous) of organic chemicals and heavy metals is a concern that requires continued research and evaluation.

Notice also that the aquifers are layered, with those closest to the surface being the most salty.

In spite of the huge quantities of water in Nassau County's groundwater system, intensive pumping in recent years has lowered water levels by as much as 15 m (50 ft) in some areas. As groundwater is removed near coastal areas, the subsurface outflow to the ocean decreases, allowing saltwater to migrate inland. Saltwater intrusion has become a problem for south shore communities, which now must pump groundwater from a deeper aquifer, below and isolated from the shallow aquifers that have saltwater-intrusion problems.

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 de-ice 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.[27] Landfills for municipal solid waste have been a significant source of shallow-aquifer pollution on Long Island because pollutants (garbage) placed on sandy soil can quickly enter shallow groundwater. For this reason, most Long Island landfills were closed in the last two decades.

19.10 Wastewater Treatment

Water used for industrial and municipal purposes is often degraded during use by the addition of suspended solids, salts, nutrients, bacteria, and oxygen-demanding material. In the United States, by law, these waters must be treated before being released back into the environment.

Wastewater treatment—sewage treatment—costs about $20 billion per year in the United States, and the cost keeps rising, but it will continue to be big business. Conventional wastewater treatment includes septic-tank disposal systems in rural areas and centralized wastewater treatment plants in cities. Recent, innovative approaches include applying wastewater to the land and renovating and reusing wastewater. We discuss the conventional methods in this section and some newer methods in later sections.

Septic-Tank Disposal Systems

In many rural areas, no central sewage systems or wastewater treatment facilities are available. As a result, individual septic-tank disposal systems, not connected to sewer systems, continue to be an important method of sewage disposal in rural areas as well as outlying areas of cities. Because not all land is suitable for a septic-tank disposal system, an evaluation of each site is required by law before a permit can be issued. An alert buyer should make sure that the site is satisfactory for septic-tank disposal before purchasing property in a rural setting or on the fringe of an urban area where such a system is necessary.

The basic parts of a septic-tank disposal system are shown in Figure 19.15. The sewer line from the house leads to an underground septic tank in the yard. The tank is designed to separate solids from liquid, digest (biochemically change) and store organic matter through a period of detention, and allow the clarified liquid to discharge into the drain field (absorption field) from a piping system through which the treated sewage seeps into the surrounding soil. As the wastewater moves through the soil, it is further treated by the natural processes of oxidation and filtering. By the time the water reaches any freshwater supply, it should be safe for other uses.

Sewage drain fields may fail for several reasons. The most common causes are failure to pump out the septic tank when it is full of solids, and poor soil drainage, which allows the effluent to rise to the surface in wet weather. When a septic-tank drain field does fail, pollution of groundwater and surface water may result. Solutions to septic-system problems include siting septic tanks on well-drained soils, making sure systems are large enough, and practicing proper maintenance.

Wastewater Treatment Plants

In urban areas, wastewater is treated at specially designed plants that accept municipal sewage from homes, businesses, and industrial sites. The raw sewage is delivered to the plant through a network of sewer pipes. Following treatment, the wastewater is discharged into the surface-water environment (river, lake, or ocean) or, in some limited cases, used for another purpose, such as crop irrigation. The main purpose of standard treatment plants is to break down and reduce the BOD and kill bacteria with chlorine. A simplified diagram of the wastewater treatment process is shown in Figure 19.16.

Wastewater treatment methods are usually divided into three categories: **primary treatment**, **secondary treatment**, and **advanced wastewater treatment**. Primary and secondary treatments are required by federal law for all municipal plants in the United States. However, treatment plants may qualify for a waiver exempting them from secondary treatment if installing secondary treatment facilities poses an excessive financial burden. Where secondary treatment is not sufficient to protect the quality of the surface water into which the treated water is discharged—for example, a river with endangered fish species that must be protected—advanced treatment may be required.[28]

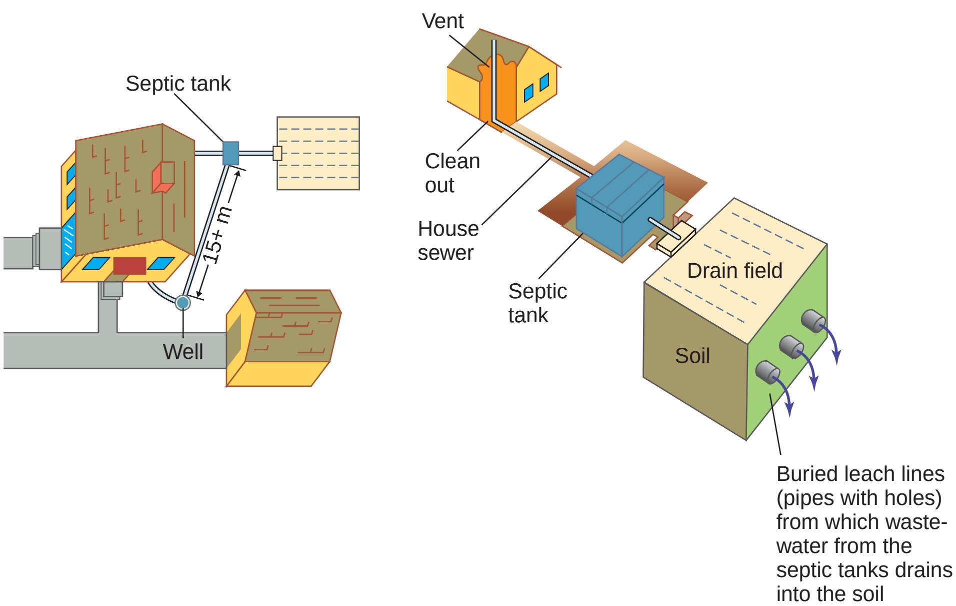


FIGURE 19.15 Septic-tank sewage system and location of the drain field with respect to the house and well. (*Source*: Based on Indiana State Board of Health.)

Primary Treatment

Incoming raw sewage enters the plant from the municipal sewer line and first passes through a series of screens to remove large floating organic material. The sewage next enters the "grit chamber," where sand, small stones, and grit are removed and disposed of. From there, it goes to the primary sedimentation tank, where particulate matter settles out to form sludge. Sometimes, chemicals are used to help the settling process. The sludge is removed and transported to the "digester" for further processing. Primary treatment removes approximately 30 to 40% of BOD by volume from the wastewater, mainly in the form of suspended solids and organic matter.[28]

Secondary Treatment

There are several methods of secondary treatment. The most common treatment is known as *activated sludge*, because it uses living organisms—mostly bacteria. In this procedure, the wastewater from the primary sedimentation tank enters the aeration tank (Figure 19.16), where it is mixed with air (pumped in) and with some of the sludge from the final sedimentation tank. The sludge contains aerobic bacteria that consume organic material (BOD) in the waste. The wastewater then enters the final sedimentation tank, where sludge settles out. Some of this "activated sludge," rich in bacteria, is recycled and mixed again in the aeration tank with air and new, incoming wastewater acting as a starter. The bacteria are used again and again. Most of the sludge from the final sedimentation tank, however, is transported to the sludge digester. There, along with sludge from the primary sedimentation tank, it is treated by anaerobic bacteria (bacteria that can live and grow without oxygen), which further degrade the sludge by microbial digestion.

Methane gas (CH_4) is a product of the anaerobic digestion and may be used at the plant as a fuel to run equipment or to heat and cool buildings. In some cases, it is burned off. Wastewater from the final sedimentation tank is next disinfected, usually by chlorination, to eliminate disease-causing organisms. The treated wastewater is then discharged into a river, lake, or ocean (see A Closer Look 19.4), or in some limited cases used to irrigate farmland. Secondary treatment removes about 90% of BOD that enters the treatment plant in the sewage.[28]

The sludge from the digester is dried and disposed of in a landfill or applied to improve soil. In some instances, treatment plants in urban and industrial areas contain many pollutants, such as heavy metals, that are not removed in the treatment process. Sludge from these plants is too polluted to use in the soil, and sludge must

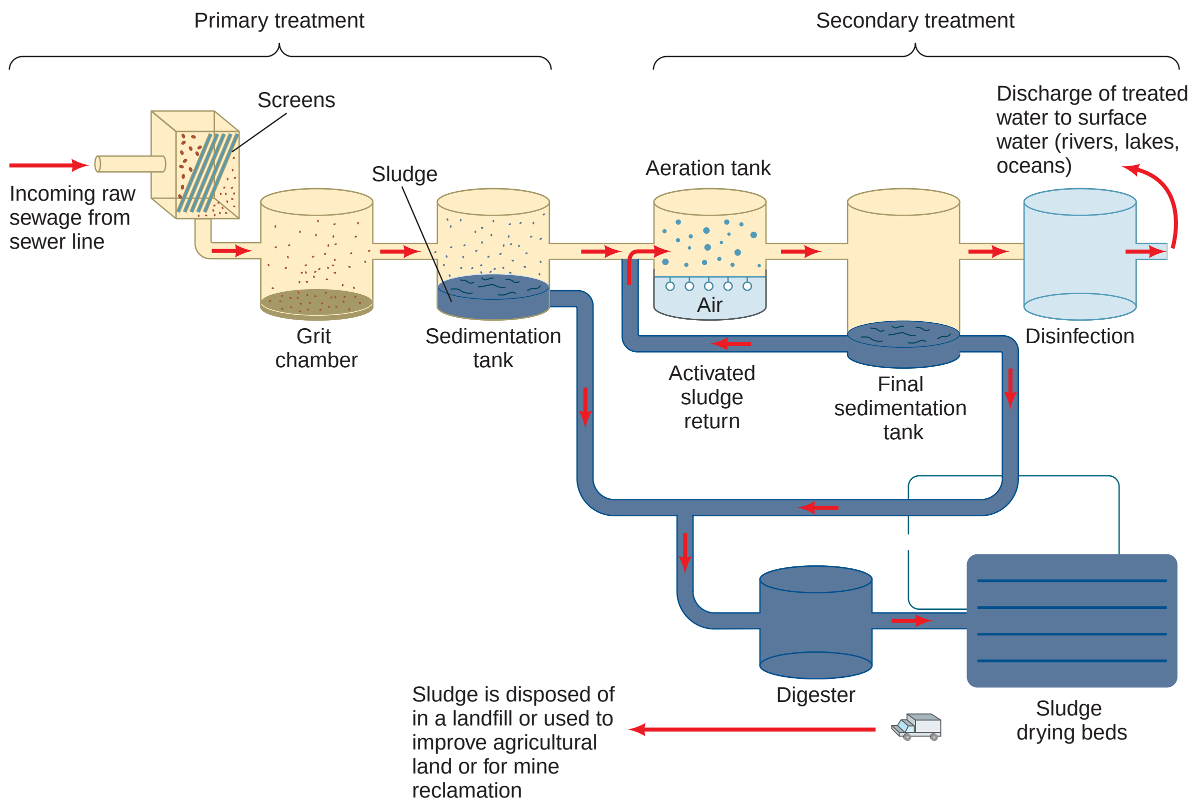


FIGURE 19.16 Diagram of sewage treatment processes. The use of digesters is relatively new, and many older treatment plants do not have them.

be disposed of. Some communities, however, require industries to pretreat sewage to remove heavy metals before the sewage is sent to the treatment plant; in these instances, the sludge can be more safely used for soil improvement.

Advanced Wastewater Treatment

As noted above, primary and secondary treatments do not remove all pollutants from incoming sewage. Some additional pollutants, however, can be removed by adding more treatment steps. For example, phosphates and nitrates, organic chemicals, and heavy metals can be removed by specifically designed treatments, such as sand filters, carbon filters, and chemicals applied to assist in the removal process.[28] Treated water is then discharged into surface water or may be used for irrigating agricultural lands or municipal properties, such as golf courses, city parks, and grounds surrounding wastewater treatment plants.

Advanced wastewater treatment is used when it is particularly important to maintain good water quality. For example, if a treatment plant discharges treated wastewater into a river and there is concern that nutrients remaining after secondary treatment may cause damage to the river ecosystem (eutrophication), advanced treatment may be used to reduce the nutrients.

Chlorine Treatment

As mentioned, chlorine is frequently used to disinfect water as part of wastewater treatment. Chlorine is very effective in killing the pathogens responsible for outbreaks of serious waterborne diseases that have killed many thousands of people. However, a recently discovered potential is that chlorine treatment also produces minute quantities of chemical by-products, some of which are potentially hazardous to people and other animals. For example, a recent study in Britain revealed that in some rivers, male fish sampled downstream from wastewater treatment plants had testes containing both eggs and sperm. This is likely related to the concentration of sewage effluent and the treatment method used.[30] Evidence also suggests that these by-products in the water may pose a risk of cancer and other human health effects. The degree of risk is controversial and currently being debated.[31]

A CLOSER LOOK 19.4

Boston Harbor: Cleaning Up a National Treasure

The city of Boston is steeped in early American history. Samuel Adams and Paul Revere immediately come to mind when considering the late 1700s, when the colonies were struggling for freedom from Britain. In 1773, Samuel Adams led a group of patriots who boarded three British ships and dumped their cargo of tea into Boston Harbor. The patriots were protesting what they considered an unfair tax on tea, and the event came to be known as the Boston Tea Party. The tea they dumped overboard did not pollute the harbor, but the growing city and the dumping of all sorts of waste eventually did.

Late in the 20th century, after more than 200 years of using Boston Harbor as a disposal site for dumping sewage, sewer overflows during storms, and treated wastewater into Massachusetts Bay, the courts demanded that measures be taken to clean up the bay. Studies concluded that the harbor had become polluted because waste being placed there moved into a small, shallow part of Massachusetts Bay, and despite vigorous tidal action between the harbor and the bay, the flushing time is about one week. It was decided that relocating the areas of waste discharge (called "outfalls") farther offshore, where the water is deeper and currents are stronger, would lower the pollution levels in Boston Harbor.

Moving the wastewater outfalls offshore was definitely a step in the right direction, but the long-term solution to protecting the marine ecosystem from pollutants will require additional measures. Even when placed farther offshore, in deeper water with greater circulation, pollutants will eventually accumulate and cause environmental damage. As a result, any long-term solution must include source reduction of pollutants. To this end, the Boston Regional Sewage Treatment Plan included a new treatment plant designed to significantly reduce the levels of pollutants discharged into the bay. This acknowledges that dilution by itself cannot solve the urban waste-management problem. Moving the sewage outfall offshore, when combined with source reduction of pollutants, is a positive example of what can be done to better manage our waste and reduce environmental problems.[29]

19.11 Land Application of Wastewater

The practice of applying wastewater to the land arose from the fundamental belief that waste is simply a resource out of place. Land application of untreated human waste was practiced for hundreds if not thousands of years before the development of wastewater treatment plants, which have sanitized the process by reducing BOD and using chlorination.

Many sites around the United States are now recycling wastewater, and the technology for wastewater treatment is rapidly evolving. An important question is: Can we develop environmentally preferred, economically viable wastewater treatment plants that are fundamentally different from those in use today? An idea for such a plant, called a resource-recovery wastewater treatment plant, is shown in Figure 19.17. The term *resource recovery* here refers to the production of resources, including methane gas (which can be burned as a fuel), as well as ornamental plants and flowers that have commercial value.[32]

Wastewater and Wetlands

Wastewater is being applied successfully to natural and constructed wetlands at a variety of locations.[33–35] Natural or man-made wetlands can be effective in treating the following water-quality problems:

- municipal wastewater from primary or secondary treatment plants (BOD, pathogens, phosphorus, nitrate, suspended solids, metals)
- stormwater runoff (metals, nitrate, BOD, pesticides, oils)
- industrial wastewater (metals, acids, oils, solvents)
- agricultural wastewater and runoff (BOD, nitrate, pesticides, suspended solids)
- mining waters (metals, acidic water, sulfates)
- groundwater seeping from landfills (BOD, metals, oils, pesticides)

Using wetlands to treat wastewater is particularly attractive to communities that find it difficult to purchase traditional wastewater treatment plants. For example,

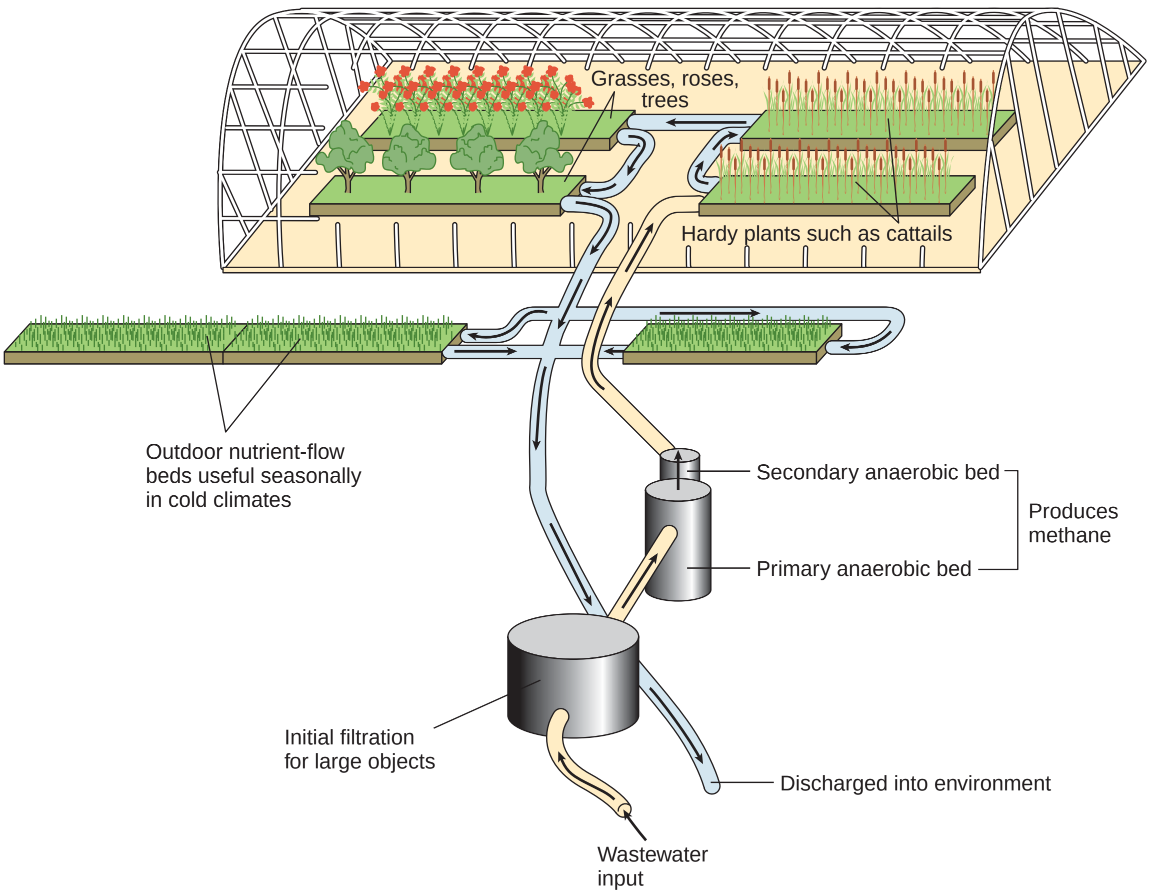


FIGURE 19.17 Components of a resource-recovery wastewater treatment plant. For this model, two resources are recovered: methane, which can be burned to produce energy from the anaerobic beds; and ornamental plants, which can be sold. (*Source*: Based on W.J. Jewell, "Resource-Recovery Wastewater Treatment," *American Scientist* [1994] 82:366–375.)

the city of Arcata, in northern California, makes use of a wetland as part of its wastewater treatment system. The wastewater comes mostly from homes, with minor inputs from the numerous lumber and plywood plants in Arcata. It is treated by standard primary and secondary methods, then chlorinated and dechlorinated before being discharged into Humboldt Bay.[33]

Louisiana Coastal Wetlands

The state of Louisiana, with its abundant coastal wetlands, is a leader in the development of advanced treatment using wetlands after secondary treatment (Figure 19.18). Wastewater rich in nitrogen and phosphorus, applied to coastal wetlands, increases the production of wetland plants, thereby improving water quality as these nutrients are used by the plants. When the plants die, their organic material (stems, leaves, roots) causes the wetland to grow vertically (or accrete), partially offsetting wetland loss due to sea-level rise.[36] There are also significant economic savings in applying treated wastewater to wetlands, because the financial investment is small compared with the cost of advanced treatment at conventional treatment plants. Over a 25-year period, a savings of about $40,000 per year is likely.[35]

In sum, the use of isolated wetlands, such as those in coastal Louisiana, is a practical way to improve water quality in small, widely dispersed communities in the coastal zone. As water-quality standards are tightened, wetland wastewater treatment will become a viable, effective alternative that is less costly than traditional treatment.[36, 37]

Phoenix, Arizona: Constructed Wetlands

Wetlands can be constructed in arid regions to treat poor-quality water. For example, at Avondale, Arizona, near Phoenix, a wetland treatment facility for agricultural wastewater is sited in a residential community (Figure 19.19). The facility is designed to eventually treat about 17,000 m^3/day (4.5 million gal/day) of water. Water entering the facility has nitrate (NO_3) concentrations as high as 20 mg/l. The artificial wetlands contain naturally occurring bacteria that reduce the nitrate to below the maximum contaminant level of 10 mg/l. Following treatment, the water flows by pipe to a recharge basin on the nearby Agua Fria River, where it seeps into the ground to become a groundwater resource. The cost of the wetland treatment facility was about $11 million, about half the cost of a more traditional treatment facility.

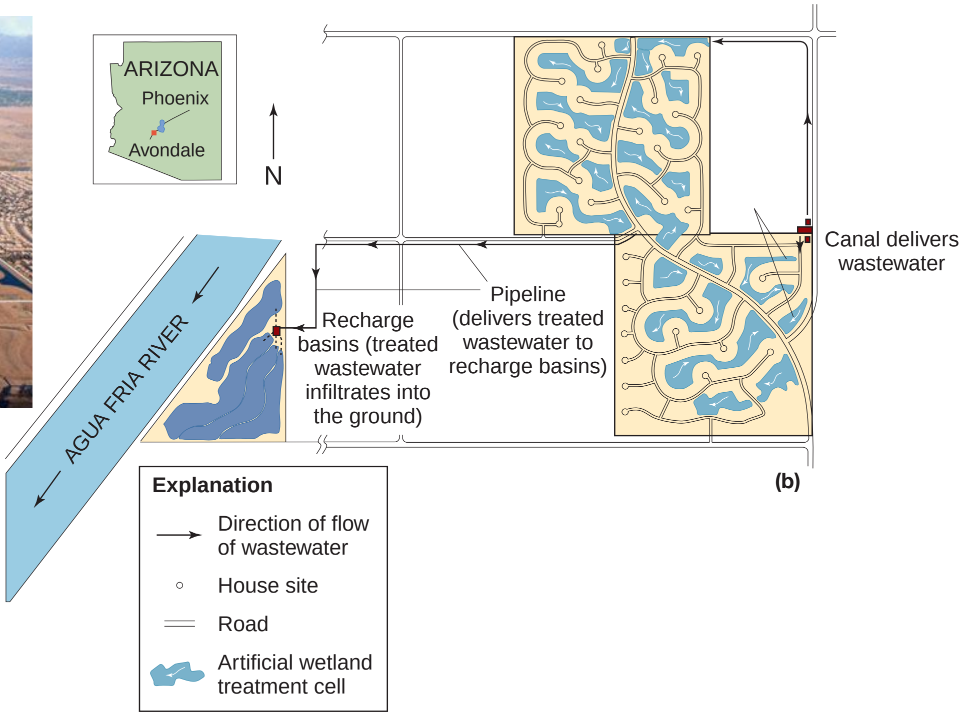
(a)


(c)


(b)

FIGURE 19.18 **(a)** Wetland Pointe au Chene Swamp, three miles south of Thibodaux, Louisiana, receives wastewater; **(b)** one of the outfall pipes delivering wastewater; and **(c)** ecologists doing field work at the Pointe au Chene Swamp to evaluate the wetland.

(a)



(b)

FIGURE 19.19 **(a)** Photograph of the site, showing wetlands integrated with housing development (lower left), and **(b)** map of an artificial wetlands for treating agricultural wastewater at Avondale, Arizona (near Phoenix). (*Source*: Integrated Water Resources, Inc., Santa Barbara, California.)

19.12 Water Reuse

Water reuse can be inadvertent, indirect, or direct. *Inadvertent water reuse* results when water is withdrawn, treated, used, treated, and returned to the environment, followed by further withdrawals and use. Inadvertent water reuse is very common and a fact of life for millions of people who live along large rivers. Many sewage treatment plants are located along rivers and discharge treated water into the rivers. Downstream, other communities withdraw, treat, and consume the water.

Several risks are associated with inadvertent reuse:

1. Inadequate treatment facilities may deliver contaminated or poor-quality water to downstream users.
2. Because the fate of all disease-causing viruses during and after treatment is not completely known, the health hazards of treated water remain uncertain.
3. Every year, new and potentially hazardous chemicals are introduced into the environment. Harmful chemicals are often difficult to detect in the water; and if they are ingested in low concentrations over many years, their effects on people may be difficult to evaluate.[33]

Indirect water reuse is a planned endeavor. For example, in the United States, several thousand cubic meters of treated wastewater per day have been applied to numerous sites to recharge groundwater and then reused for agricultural and municipal purposes.

Direct water reuse refers to use of treated wastewater that is piped directly from a treatment plant to the next user. In most cases, the water is used in industry, in agricultural activity, or for irrigating golf courses, institutional grounds (such as university campuses), and parks. Direct water reuse is growing rapidly and is the norm for industrial processes in factories. In Las Vegas, Nevada, new resort hotels that use a great deal of water for fountains, rivers, canals, and lakes are required to treat wastewater and reuse it (Figure 19.20). Because of perceived risks and negative cultural attitudes toward using treated wastewater, there has been little direct reuse of water for human consumption, except in emergencies. However, that is changing in Orange County, California, where an ambitious program to reuse treated wastewater is under way. The program processes 70 million gallons a day by injecting treated wastewater into the groundwater system to be further filtered underground. The water is then pumped out, further treated, and used in homes and businesses.[38]

FIGURE 19.20 Water reuse at a Las Vegas, Nevada, resort hotel.

19.13 Conditions of Stream Ecosystems in the United States

Assessment of stream ecosystem conditions in the United States has been an important research goal since passage of the Clean Water Act of 1977. Until recently, no straightforward way to do this had been seriously attempted, so the condition of small streams that can be waded was all but unknown. That void is now partly filled by recent studies aimed at providing a credible, broad-scale assessment of small streams in the United States. A standardized field collection of data was an important step, and the data at each site include the following:

- measurement of stream channel morphology and habitat characteristic
- measurement of the streamside and near-stream vegetation, known as the *riparian vegetation*
- measurement of water chemistry
- measurement of the assemblage and composition of the stream environment (biotic environment)

The evaluation includes two key biological indicators: (1) an index of how pristine a stream ecosystem is and (2) an index that represents a loss of biodiversity. Results of the study are shown in Figure 19.21. The top graph is for the entire United States, while the three lower graphs are done on a regional basis. The ratings range from poor conditions—that is, those most disturbed by environmental stress—to good conditions that mostly correspond with undisturbed stream systems. Streams with poor quality are most numerous in the northeastern part of the United States, as well as in the midsection of the country. The percentage of stream miles in good condition is considerably higher in the West.

This is not surprising, given the extent of stream-channel modifications and changes in land use in the eastern half of the country compared to the western half. Western states tend to have more mountains and more areas of natural landscape that have not been modified by agriculture and other human activities. However, streams in the West were deemed to have a higher risk of future degradation than those in other areas because there are more pristine streams to measure changes against and because there are more high-quality stream ecosystem conditions to potentially be degraded in the West than there are in other parts of the country.[39]

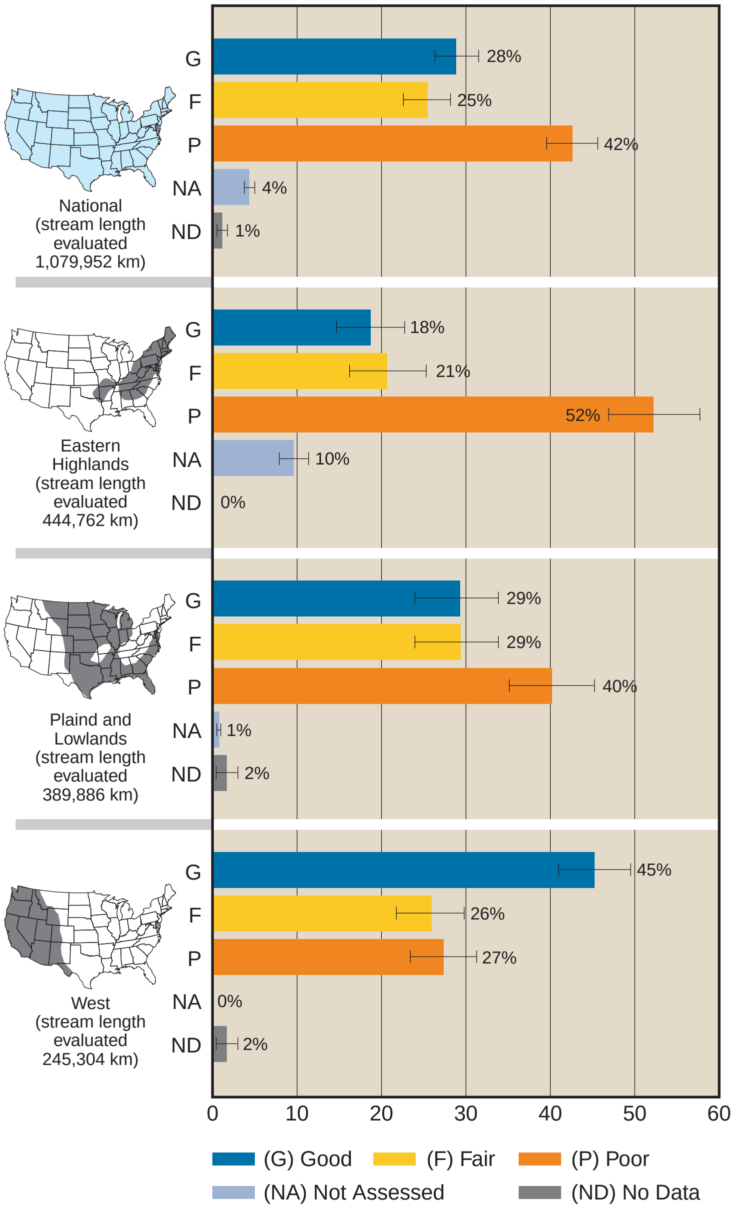


FIGURE 19.21 Condition of ecosystems of small streams that can be waded in the U.S. (*Source*: Modified after J.M. Faustini et al. 2009, "Assessing Stream Ecosystem Condition in the United States." *EOS, Transactions, American Geophysical Union* 36: 309–310).

19.14 Water Pollution and Environmental Law

Environmental law, the branch of law dealing with conservation and use of natural resources and control of pollution, is very important as we debate environmental issues and make decisions about how best to protect our environment. In the United States, laws at the federal, state, and local levels address these issues.

Federal laws to protect water resources go back to the Refuse Act of 1899, which was enacted to protect navigable streams, rivers, and lakes from pollution. Table 19.5 lists major federal laws that have a strong water-resource/pollution component. Each of these major pieces of legislation has had a significant impact on water-quality issues. Many federal laws have been passed with the purpose of cleaning up or treating pollution problems or treating wastewater. However, there has also been a focus on preventing pollutants from entering water. Prevention has the advantage of avoiding environmental damage and costly cleanup and treatment.

From the standpoint of water pollution, the mid-1990s in the United States was a time of debate and controversy. In 1994, Congress attempted to rewrite major environmental laws, including the Clean Water Act (1972, amended in 1977). The purpose was to give industry greater flexibility in choosing how to comply with environmental regulations concerning water pollution. Industry interests favored proposed new regulations that, in their estimation, would be more cost-effective without causing increased environmental degradation. Environmentalists, on the other hand, viewed attempts to rewrite the Clean Water Act as a giant step backward in the nation's fight to clean up our water resources. Apparently, Congress had incorrectly assumed it knew the public's values on this issue. Survey after survey has established that there is strong support for a clean environment in the United States and that people are willing to pay to have clean air and clean water. Congress has continued to debate changes in environmental laws, but little has been resolved.[40]

Table 19.5 FEDERAL WATER LEGISLATION

DATE	LAW	OVERVIEW
1899	Refuse Act	Protects navigable water from pollution
1956	Federal Water and Pollution Control Act	Enhances the quality of water resources and prevents, controls, and abates water pollution.
1958	Fish and Wildlife Coordination Act	Mandates the coordination of water resources projects such as dams, power plants, and flood control must coordinate with U.S Fish and Wildlife Service to enact wildlife conservation measures
1969	National Environmental Policy Act	Requires environmental impact statement prior to federal actions (development) that significantly affect the quality of the environment. Included are dams and reservoirs, channelization, power plants, bridges, and so on
1970	Water Quality Improvement Act	Expands power of 1956 act through control of oil pollution and hazardous pollutants and provides for research and development to eliminate pollution in Great Lakes and acid mine drainage.
1972 (amended in 1977)	Federal Water Pollution Control Act (Clean Water Act)	Seeks to clean up nation's water. Provides billions of dollars in federal grants for sewage treatment plants. Encourages innovative technology, including alternative water treatment methods and aquifer recharge of wastewater.
1974	Federal Safe Drinking Water Act	Aims to provide all Americans with safe drinking water. Sets contaminant levels for dangerous substances and pathogens
1980	Comprehensive Environmental Response, Compensation, and Liability Act	Established revolving fund (Superfund) to clean up hazardous waste disposal sites, reducing ground water pollution.
1984	Hazardous and Solid Waste Amendments to the Resource Conservation and Recovery Act	Regulates underground gasoline storage tanks. Reduces potential for gasoline storage tanks. Reduces potential for gasoline to pollute groundwater
1987	Water Quality Act	Established national policy to control nonpoint sources of water pollution. Important in development of state management plants to control nonpoint water pollution sources.

CRITICAL THINKING ISSUE

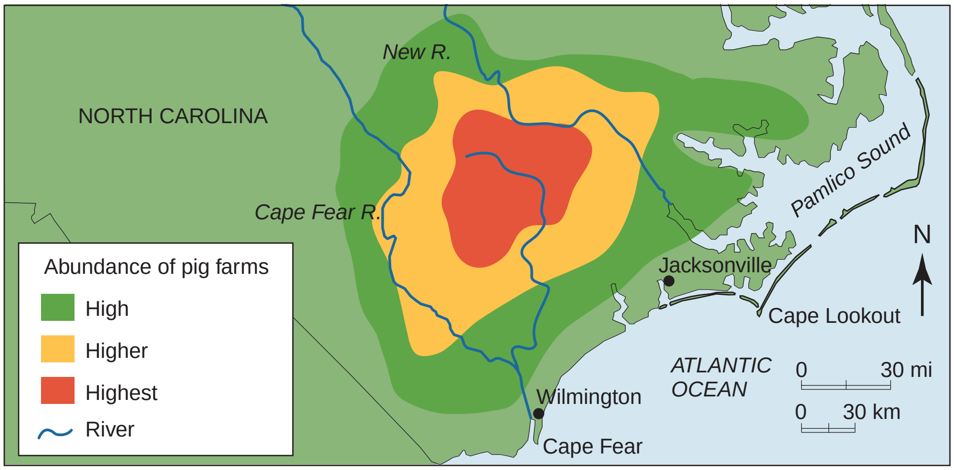
Is Water Pollution from Pig Farms Unavoidable?

Hurricane Floyd struck the Piedmont area of North Carolina in September 1999. The killer storm took a number of lives while flooding many homes and forcing some 48,000 people into emergency shelters. The storm had another, more unusual effect as well. Floodwaters containing thousands of dead pigs, along with their feces and urine, flowed through schools, churches, homes, and businesses. The stench was reportedly overwhelming, and the count of pig carcasses may have been as high as 30,000. The storm waters had overlapped and washed out over 38 pig lagoons with as much as 950 million liters (250 million gal) of liquid pig waste, which ended up in flooded creeks, rivers, and wetlands. In all, something like 250 large commercial pig farms flooded out, drowning hogs whose floating carcasses had to be collected and disposed of (Figure 19.22).

Prior to Hurricane Floyd, the pig farm industry in North Carolina had been involved in a scandal reported by newspapers and television—and even by *60 Minutes*. North Carolina has a long history of hog production, and the population of pigs swelled from about 2 million in 1990 to nearly 10 million in 1997. At that time, North Carolina became the second-largest pig-farming state in the nation.[41] As the number of large commercial pig farms grew, the state allowed the hog farmers to build automated and very confining farms housing hundreds or thousands of pigs. There were no restrictions on farm location, and many farms were constructed on floodplains.

Each pig produces approximately 2 tons of waste per year. The North Carolina herd was producing approximately 20 million tons of waste a year, mostly manure and urine, which was flushed out of the pig barns and into open, unlined lagoons about the size of football fields. Favorable regulations, along with the availability of inexpensive waste-disposal systems (the lagoons), were responsible for the tremendous growth of the pig population in North Carolina in the 1990s.

(a)



(b)

FIGURE 19.22 North Carolina's "Bay of Pigs." **(a)** Map of areas flooded by Hurricane Floyd in 1999 with relative abundance of pig farms. **(b)** Collecting dead pigs near Boulaville, North Carolina. The animals were drowned when floodwaters from the Cape Fear River inundated commercial pig farms

After the hurricane, mobile incinerators were moved into the hog region to burn the carcasses, but there were so many that hog farmers had to bury some animals in shallow pits. The pits were supposed to be at least 1 meter deep, and dry, but there wasn't always time to find dry ground, and for the most part the pits were dug and filled on floodplains. As these pig carcasses rot, bacteria will leak into the groundwater and surface water for some appreciable time.

An early warning occurred in 1995, when a pig-waste lagoon failed and sent approximately 950 million liters (250 million gal) of concentrated pig feces down the New River past the city of Jacksonville, South Carolina, and into the New River estuary. The spill's adverse effects on marine life lasted for approximately three months.

The lesson to be learned from North Carolina's so-called Bay of Pigs is that we are vulnerable to environmental catastrophes caused by large-scale industrial agriculture. Economic growth and production of livestock must be carefully planned to anticipate problems, and waste-management facilities must be designed so as not to pollute local streams, rivers, and estuaries.

Was the lesson learned in North Carolina? The pig farmers had powerful friends in government and big money. Incredible as it may seem, following the hurricane, the farmers asked for $1 billion in grants to help repair and replace the pig facilities, including waste lagoons, destroyed by the hurricane. Furthermore, they asked for exemptions from the Clean Water Act for a period of six months so that waste from the pig lagoons could be discharged directly into streams.[42] This was not allowed.

With regard to future management, considering that North Carolina is frequently struck by hurricanes, barring pig operations from floodplains seems obvious. However, this is only the initial step. The whole concept of waste lagoons needs to be rethought and alternative waste-management practices put into effect if pollution of surface waters and groundwaters is to be avoided. To this end, North Carolina in 2007 passed legislation to ban construction or expansion of new waste lagoons and encouraged pig farms to treat pig waste to extract methane (gas) as an energy source. Other methods of on-site treatment to reduce organic matter and nutrients is ongoing

North Carolina's pig problem led to the formation of what is called the "Hog Roundtable," a coalition of civic, health, and environmental groups with the objective of controlling industrial-scale pig farming. Its efforts, with others, resulted in a mandate to phase out pig-waste lagoons and expand regulations to require buffers between pig farms and surface waters and water wells. The coalition also halted construction of a proposed slaughterhouse that would have allowed more pig farms to be established.

Critical Thinking Questions

1. Can future pollution from large pig farms in areas with recurring hurricane hazards be eliminated or minimized? If so, how?
2. Do you think the pollution caused by pig farm flooding as a result of hurricanes is a natural event, a so-called act of God? Pig farmers blamed the hurricane for the water pollution. Are they right, or are people responsible?
3. Do you think the actions of the Hog Roundtable can succeed over the long term in minimizing environmental problems caused by large pig farms?
4. Discuss the moral and ethical issues of industrial-scale agriculture that confines large numbers of animals, often in small spaces. Is there a better way to produce our food? What are alternatives?

SUMMARY

- The primary water-pollution problem in the world today is the lack of disease-free drinking water.
- Water pollution is degradation of quality that renders water unusable for its intended purpose.
- Major categories of water pollutants include disease-causing organisms, dead organic material, heavy metals, organic chemicals, acids, sediment, heat, and radioactivity.
- Sources of pollutants may be point sources, such as pipes that discharge into a body of water, or nonpoint sources, such as runoff, which are diffused and intermittent.
- Eutrophication of water is a natural or human-induced increase in the concentration of nutrients, such as phosphorus and nitrogen, required for living things. A high concentration of such nutrients may cause a population explosion of photosynthetic bacteria. As the bacteria die and decay, the concentration of dissolved oxygen in the water is lowered, leading to the death of fish.
- Sediment is a twofold problem: Soil is lost through erosion, and water quality suffers when sediment enters a body of water.
- Acid mine drainage is a serious water-pollution problem because when water and oxygen react with sulfide minerals that are often associated with coal or metal sulfide deposits, they form sulfuric acid. Acidic water draining from mines or tailings pollutes streams and other bodies of water, damaging aquatic ecosystems and degrading water quality.
- Urban processes—for example, waste disposal in landfills, application of fertilizers, and dumping of chemicals such as motor oil and paint—can contribute to shallow-aquifer contamination. Overpumping of aquifers near the ocean may cause saltwater, found below the freshwater, to rise closer to the surface, contaminating the water resource by a process called saltwater intrusion.

- Wastewater treatment at conventional treatment plants includes primary, secondary, and, occasionally, advanced treatment. In some locations, natural ecosystems, such as wetlands and soils, are being used as part of the treatment process.
- Water reuse is the norm for millions of people living along rivers where sewage treatment plants discharge treated wastewater back into the river. People who withdraw river water downstream are reusing some of the treated wastewater.
- Industrial reuse of water is the norm for many factories.
- Deliberate use of treated wastewater for irrigating agricultural lands, parks, golf courses, and the like is growing rapidly as demand for water increases.
- Cleanup and treatment of both surface water and groundwater pollution are expensive and may not be completely successful. Furthermore, environmental damage may result before a pollution problem i s identified and treated. Therefore, we should continue to focus on preventing pollutants from entering water, which is a goal of much water-quality legislation.

REEXAMINING THEMES AND ISSUES

Human Population

We state in this chapter that the number one water-pollution problem in the world today is the lack of disease-free drinking water. This problem is likely to get worse in the future as the number of people, particularly in developing countries, continues to increase. As population increases, so does the possibility of continued water pollution from a variety of sources relating to agricultural, industrial, and urban activities.

Sustainability

Any human activity that leads to water pollution—such as the building of pig farms and their waste facilities on floodplains—is antithetical to sustainability. Groundwater is fairly easy to pollute and, once degraded, may remain polluted for a long time. Therefore, if we wish to leave a fair share of groundwater resources to future generations, we must ensure that these resources are not polluted, degraded, or made unacceptable for use by people and other living organisms.

Global Perspective

Several aspects of water pollution have global implications. For example, some pollutants may enter the atmosphere and be transported long distances around the globe, where they may be deposited and degrade water quality. Examples include radioactive fallout from nuclear reactor accidents or experimental detonation of nuclear devices. Waterborne pollutants from rivers and streams may enter the ocean and circulate with marine waters around the ocean basins of the world.

Urban World

Urban areas are centers of activities that may result in serious water pollution. A broad range of chemicals and disease-causing organisms are present in large urban areas and may enter surface waters and groundwaters. An example is bacterial contamination of coastal waters, resulting in beach closures. Many large cities have grown along the banks of streams and rivers, and the water quality of those streams and rivers is often degraded as a result. There are positive signs that some U.S. cities are viewing their rivers as valuable resources, with a focus on environmental and economic renewal. Thus, rivers flowing through some cities are designated as greenbelts, with parks and trail systems along river corridors. Examples include New York City; Cleveland, Ohio; San Antonio, Texas; Corvallis, Oregon; and Sacramento and Los Angeles, California.

People and Nature

Polluting our water resources endangers people and ecosystems. When we dump our waste in rivers, lakes, and oceans, we are doing what other animals have done for millions of years—it is natural. For example, a herd of hippopotamuses in a small pool may pollute the water with their waste, causing problems for other living things in the pond. The difference is that we understand that dumping our waste damages the environment, and we know how to reduce our impact.

Science and Values

It is clear that the people of the United States place a high value on the environment and, in particular, on critical resources such as water. Attempts to weaken water-quality standards are viewed negatively by the public. There is also a desire to protect water resources necessary for the variety of ecosystems found on Earth. This has led to research and development aimed at finding new technologies to reduce, control, and treat water pollution. Examples include development of new wastewater treatments and support of laws and regulations that protect water resources.

KEY TERMS

acid mine drainage **409**
advanced wastewater treatment **415**
biological or biochemical oxygen demand (BOD) **403**
bioremediation **412**
cultural eutrophication **406**
ecosystem effect **406**
environmental law **421**
eutrophication **405**
fecal coliform bacteria **404**
nanotechnology **411**
nonpoint sources **410**
outbreaks **404**
point sources **410**
primary treatment **415**
urban-runoff naturalization **411**
secondary treatment **415**
wastewater treatment **414**
water reuse **420**

STUDY QUESTIONS

1. Do you think outbreaks of waterborne diseases will be more common or less common in the future? Why? Where are outbreaks most likely to occur?

2. What was learned from the *Exxon Valdez* oil spill that might help reduce the number of future spills and their environmental impact?

3. What is meant by the term *water pollution*, and what are several major processes that contribute to water pollution?

4. Compare and contrast point and nonpoint sources of water pollution. Which is easier to treat, and why?

5. What is the twofold effect of sediment pollution?

6. In the summer, you buy a house with a septic system that appears to function properly. In the winter, effluent discharges at the surface. What could be the environmental cause of the problem? How could the problem be alleviated?

7. Describe the major steps in wastewater treatment (primary, secondary, advanced). Can natural ecosystems perform any of these functions? Which ones?

8. In a city along an ocean coast, rare waterbirds inhabit a pond that is part of a sewage treatment plant. How could this have happened? Is the water in the sewage pond polluted? Consider this question from the birds' point of view and from your own.

9. How does water that drains from coal mines become contaminated with sulfuric acid? Why is this an important environmental problem?

10. What is eutrophication, and why is it an ecosystem effect?

11. How safe do you believe the drinking water is in your home? How did you reach your conclusion? Are you worried about low-level contamination by toxins in your water? What could be the sources of contamination?

12. Do you think our water supply is vulnerable to terrorist attacks? Why? Why not? How could potential threats be minimized?

13. Would you be willing to use treated wastewater in your home for personal consumption, as they are doing in Orange County, California? Why? Why not?

14. How would you design a system to capture runoff where you live before it enters a storm drain?

FURTHER READING

Borner, H., ed., *Pesticides in Ground and Surface Water*. Vol. 9 of *Chemistry of Plant Protection* (New York: Springer-Verlag, 1994). Essays on the fate and effects of pesticides in surface water and groundwater, including methods to minimize water pollution from pesticides.

Dunne, T., and L.B. Leopold, *Water and Environmental Planning* (San Francisco: W.H. Freeman, 1978). A great summary and detailed examination of water resources and problems.

Hester, R.E., and R.M. Harrison, eds., *Agricultural Chemicals and the Environment* (Cambridge: Royal Society of Chemistry, Information Services, 1996). A good source of information about the impact of agriculture on the environment, including eutrophication and the impact of chemicals on water quality.

Manahan, S.E., *Environmental Chemistry* (Chelsea, MI: Lewis, 1991). A detailed primer on the chemical processes pertinent to a broad array of environmental problems, including water pollution and treatment.

Newman, M.C., *Quantitative Methods in Aquatic Ecotoxicology* (Chelsea, MI: Lewis, 1995). Up-to-date text on the fate, effects, and measurement of pollutants in aquatic ecosystems.

Nichols, C. "Trouble at the Waterworks," *The Progressive* 53 (1989): 33–35. A concise report on the problem of tainted water supplies in the United States.

Rao, S.S., ed., *Particulate Matter and Aquatic Contaminants* (Chelsea, MI.: Lewis, 1993). Coverage of the biological, microbiological, and ecotoxicological principles associated with interaction between suspended particulate matter and contaminants in aquatic environments.

CHAPTER 20

The Atmosphere, Climate, and Global Warming

The years of the Medieval Warm Period, from about A.D. 950 to 1250, were good times for the people in Western Europe. Harvests were good, cultures flourished, the population expanded, and great cathedrals were built. In the southwestern United States, Mexico, and Central America, the same period brought persistent droughts that contributed to the collapse of some civilizations, including the Maya.

LEARNING OBJECTIVES

Earth's atmosphere—the layer of gases surrounding the Earth—is a complex, dynamic system that is changing continuously. After reading this chapter, you should understand . . .

- The basic composition and structure of the atmosphere;
- How the processes of atmospheric circulation and climate work;
- How the climate has changed over the Earth's history;
- What the term *greenhouse gas* means and what the major greenhouse gases are;
- What global warming is and what major kinds of evidence point to it;
- What effects global warming might have and how we can adjust to them.

CASE STUDY

What Does History Tell Us about Global Warming's Potential Consequences for People?

During an approximate 300-year period from A.D. 950 to 1250, Earth's surface was considerably warmer than what climatologists today call normal (meaning the average surface temperature during the past century or some shorter interval, such as 1960–1990). This warm time is known as the Medieval Warm Period (MWP). With all the concerns today about climate change, perhaps we can learn some lessons from that time. Since weather records were not kept then, we do not have a global picture of what it was like. What we do know is that parts of the world, in particular Western Europe and the Atlantic, may have been warmer some of the time than they were in the last decade of the 20th century. However on a global basis the MWP was not as warm as it is today.

In Western Europe, it was a time of flourishing culture and activity, as well as expansion of the population; a time when harvests were plentiful, people generally prospered, and many of Europe's grand cathedrals were constructed.[1, 2] Sea temperatures evidently were warmer, and there was less sea ice. Viking explorers from Scandinavia traveled widely in the Far North and established settlements in Iceland, Greenland, and even briefly in North America. Near the end of the 10th century, Erik the Red, the famous Viking explorer, arrived at Greenland with his ships and set up settlements that flourished for several hundred years. The settlers were able to raise domestic animals and grow a variety of crops that had never before been cultivated in Greenland (Figure 20.1). During the same warm period, Polynesian people in the Pacific, taking advantage of winds flowing throughout the Pacific, were able to sail to and colonize islands over vast areas of the Pacific, including Hawaii.[2]

While some prospered in Western Europe and the Pacific during the Medieval Warm Period, other cultures appear to have been less fortunate. Associated with the warming period were long, persistent droughts (think human-generational length) that appear to have been partially responsible for the collapse of sophisticated cultures in North and Central America. The collapses were not sudden but occurred over a period of many decades, and in some cases the people just moved away. These included the people living near Mono Lake on the eastern side of the Sierra Nevada in California, the Chacoan people in what is today Chaco Canyon in New Mexico, and the Mayan civilization in the Yucatán of southern Mexico and Central America.

FIGURE 20.1 Remains of a Viking settlement in Greenland from the Medieval Warm Period.

The Medieval Warm Period was followed by the Little Ice Age (LIA), which lasted from approximately mid-1400 to 1700. The cooling made life more difficult for people in Western Europe and North America. Crop failures occurred in Western Europe, and some mountain glaciers in the Swiss Alps advanced to the extent that they filled valleys and destroyed villages. Areas to the north that had enjoyed abundant crop production were under ice.[3] The population was devastated by the Black Plague, whose effects may have been exacerbated by poor nutrition as a result of crop failures and by the damp and cold that reached out across Europe and even to Iceland by about 1400.

Travel and trade became difficult in the Far North. Eventually, the Viking colonies in North America were abandoned and those in Greenland declined greatly. Part of the reason for the abandonment in North America, and particularly in Newfoundland, was that the Vikings may not have been able to adapt to the changing conditions, as did the Inuit peoples living there. As times became tough, the two cultures collided, and the Vikings, despite their fierce reputation, were less able than the Inuit to adapt to the cooling climate.

We do not know what caused the Medieval Warm Period, and the details about it are obscured by insufficient climate data to help us estimate temperatures during that period. We do know that it was relatively warm (in Western Europe). We can't associate the warming 1000 years ago with burning of fossil fuels. This suggests that more than one factor can cause warming. In this chapter we will explore climate dynamics so you can better understand what may be the causes of climate change and what might be the best estimates of how it could affect life on Earth and civilizations.[1–5]

20.1 Fundamental Global Warming Questions

The modern concern about global warming arose from two kinds of observations. The first, shown in Figure 20.2, is of the average surface temperature of the Earth from 1850 to the present. This graph shows an increase beginning in the 1930s and accelerating, especially after 1960, when the increase was about 0.2°C per decade.

The second kind of key observation is the measurement of carbon dioxide concentrations in the atmosphere. Of these, the best-known were made on Mauna Loa Mountain, Hawaii, by Charles Keeling and are now known as the Keeling Curve (Figure 20.3). Taken at 3,500 m (11,500 ft) on an island far from most human activities, these measurements provide an excellent estimate of the background condition of the atmosphere.

Here are the fundamental questions about global warming:

- What is the origin of known periods of rapid warming in the geologic record? This fundamental question is the subject of intense ongoing research and is not yet solved.
- Is the present rapid warming unprecedented or at least so rare that many living things will not be able to respond successfully to it?
- To what extent, have people caused it?
- What are likely to be the effects on people?
- What are likely to be the effects on all life on Earth?
- How can we make forecasts about it and other kinds of climate change?
- What can we do to minimize potential negative effects?

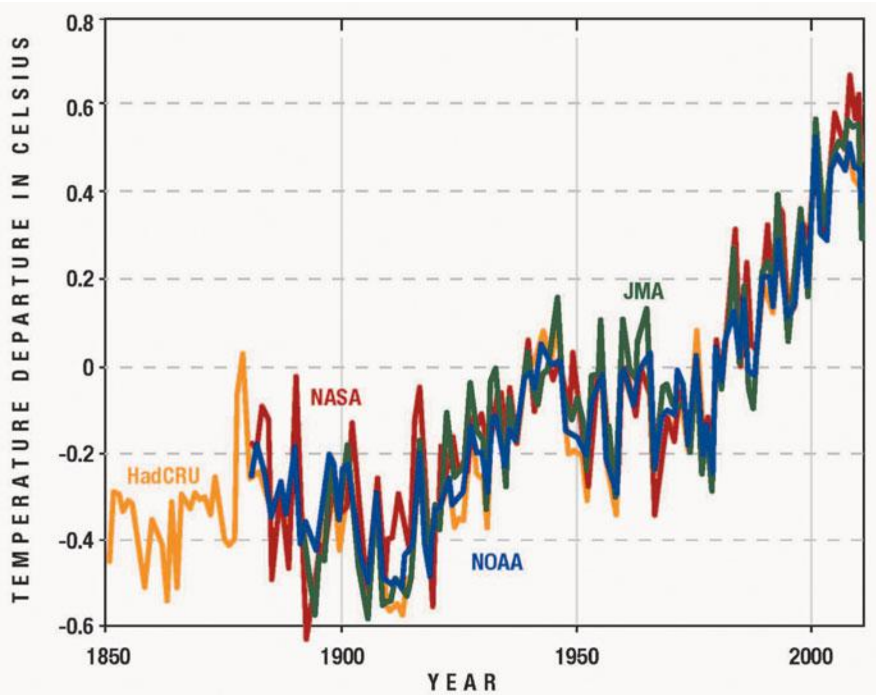
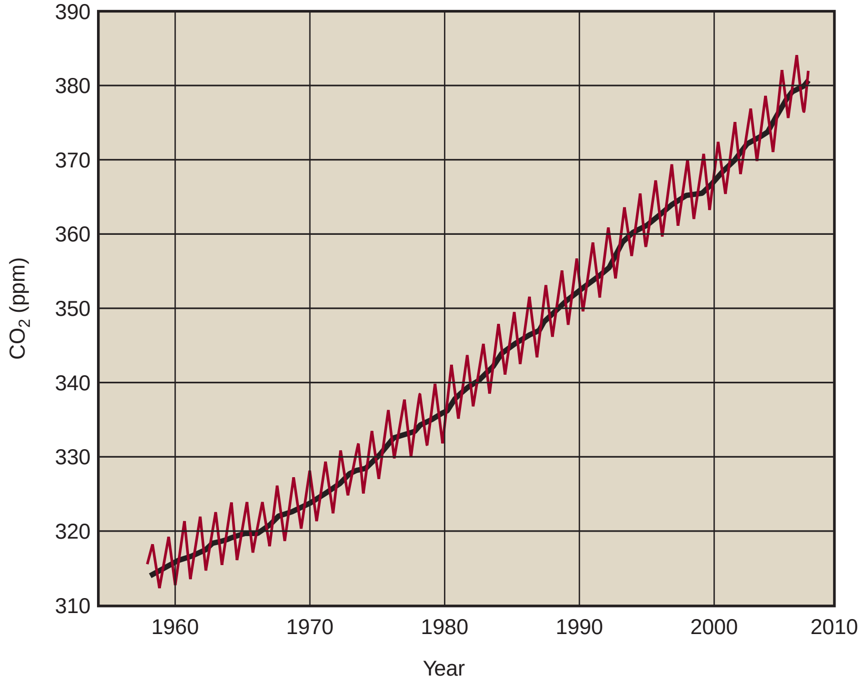


FIGURE 20.2 The temperature difference between the average at the end of the 19th century and the years between 1860 and today. This graph shows the difference between calculated world surface temperatures for each year and the average at the end of the 19th century. Temperature departure refers to changes in mean global temperature from some standard such as 1951–1980. Climatologists studying climate change prefer, in general, to look at the difference between temperatures at one time compared to another, rather than the actual temperature, for a variety of technical reasons. (*Source:* Hadley Meteorological Center, Great Britain.) http://www.metoffice.gov.uk/corporate/pressoffice/myths/2.html)



(a)

(b)

FIGURE 20.3 **(a)** Carbon dioxide concentrations in the air above Mauna Loa, Hawaii; **(b)** the NOAA Observatory on Mauna Loa, where these measurements were made. (*Sources:* **(a)** *Encyclopedia of Earth,* http://www.eoearth.org/article/Climate_change; taken from C.D. Keeling and T.P. Whorf, 2005. "Atmospheric CO_2 records from sites in the SIO air sampling network," in *Trends: A Compendium of Data on Global Change.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN).

20.2 Weather and Climate

Weather is what's happening now or over some short time period—this hour, today, this week—in the atmosphere near the ground: its temperature, pressure, cloudiness, precipitation, winds. **Climate** is the average weather and usually refers to average weather conditions over long periods, at least seasons, but more often years or decades. When we say it's hot and humid in New York today or raining in Seattle, we are speaking of weather. When we say Los Angeles has cool, wet winters and warm, dry summers, we are referring to the Los Angeles climate.

Since climates are characteristic of certain latitudes (and other factors that we will discuss later), they are classified mainly by latitude—tropical, subtropical, midlatitudinal (continental), sub-Arctic (continental), and Arctic—but also by wetness/dryness, such as humid continental, Mediterranean, monsoon, desert, and tropical wet–dry (Figure 20.4). Recall from the discussion of biogeography in Chapter 7 that similar climates produce similar kinds of ecosystems. Therefore, knowing the climate, we can make pretty good predictions about what kinds of life we will find there and what kinds could survive there if introduced.

The Climate Is Always Changing at a Variety of Time Scales

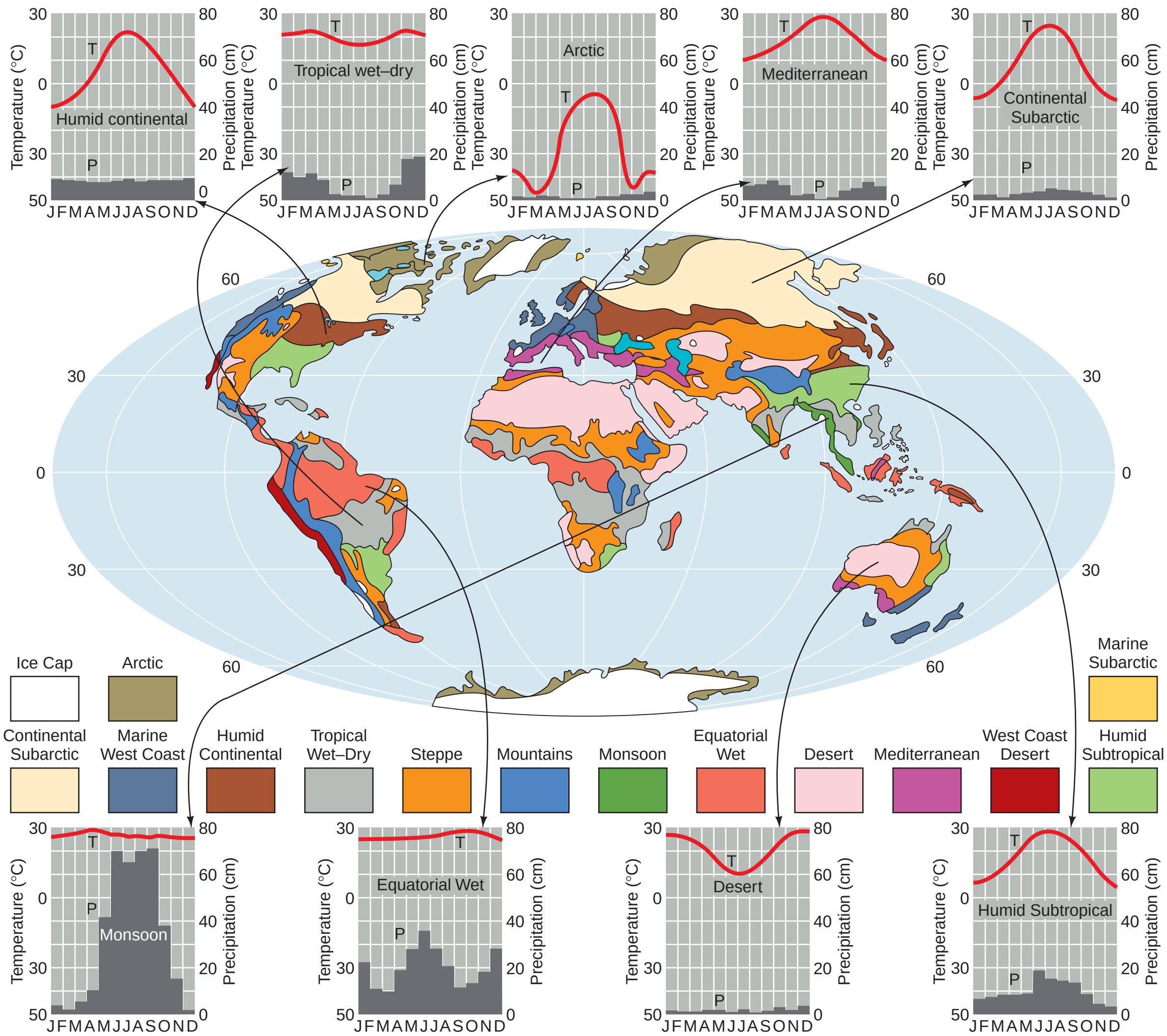
Answering questions about climate change is especially complicated because—and this is a key point about climate and life—the climate is always changing. This has been happening as far back in Earth's history as scientists have been able to study. The Precambrian Era, around 550 million years ago, averaged a relatively cool 12°C. Things warmed up to about 22°C in the Cambrian Period, got very cool in the Ordovician/Silurian transition, warmed again in the Devonian, cooled a lot again at the end of the Carboniferous, and warmed again in the Triassic. It's been quite a roller-coaster ride.

Climate changes have continued in more recent times—"recent" geologically speaking, that is. The mean annual temperature of Earth has swung up and down by several degrees Celsius over the past million years (Figure 20.5). Times of high temperature involve relatively ice-free periods (interglacial periods) over much of the planet; times of low temperature involve glacial events (Figure 20.5 a, b).[6-8]

Climate change over the last 18,000 years, during the last major time of continental glaciations, has greatly affected people. Continental glaciation ended about 12,500 years ago with a rapid warming, perhaps as brief as 100 years to a few decades.[7] This was followed by a global cooling about 11,000–13,000 years ago known as the Younger Diyas that occurred suddenly as Earth was warming (Figure 20.5c). The Younger Diyas was followed by the Medieval Warm Period, and then by the Little Ice Age, (Figure 12.5d) as discussed in the opening case study.

A warming trend began around 1850 and lasted until the 1940s, when temperatures began to cool again, followed by a leveling off in the 1950s and a further drop during the 1960s. After that, the average surface temperature rose (Figure 12.5e). The past two decades have been the warmest since global temperatures have been monitored.[6, 8]

FIGURE 20.4 The climates of the world and some of the major climate types in terms of characteristic precipitation and temperature conditions. (*Source:* Modified from W.M. Marsh and J. Dozier, *Landscape* [New York: John Wiley & Sons, 1981. Reprinted with permission of John Wiley & Sons, Inc.]).



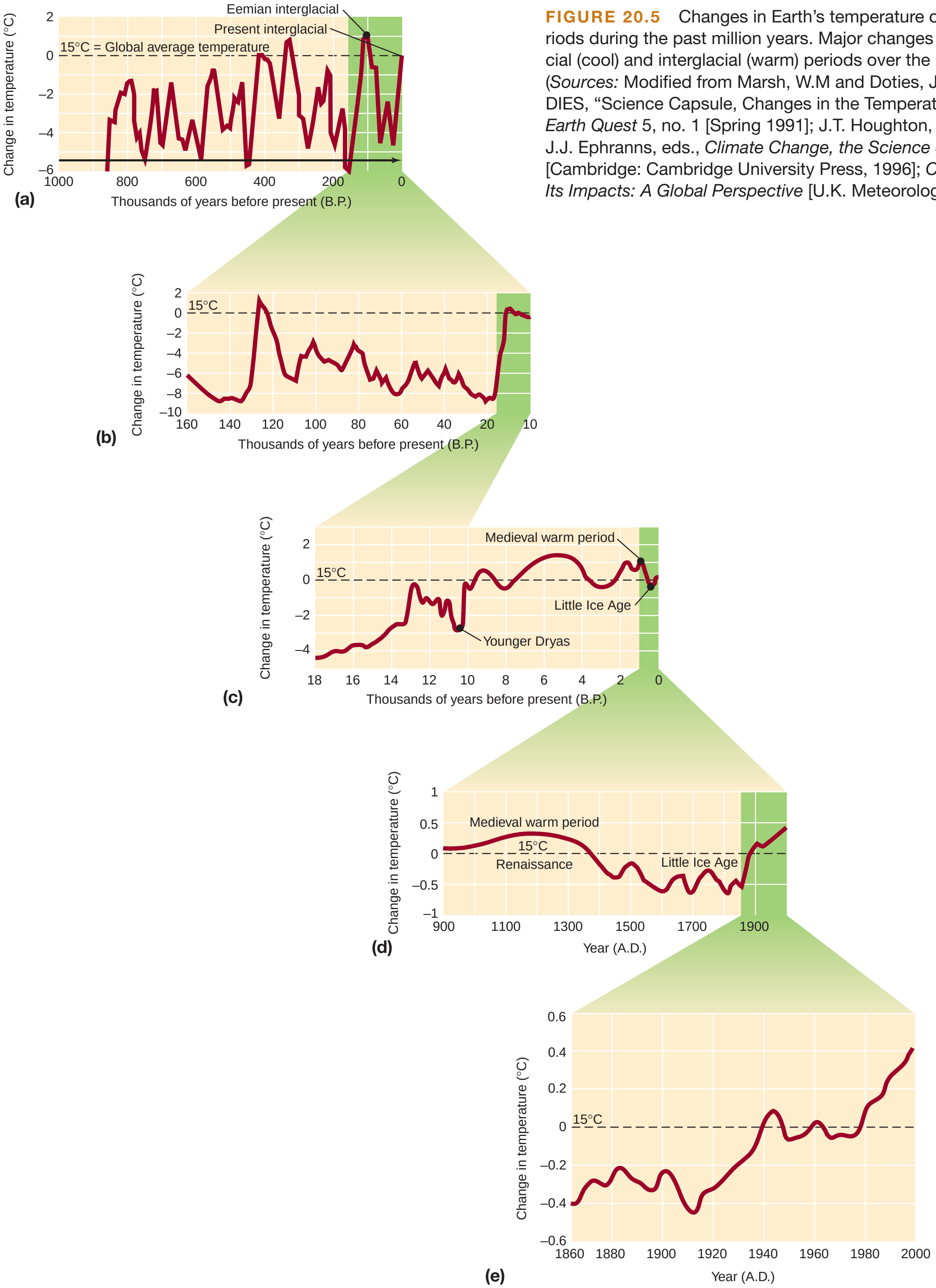


FIGURE 20.5 Changes in Earth's temperature over varying time periods during the past million years. Major changes correspond to glacial (cool) and interglacial (warm) periods over the past 800,000 years. (*Sources:* Modified from Marsh, W.M and Doties, J., 1981; and UCAR/DIES, "Science Capsule, Changes in the Temperature of the Earth," *Earth Quest* 5, no. 1 [Spring 1991]; J.T. Houghton, G.L. Jenkins, and J.J. Ephranns, eds., *Climate Change, the Science of Climate Change* [Cambridge: Cambridge University Press, 1996]; *Climate Change and Its Impacts: A Global Perspective* [U.K. Meteorological Office, 1997].

20.3 The Origin of the Global Warming Issue

That burning fossil fuels might enhance the levels of **greenhouse gases**—gases that warm the Earth's surface—was first proposed in the early 19th century, about half a century after the discovery of carbon dioxide, oxygen, and the other gases that make up the atmosphere. But well into the 20th century most scientists did not take the idea of global warming seriously. It just seemed impossible that people could be affecting the entire planet. For example, in 1938 the scientist Gary Stewart Callendar studied measurements of carbon dioxide concentration in the atmosphere taken in the 19th century and found that they were considerably lower than measurements made at his time.[9] He made some other calculations that suggested the difference could be accounted for by the amount of carbon dioxide added to the atmosphere from the burning of coal, oil, and natural gas since the beginning of the Industrial Revolution.

As it has today, the idea created a controversy. Callendar was attacked by his scientific colleagues, some of whom dismissed the notion simply on the grounds that 19th-century scientists could not have done as good a job as scientists in the 1930s, so the earlier measurements were likely inaccurate. It took modern measurement, monitoring, study of Earth's history, and new concepts to change the way scientists understood life and its environment at a global level. We turn now to that new understanding.

20.4 The Atmosphere

To understand and answer the fundamental global warming questions, we need a basic understanding of Earth's atmosphere. This atmosphere is the thin layer of gases that envelop Earth. These gases are almost always in motion, sometimes rising, sometimes falling, most of the time moving across Earth's surface. The atmosphere's gas molecules are held near to the Earth's surface by gravity and pushed upward by thermal energy—heating—of the molecules. Approximately 90% of the weight of the atmosphere is in the first 12 km above Earth's surface. Major gases in the atmosphere include nitrogen (78%), oxygen (21%), argon (0.9%), carbon dioxide (0.03%), and water vapor in varying concentrations in the lower few kilometers. The atmosphere also contains trace amounts of methane ozone, hydrogen sulfide, carbon monoxide, oxides of nitrogen and sulfur, and a number of small hydrocarbons, as well as synthetic chemicals, such as chlorofluorocarbons (CFCs). Methane at about 0.00017% of the atmosphere is emerging as an important gas that tracks closley with climate change (more so than CO_2).

Thus the atmosphere is a dynamic system, changing continuously. It is a vast, chemically active system, fueled by sunlight, affected by high-energy compounds emitted by living things (for example, oxygen, methane, and carbon dioxide) and by our industrial and agricultural activities. Many complex chemical reactions take place in the atmosphere, changing from day to night and with the chemical elements available.

Structure of the Atmosphere

You might think that the atmosphere is homogeneous, since it is a collection of gases that mix and move continuously. Actually, however, it has a surprisingly complicated structure. The **atmosphere** is made up of several vertical layers, beginning at the bottom with the **troposphere,** most familiar to us because we spend most of our lives in it. Above the troposphere is the **stratosphere,** which we visit occasionally when we travel by jet airplane, and then several other layers at higher altitudes, less familiar to us, each characterized by a range of temperatures and pressures (Figure 20.6).

The troposphere, which extends from the ground up to 10–20 km, is where weather occurs. Within the troposphere, the temperature decreases with elevation, from an average of about 17°C at the surface to –60°C at 12 km elevation. At the top of the troposphere is a boundary layer called the *tropopause,* which has a constant temperature of about –60°C and acts as a lid, or

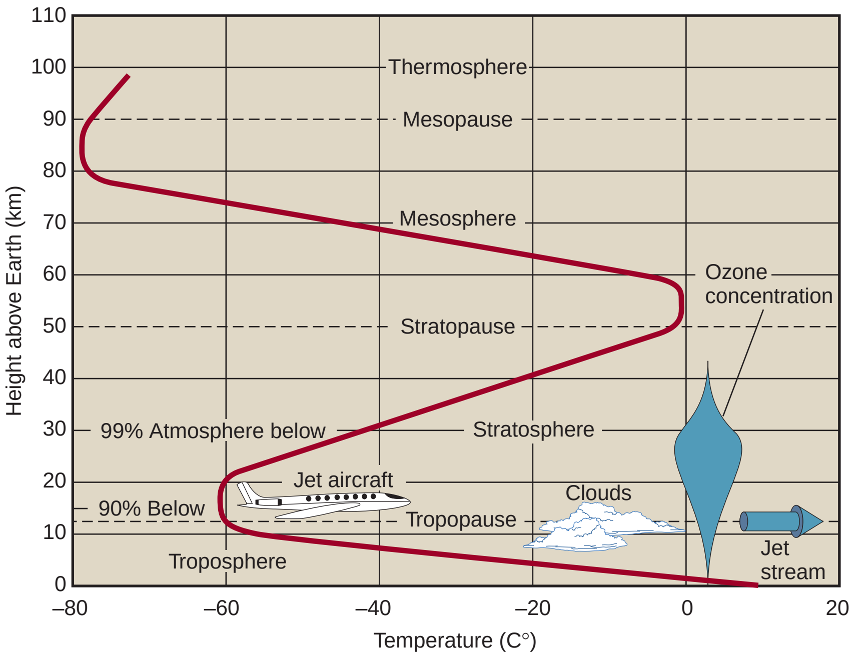


FIGURE 20.6 An idealized diagram of the structure of the atmosphere showing temperature profile and the ozone layer of the atmosphere to an altitude of 110 km. Note that 99% of the atmosphere (by weight) is below 30 km, the ozone layer is thickest at about 25–30 km, and the weather occurs below about 11 km—about the elevation of the jet stream. (*Source:* A.C. Duxbury and A.B. Duxbury, *An Introduction to the World's Oceans* [Dubuque, Iowa: Wm. C. Brown Publishers, 1997, 5th ed.].)

cold trap, on the troposphere because it is where almost all remaining water vapor condenses.

Another important layer for life is the *stratospheric ozone layer,* which extends from the tropopause to an elevation of approximately 40 km (25 mi), with a maximum concentration of ozone above the equator at about 25–30 km (16–19 mi) (Figure 20.6). Stratospheric ozone (O_3) protects life in the lower atmosphere from receiving harmful doses of ultraviolet radiation (see Chapter 21).

Atmospheric Processes: Temperature, Pressure, and Global Zones of High and Low Pressure

Two important qualities of the atmosphere are *pressure* and *temperature.* Pressure is force per unit area. Atmospheric pressure is caused by the weight of overlying atmospheric gases on those below and therefore decreases with altitude. At sea level, atmospheric pressure is 10^5 N/m^2 (newtons per square meter) (14.7 lb/in). We are familiar with this as **barometric pressure**, which the weatherman gives to us in units that are the height to which a column of mercury is raised by that pressure. We are also familiar with low- and high-pressure systems in the atmosphere. When the air pressure is low, air tends to rise, cooling as it rises and condensing its water vapor; it is therefore characterized by clouds and precipitation. When air pressure is high, it is moving downward, which warms the air, changing the condensed water drops in clouds to vapor; therefore high-pressure systems are clear and sunny.

Temperature, familiar to us as the relative warmth or coldness of materials, is a measure of thermal energy, which is the *kinetic* energy—the motion of atoms and molecules in a substance.

Water vapor content is another important characteristic of the lower atmosphere. It varies from less than 1% to about 4% by volume, depending on air temperature, air pressure, and availability of water vapor from the surface.

The atmosphere moves because of the Earth's rotation and differential heating of Earth's surface and atmosphere. These produce global patterns that include prevailing winds and latitudinal belts of low and high air pressure from the equator to the poles. Three cells of atmospheric circulation (Hadley cells) are present in

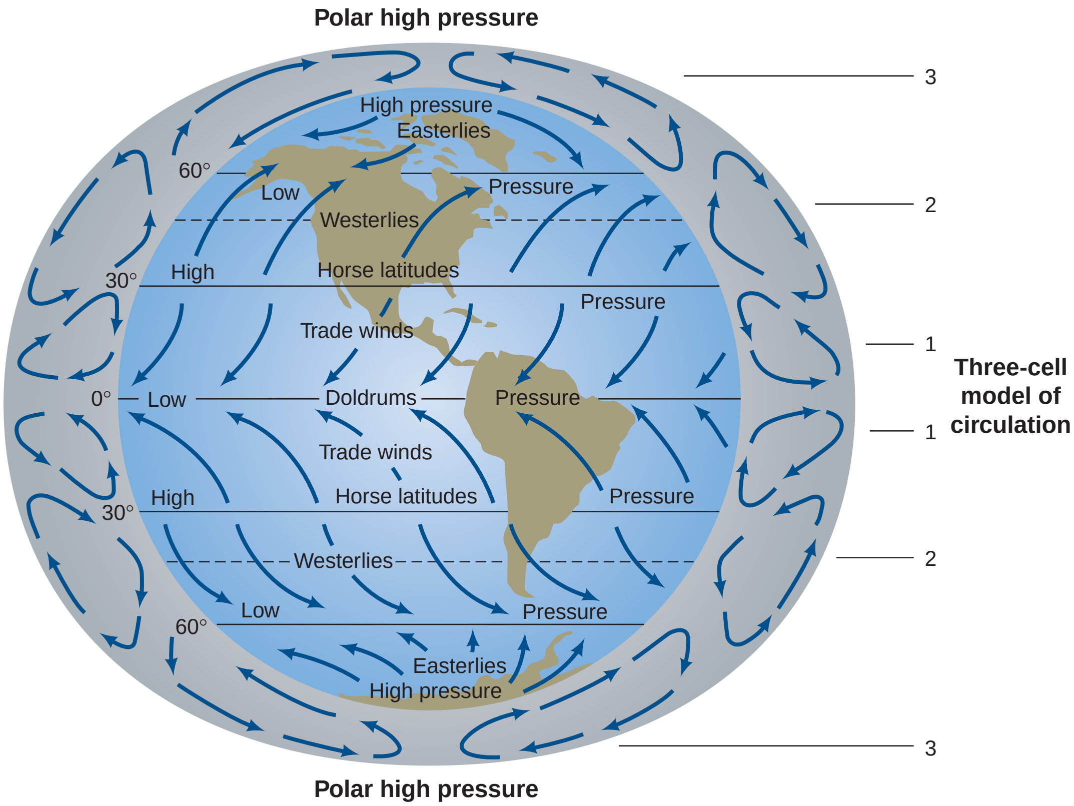


FIGURE 20.7 Generalized circulation of the atmosphere. The heating of the surface of the Earth is uneven, producing pressure differences (warm air is less dense than cooler air). There is rising warm air at the equator and sinking cool air at the poles. With rotation of Earth three cells of circulating air are formed in each hemisphere (called Hadley Cells after George Hadley who first proposed a model of atmospheric circulation in 1735). (*Source:* Samuel J. Williamson, *Fundamentals of Air Pollution*, Figure 5.5 [Reading, MS: Addison-Wesley, 1973]. Reprinted with permission of Addison-Wesley.)

each hemisphere (see Figure 20.7 for more details). In general belts of low air pressure develop at the equator where the air is warmed most of the time during the day by the sun. The heated air rises, creating an area of low pressure and a cloudy and rainy climate (cell 1 Figure 20.7). This air then moves to higher latitudes (toward the poles), and because it is cooler at higher elevations and because sunlight is less intense at the higher latitudes. By the time the air that was heated at the equator reaches about 30° latitude, it has cooled enough to become heavier, and it descends, creating a region of high pressure, with its characteristic sunny skies and low rainfall, forming a latitude belt where many of the world's deserts are found. Then the air that descended at 30° latitude moves poleward along the surface warms and rises again, creating another region of generally low pressure around 50° to 60° (cell 2, Figure 20.7) latitude and once again becoming a region of clouds and precipitation. Atmospheric orientation in cell 3 (Figure 20.7) moves air toward the poles at higher elevation and toward the equator along the surface. Sinking cool air at the poles produces the polar high-pressure zones at both poles. At the most basis level warm air rises at the equator moves toward the poles where it sinks after going through (cell 2) and return flow is along the surface of Earth toward the equator.

Of course, the exact locations of the areas of rising (low-pressure) and falling (high-pressure) air vary with the season, as the sun's position moves north and south relative to the Earth's surface. You can begin to understand that what would seem at first glance to be just a simple container of gases has complicated patterns of movement and that these change all the time for a variety of reasons.

The latitudinal belts (cells) just described have names, most of which came about during the days of sailing ships. Such names include the "doldrums," regions at the equator with little air movement; "trade winds," northeast and southeast winds important when clipper ships moved the world's goods; and "horse latitudes," two belts centered about 30° north and south of the equator with descending air and high pressure.

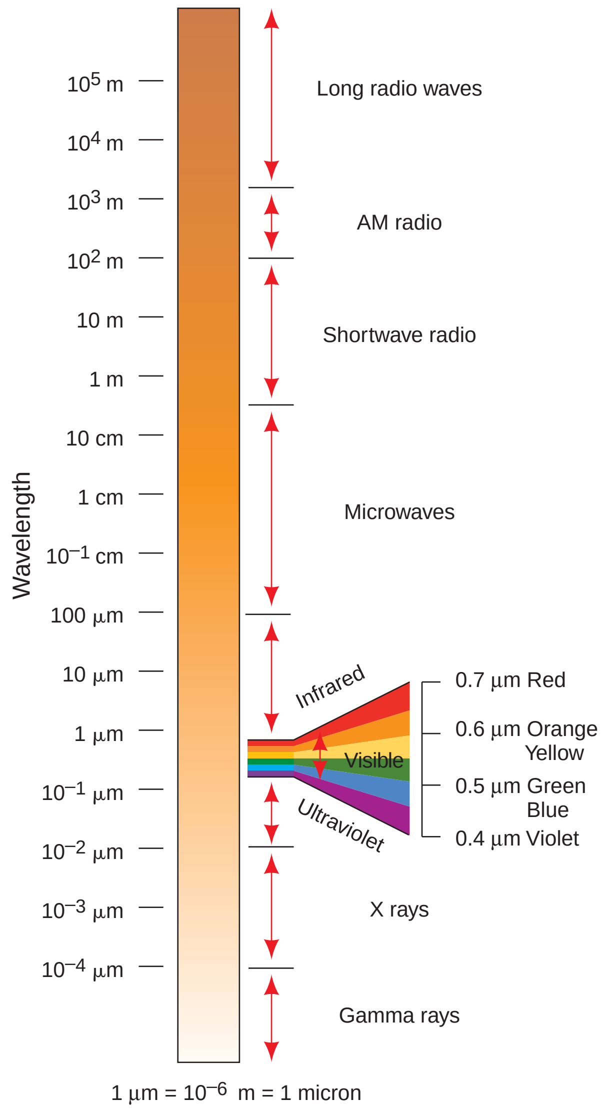


FIGURE 20.8 Kinds of electromagnetic radiation the Earth receives.

Energy and the Atmosphere: What Makes the Earth Warm

Almost all the energy the Earth receives is from the sun (a small amount comes from the interior of the Earth and an even smaller amount from frictional forces due to the moon revolving around the Earth). Sunlight comes in a wide range of electromagnetic radiation, from very long radio waves to much shorter infrared waves, then shorter wavelengths of visible light, even shorter wavelengths of ultraviolet, and then on to shorter and shorter wavelengths (Figure 20.8).

Most of the sun's radiation that reaches the Earth is in the visible and near infrared wavelengths (Figure 20.9), while the Earth, much cooler, radiates energy mostly in the far infrared, which has longer wavelengths. (The hotter the surface of any object, the shorter the dominant wavelengths. That's why a hot flame is blue and a cooler flame red.)

Under typical conditions, the Earth's atmosphere reflects about 30% of the electromagnetic (radiant) energy that comes in from the sun and absorbs about 25%. The remaining 45% gets to the surface (Figure 20.10). As the surface warms up, it radiates more energy back to the atmosphere, which absorbs some of it. The warmed atmosphere radiates some of its energy upward into outer space and some downward to the Earth's surface.

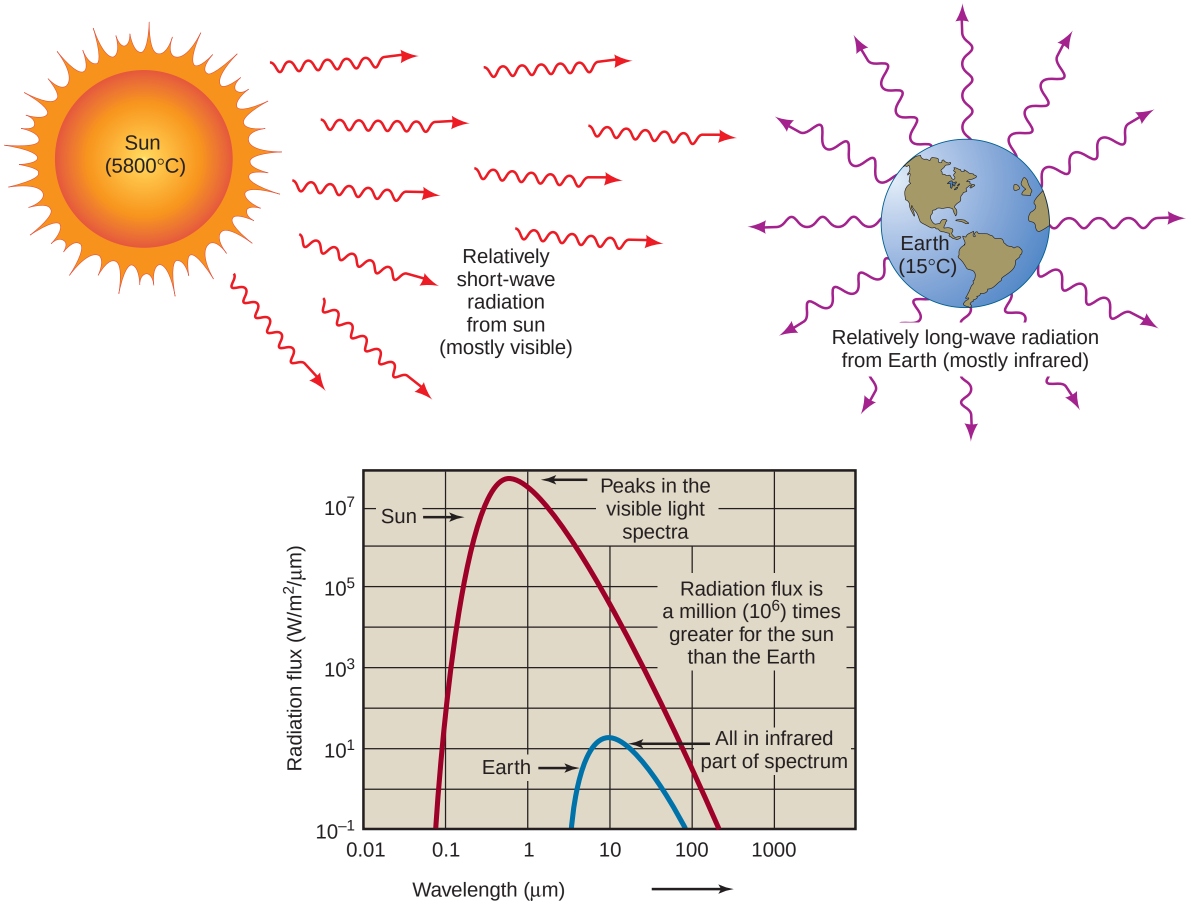


FIGURE 20.9 The sun, much hotter than the Earth, mostly emits energy in the visible and near infrared. The cooler Earth emits energy mostly in the far (longer-wavelength) infrared.

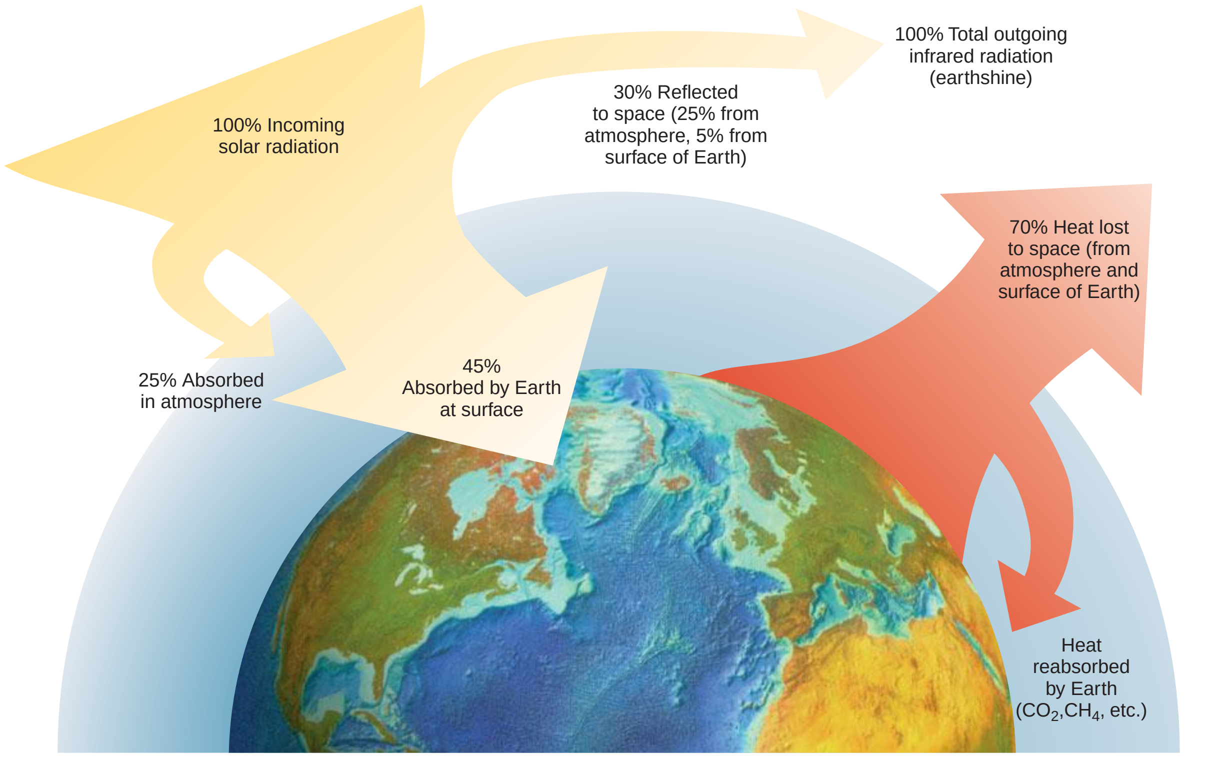


FIGURE 20.10 Earth's energy budget.

20.5 How We Study Climate

Data to document and understand climate change come from three main time periods grouped as the Instrumental Record; the Historical Record; and the Paleo-Proxy Record.[3, 10]

The Instrumental Record

The use of instruments to make climate measurements began around 1860. Since then, temperatures have been measured at various places on land and in the oceans. The average of these observations produces the graph shown earlier in Figure 20.2. In addition, the concentration of carbon dioxide in the atmosphere has been measured continuously since about 1957, and energy produced by the sun has been carefully measured over the past several decades. The problem in using these records to accurately estimate the global average is that few places have a complete record since 1850, and the places that do—such as London and Philadelphia, where people were especially interested in the weather and where scientists could readily make continual measurements—are not very representative of the global average. Until the advent of satellite remote sensing, air temperature over the oceans was measured only where ships traveled (which is not the kind of sampling that makes a statistician happy), and many of Earth's regions have never had good long-term, ground-based temperature measurements. As a result, when we want or need to know what the temperatures were like in the 19th century, before carbon dioxide concentrations began to rise from the burning of fossil fuels, experts seek ways to extrapolate, interpolate, and estimate.

Several groups have tried to reconstruct the average surface temperature of the Earth using available observations. For example, the Hadley Meteorological Center in Great Britain created a data set that divides Earth's surface into areas that are 5° longitude wide and 5° latitude high for every month of each year starting with 1850. Where historical records exist, these data are placed within the appropriate geographic rectangle. Where they are not, either the rectangle is left empty or various attempts are made to estimate what might be reasonable for that location and time. Recently, the extrapolation methods used to make these reconstructions have come under criticism, and today there is controversy over the reliability and usefulness of such attempts.

Temperature measurement has improved greatly in recent years thanks to such devices as ocean platforms with automatic weather-monitoring equipment, coordinated by the World Meteorological Organization. Thus, we have more accurate records since about 1960.

The Historical Record

A variety of documents are available from the historical records, which in some cases go back several centuries. Included here would be people's written recollections in books, newspapers, journal articles, personal journals, ships' logs, travelers' diaries, and farmers' logs, along with dates of wine harvests and small-grain harvests.[3, 10] Although these are mostly recorded as qualitative data, we can sometimes get quantitative information from them. For example, a painting of a mountain glacier in Switzerland can be used to determine the elevation to which the glacier had descended by the year it was painted. Then, as the climate cooled further, someone may have written that the same glacier reached farther down the mountain, eventually blocking a river in the valley, which flooded and destroyed a town, whose elevation is also known.

The Paleo-Proxy Record

The term *proxy data* refers to scientific data that are not strictly climatic in nature but can be correlated with climate data, such as temperature of the land or sea. Proxy data provides important insights into climate change. Information gathered as proxy data includes natural records of climate variability as indicated by tree rings, sediments, ice cores, fossil pollen, corals, and carbon-14 (^{14}C).[10]

Proxy Climate Records

Ice Cores

Polar ice caps and mountain glaciers have an accumulation record of snow that has been transformed into glacial ice over hundreds to thousands of years. Ice cores often contain small bubbles of air deposited at the time of the snow, and we can measure the atmospheric gases in these. Two important gases being measured in ice cores are carbon-dioxide (CO_2) and methane (CH_4). Of the two it appears methane most closely follows climate change determined from the geologic record over the past 1,000,000 years. As a result CO_2 and CH_4 are the most relevant proxy for climate change. The ice cores also contain a variety of chemicals and materials, such as volcanic ash and dust,

FIGURE 20.11 Scientist examining an ice core from a glacier. The core was stored in a freezer so that ice bubbles could be extracted from it to provide data about the atmosphere in the past (CO_2, dust, lead, etc.).

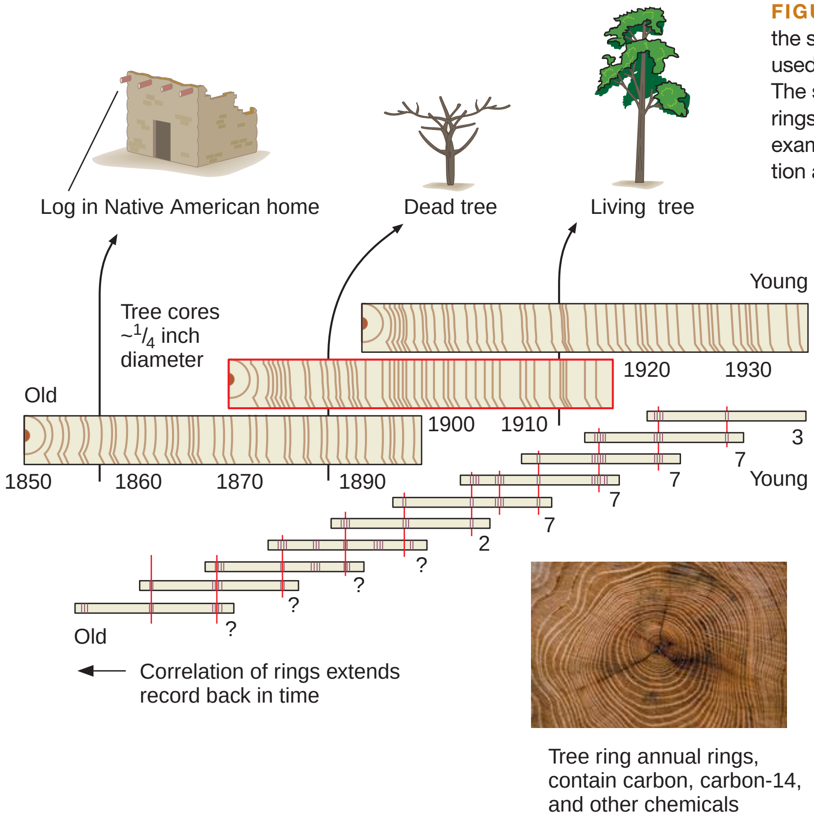


FIGURE 20.12 Dendrochronology, the study of tree growth rings, can be used as an indicator of past climate. The spacing (relative volume of wood) of rings and the isotopic content (^{14}C, for example) of wood can provide information about past rainfall and solar activity.

which may provide additional insights into possible causes of climate change. Ice cores are obtained by drilling into the ice (Figure 20.11). The age of glacial ice back to about 800,000 years is estimated by correlating ice accumulation rates linked to the geologic record of climate change from other proxy sources

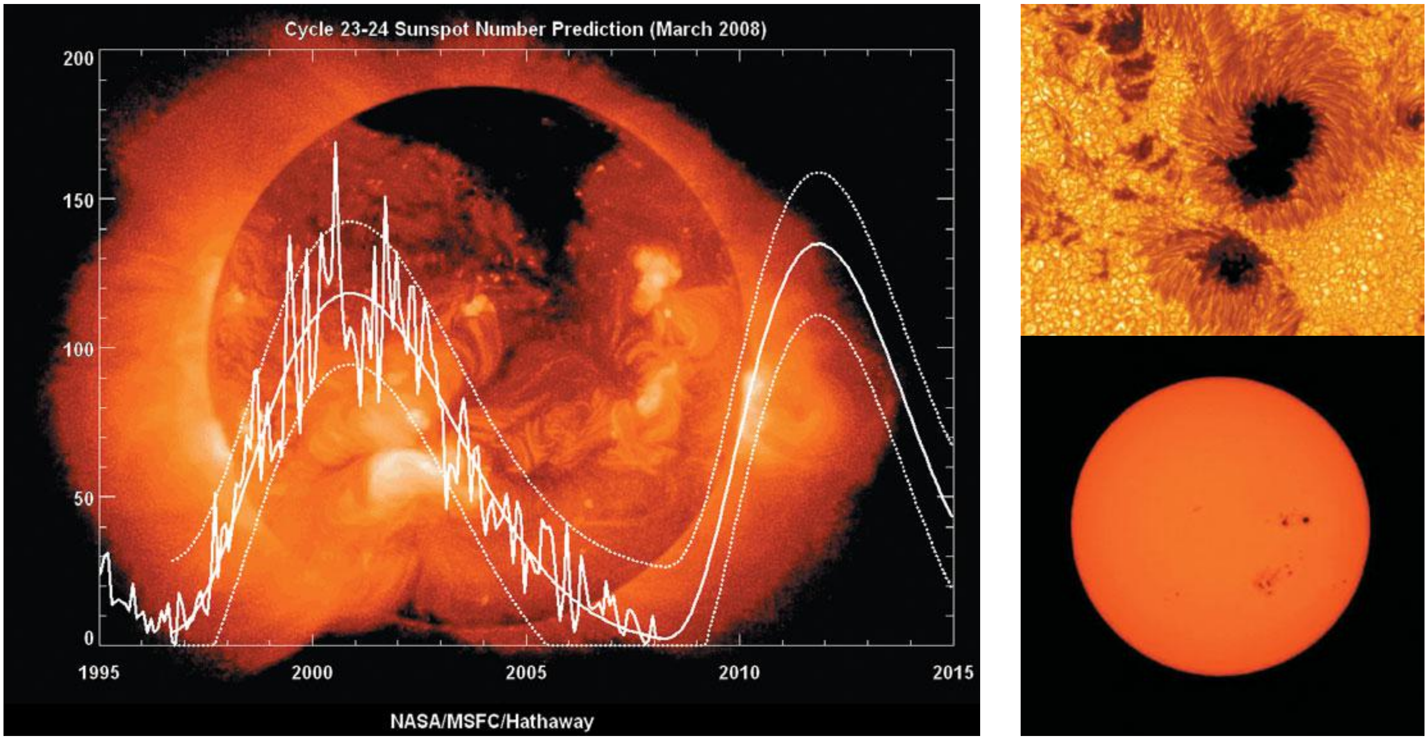
Tree Rings

The growth of trees is influenced by climate, both temperature and precipitation. Many trees put on one growth ring per year, and patterns in the tree rings—their width, density, and isotopic composition—tell us something about the variability of the climate. When conditions are good for growth, a ring is wide; when conditions are poor, the ring is narrow. Tree-ring chronology, known as dendrochronology, has produced a proxy record of climate that extends back over 10,000 years (Figure 20.12).

Sediments

Biological material, including pollen from plants, is deposited on the land and stored for very long periods in lake, bog, and pond sediments and, once transported downstream to the coast, in the oceans. Samples may be taken of very small fossils and of chemicals in the sediments, and these may be interpreted to study past climates and extend our knowledge back hundreds of thousand years (Figure 20.13). Pollen is useful because (1) the quantity of pollen is an indicator of the relative abundance of each plant species; (2) the pollen can be dated, and since the grains are preserved in sedimentary layers that also might be dated, we can develop a chronology; and (3) based on the types of plants found at different times, we can construct a climatic history.

FIGURE 20.13 Scientist examining a sediment core taken by drilling into the seafloor.



(a) (b)

FIGURE 20.14 **(a)** Sunspot cycle with number of sunspots per year, from 1995 to 2009 and **(b)** photos of sunspots in 2003. The large sunspots are about 150,000 km across (for comparison, Earth's diameter is about 12,750 km). The sunspots are the dark areas, and each is surrounded by an orange ring and then a hot gold color. Notice the great variety in the number of sunspots from year to year in the 11-year cycle (over 150 in 2001 and very few in 2008 and 2009). (*Source:* NOAA Images.)

Sediments recovered by drilling in the bottom of the ocean basin provide some of the very strongest evidence of past climate change.

Corals

Corals have hard skeletons composed of calcium carbonate ($CaCO_3$), a mineral extracted by the corals from seawater. The carbonate contains isotopes of oxygen, as well as a variety of trace metals, which have been used to determine the temperature of the water in which the coral grew. The growth of corals has been dated directly with a variety of dating techniques over short time periods of coral growth thereby revealing the chronology of climate change over variable time periods.

Carbon-14

Radioactive carbon-14 (^{14}C) is produced in the upper atmosphere by the collision of cosmic rays and nitrogen-14 (^{14}N). Cosmic rays come from outer space; those the Earth receives are predominantly from the sun. The abundance of cosmic rays varies with the number of sunspots, so called because they appear as dark areas on the sun (Figure 20.14). The frequency of sunspots has been accurately measured for decades and observed by people for nearly 1,000 years. As sunspot activity increases, more energy from the sun reaches Earth. There is an associated solar wind, which produces ionized particles consisting mostly of protons and electrons, emanating from the sun. The radioactive ^{14}C is taken up by photosynthetic organisms—green plants, algae, and some bacteria—and stored in them. If these materials become part of sediments (see above), the year at which they were deposited can be estimated from the decay rate of the ^{14}C.

The record of ^{14}C in the atmosphere has been correlated with tree-ring chronology. Each ring of wood of known age contains carbon, and the amount of ^{14}C can be measured. Then, given the climatic record, it may be correlated with ^{14}C, and that correlation has been shown to be very strong.[10]

Thus, we can examine the output of the sun, going back thousands of years, by studying tree rings and the carbon-14 they contain. This connects to our opening case study about the Medieval Warm Period. Based on these records, it appears that the production of solar energy was slightly higher around A.D. 1000, during the Medieval Warm Period, and slightly lower during the Little Ice Age that followed several hundred years later and lasted from A.D. 1300 to 1850.

20.6 The Greenhouse Effect

Each gas in the atmosphere has its own absorption spectrum—which wavelengths it absorbs and which it transmits. Certain gases in Earth's atmosphere are especially strong absorbers in the infrared and therefore absorb radiation emitted by the warmed surfaces of the Earth. Warmed by this, the gases reemit this radiation. Some of it reaches back to the surface, making Earth warmer than it otherwise would be. The process by which the heat is trapped is not the same as in a greenhouse (air in a closed greenhouse has restricted circulation and will heat up). Still, in trapping heat this way, the gases act a little like the glass panes, which is why it is called the **greenhouse effect.** The major greenhouse gases are water vapor, carbon dioxide, methane, some oxides of nitrogen, and chlorofluorocarbons (CFCs). The greenhouse effect is a natural phenomenon that occurs on Earth and on other planets in our solar system. Most natural greenhouse warming is due to water in the atmosphere—water vapor and small particles of water in the atmosphere produce about 85% and 12%, respectively, of the total greenhouse warming.

How the Greenhouse Effect Works

Figure 20.15 is a highly idealized diagram of some important aspects of the greenhouse effect. The arrows labeled "energy input" represent the energy from the sun absorbed at or near Earth's surface. The arrows labeled "energy output" represent energy emitted from the upper atmosphere and Earth's surface, which balances input, consistent with Earth's energy balance. The highly contorted lines near the surface of the Earth represent the absorption of infrared radiation (IR) occurring there and producing the 15°C (59°F) near-surface temperature. Following many scatterings and absorptions and reemissions, the infrared radiation emitted from levels near the top of the atmosphere (troposphere) corresponds to a temperature of approximately 18°C (0°F). The one output arrow that goes directly through Earth's atmosphere represents radiation emitted through what is called the atmospheric window (Figure 20.16). The atmospheric window, centered on a wavelength of 10 m, is a region of wavelengths (8–12 m) where outgoing radiation from Earth is not absorbed well by natural greenhouse gases (water vapor and carbon dioxide). Anthropogenic CFCs do absorb in this region, however, and CFCs significantly contribute to the greenhouse effect in this way.

Let us look more closely at the relation of the greenhouse effect to Earth's energy balance, which was introduced in a simple way. The figure showed that, of the simple solar radiation, approximately 30% is reflected back to space from the atmosphere as shortwave solar radiation, while 70% is absorbed by Earth's surface and atmosphere. The 70% that is absorbed is eventually reemitted as infrared radiation into space. The sum of the reflected solar radiation and the outgoing infrared radiation balances with the energy arriving from the sun.

This simple balance becomes much more complicated when we consider exchanges of infrared radiation within the atmosphere and Earth surface. In some instances, these internal radiation fluxes (rates of transfer) may have magnitudes greater than the amount of energy entering Earth's atmospheric system from the sun, as shown in Figure 20.17. A major contributor to the fluxes is the greenhouse effect. At first glance, you might think it would be impossible to have internal radiation fluxes greater than the total amount of incoming solar radiation (shown as 100 units in Figure 20.17). It is possible because the infrared radiation is reabsorbed and readmitted many times in the

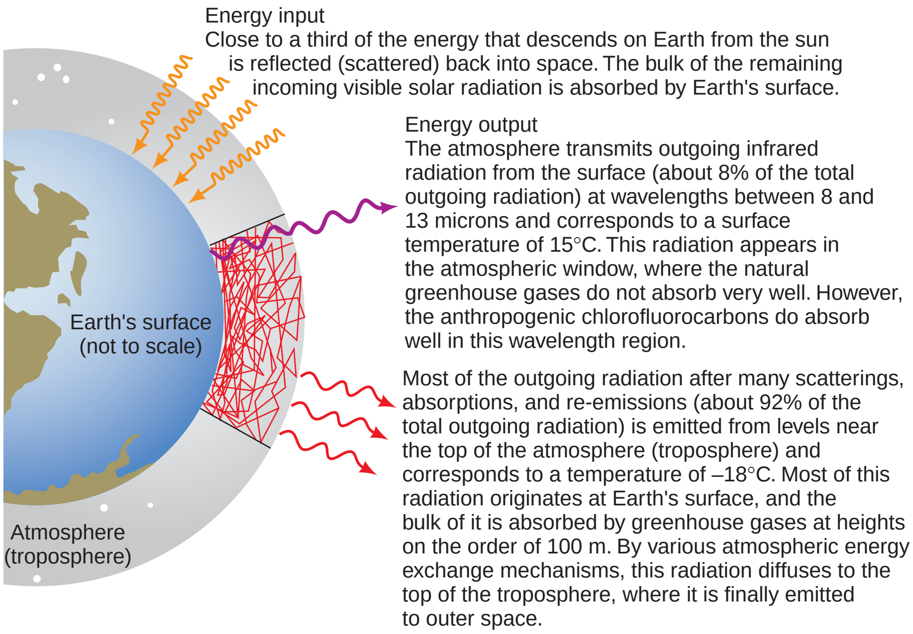


FIGURE 20.15 Idealized diagram showing the greenhouse effect. Incoming visible solar radiation is absorbed by Earth's surface, to be reemitted in the infrared region of the electromagnetic spectrum. Most of this reemitted infrared radiation is absorbed by the atmosphere, maintaining the greenhouse effect. (*Source*: Developed by M.S. Manalis and E.A. Keller, 1990.)

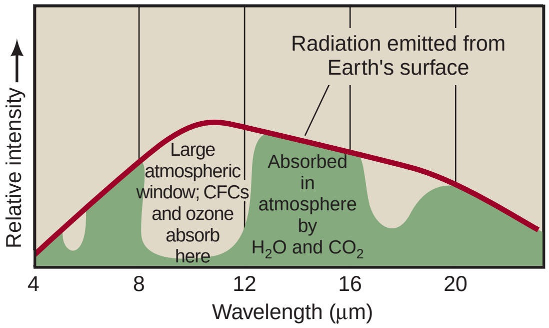


FIGURE 20.16 What the major greenhouse gases absorb in the Earth's atmosphere. Earth's surface radiates mostly in the infrared, which is the range of electromagnetic energy shown here. Water and carbon dioxide absorb heavily in some wavelengths within this range, making them major greenhouse gases. The other greenhouse gases, including methane, some oxides of nitrogen, CFCs, and ozone, absorb smaller amounts but in wavelengths not absorbed by water and carbon dioxide. (*Source*: Modified from T.G. Spiro and W.M. Stigliani, *Environmental Science in Perspective* [Albany: State University of New York Press, 1980].)

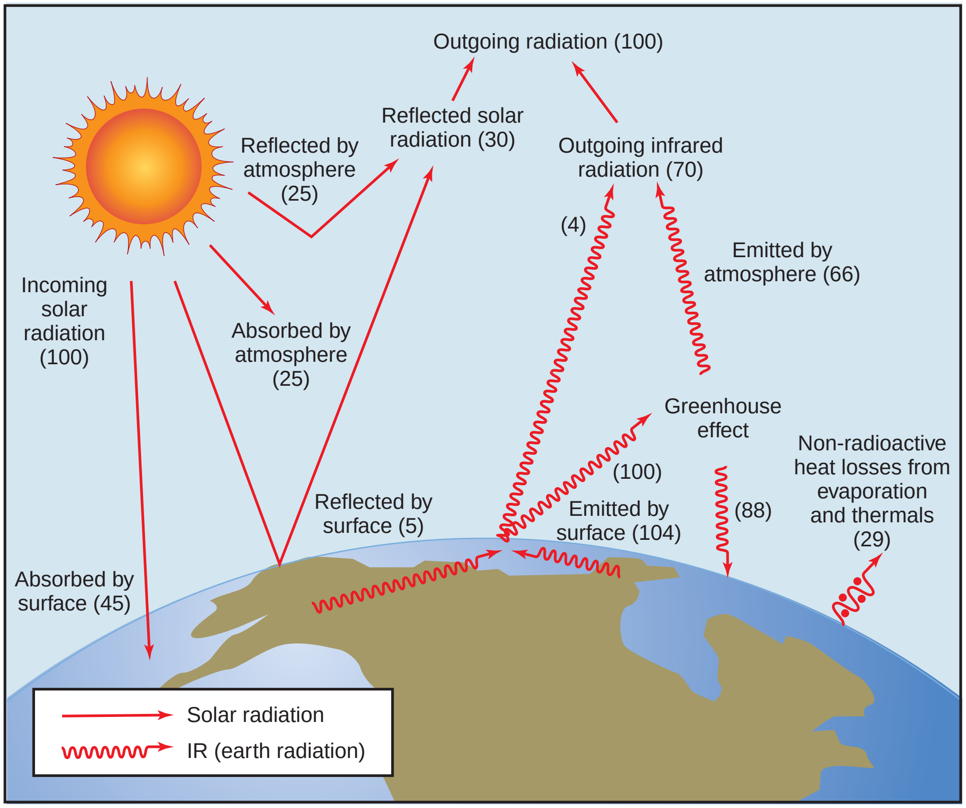


FIGURE 20.17 Idealized diagram showing Earth's energy balance and the greenhouse effect. Incoming solar radiation is arbitrarily set at 100 units, and this is balanced by outgoing radiation of 100 units. Notice that some of the fluxes (rates of transfer) of infrared radiation (IR) are greater than 100, reflecting the role of the greenhouse effect. Some of these fluxes are explained in the diagram. (*Source*: Modified from D.I. Hartmann, *Global Physical Climatology, International Geophysics Series*, vol. 56 [New York: Academic Press. 1994] and S. Schneider, "Climate Modeling," *Scientific American* 256 No. 5.)

- Total incoming solar radiation = 100 units

- Total absorbed by surface = 133 units
  45 from solar radiation (shortwave)
  88 from greenhouse effect IR (infrared)

- Total emitted by surface = 133 units
  104 IR (of this, only 4 units pass directly to space without being absorbed or re-emitted in greenhouse effect)
  29 from evaporation and thermals (non-radioactive heat loss)

- Total IR emitted by upper atmosphere to space = 70 units
  66 units emitted by atmosphere
  4 units emitted by surface

- The 25 units of solar radiation absorbed by atmosphere are eventually emitted as IR (part of the 66 units)

- Total outgoing radiation = 100 units
  70 IR
  30 reflected solar radiation

atmosphere, resulting in high internal fluxes. For example, in terms of the figure, the amount of IR absorbed at Earth's surface from the greenhouse effect is approximately 88 units, which is about twice the amount of shortwave solar radiation (45 units) absorbed by Earth's surface. Despite the large internal fluxes, the overall energy balance remains the same. At the top of the atmosphere, the net downward solar radiation (70 units, 45 units + 25 units) balances the outgoing IR from the top of the atmosphere (70 units).

The important point here is recognizing the strength of the greenhouse effect. For example, notice in the figure that of the 104 units of IR emitted by the surface of Earth, only 4 go directly to the upper atmosphere and are emitted. The rest is reabsorbed and reemitted by greenhouse gases. Of these, 88 units are directed downward to Earth and 66 units upward to the upper atmosphere.

All this may sound somewhat complicated, but if you read and study the points mentioned in Figures 20.15 to 20.17 carefully and work through the balances of the various parts of the energy fluxes, you will gain a deeper understanding of why the greenhouse effect is so important. The greenhouse effect keeps Earth's lower atmosphere approximately 33°C warmer than it would otherwise be and performs other important service functions as well. For example, without the strong downward emission of IR from the greenhouse effect, the land surface would cool much faster at night and warm much more quickly during the day. In sum, the greenhouse effect helps to limit temperature swings from day to night and maintain relatively comfortable surface temperatures. It is, then, not the greenhouse effect itself but the changes in greenhouse gases that are a concern.

20.7 The Major Greenhouse Gases

The major anthropogenic greenhouse gases are listed in Table 20.1. The table also lists the recent rate of increase for each gas and its relative contribution to the anthropogenic greenhouse effect.

Carbon Dioxide

Current estimates suggest that approximately 200 billion metric tons of carbon in the form of carbon dioxide (CO_2) enter and leave Earth's atmosphere each year as a result of a number of biological and physical processes: 50 to 60% of the anthropogenic greenhouse effect is attributed to this gas. Measurements of carbon dioxide trapped in air bubbles in the Antarctic ice sheet suggest that 160,000 years before the Industrial Revolution the atmospheric concentration of carbon dioxide varied from approximately 200 to 300 ppm.[12] The highest level or concentration of carbon dioxide in the atmosphere, other than today's, occurred during the major interglacial period about 125,000 years ago.

About 140 years ago, just before the major use of fossil fuels began as part of the Industrial Revolution, the atmospheric concentration of carbon dioxide was approximately 280 ppm.[13] Since then, and especially in the past few decades, the concentration of CO_2 in the atmosphere has grown rapidly. Today, the CO_2 concentration is about 392 ppm, and at its current rate of increase of about 0.5% per year, the level may rise to approximately 450 ppm by the year 2050—more than 1.5 times the preindustrial level.[13]

Table 20.1 MAJOR GREENHOUSE GASES

TRACE GASES	RELATIVE CONTRIBUTION (%)	GROWTH RATE (%/YR)
CFC	15[a]-25[b]	5
CH_4	12[a]-20[b]	0.4[c]
O_3(troposphere)	8[d]	0.5
N_2O	5[d]	0.2
Total	40–50	
Contribution of CO_2	50–60	0.3[e]–0.5[d,f]

[a]W. A. Nierenberg, "Atmospheric CO_2: Causes, Effects, and Options," *Chemical Engineering Progress* 85, no.8 (August 1989): 27

[b]J. Hansen, A. Lacis, and M. Prather, "Greenhouse Effect of Chlorofluorocarbons and Other Trace Gases," *Journal of Geophysical Research* 94 (November 20, 1989): 16, 417.

[c]Over the past 200 yrs.

[d]H. Rodha, "A Comparison of the Contribution of Various Gases to the Greenhouse Effect," *Science* 248 (1990): 1218, Table 2.

[e]W. W. Kellogg, "Economic and Political Implications of Climate Change," paper presented at Conference on Technology-based Confidence Building: Energy and Environment, University of California, Los Alamos National Laboratory, July 9–14, 1989.

[f]H. Abelson, "Uncertainties about Global Warming," *Science* 247 (March 30,1990): 1529.

Methane

The concentration of methane (CH_4) in the atmosphere more than doubled in the past 200 years and is thought to contribute approximately 12 to 20% of the anthropogenic greenhouse effect.[14, 15] Certain bacteria that can live only in oxygenless atmospheres produce methane and release it. These bacteria live in the guts of termites and the intestines of ruminant mammals, such as cows, which produce methane as they digest woody plants. These bacteria also live in oxygenless parts of freshwater wetlands, where they decompose vegetation, releasing methane as a decay product. Methane is also released with seepage from oil fields and seepage from methane hydrates (see Chapter 15).

Our activities also release methane. These activities include landfills (the major methane source in the United States), the burning of biofuels, production of coal and natural gas, and agriculture, such as raising cattle and cultivating rice. (Methane is also released by anaerobic activity in flooded lands where rice is grown.) As with carbon dioxide, there are important uncertainties in our understanding of the sources and sinks of methane in the atmosphere.

Chlorofluorocarbons

Chlorofluorocarbons (CFCs) are inert, stable compounds that have been used in spray cans as aerosol propellants and in refrigerators. The rate of increase of CFCs in the atmosphere in the recent past was about 5% per year, and it has been estimated that approximately 15 to 25% of the anthropogenic greenhouse effect may be related to CFCs. Because they affect the stratospheric ozone layer and also play a role in the greenhouse effect, the United States banned their use as propellants in 1978. In 1987, 24 countries signed the Montreal Protocol to reduce and eventually eliminate production of CFCs and accelerate the development of alternative chemicals. As a result of the treaty, production of CFCs was nearly phased out by 2000.

Potential global warming from CFCs is considerable because they absorb in the atmospheric window, as explained earlier, and each CFC molecule may absorb hundreds or even thousands of times more infrared radiation emitted from Earth than is absorbed by a molecule of carbon dioxide. Furthermore, because CFCs are highly stable, their residence time in the atmosphere is long. Even though their production was drastically reduced, their concentrations in the atmosphere will remain significant (although lower than today's) for many years, perhaps for as long as a century.[16, 17] (CFCs are discussed in Chapter 21, which examines stratospheric ozone depletion.)

Nitrous Oxide

Nitrous oxide (N_2O) is increasing in the atmosphere and probably contributes as much as 5% of the anthropogenic greenhouse effect.[18] Anthropogenic sources of nitrous oxide include agricultural application of fertilizers and the burning of fossil fuels. This gas, too, has a long residence time; even if emissions were stabilized or reduced, elevated concentrations of nitrous oxide would persist for at least several decades.

20.8 Climate Change and Feedback Loops

Part of the reason climate change is so complex is that there can be many positive and negative feedback loops. Only a few possible feedback loops of many are discussed here. Negative feedbacks are self-inhacing and help stabilize a system. Positive feedbacks are self-regulating, so a greater change now will result in an even greater change in the future. This is a simplistic statement about feedback and climate because some changes are associated with both positive and negative feedback. With this caveat stated, we will discuss positive and negative feedbacks with respect to climate change. We discussed feedback in Chapter 3; you may wish to review those concepts.

Here are some feedback loops that have been suggested for climate change.[19]

Possible Negative Feedback Loops for Climate Change

- As global warming occurs, the warmth and additional carbon dioxide could stimulate algae growth. This, in turn, could absorb carbon dioxide, reducing the concentration of CO_2 in the atmosphere and cooling Earth's climate.
- Increased CO_2 concentration with warming might similarly stimulate growth of land plants, leading to increased CO_2 absorption and reducing the greenhouse effect.
- If polar regions receive more precipitation from warmer air carrying more moisture, the increasing snowpack and ice buildup could reflect solar energy away from Earth's surface, causing cooling.
- Increases in water evaporation with warming from the ocean and the land could lead to cloudier conditions (the water vapor condenses), and the clouds would reflect more sunlight and cool the surface.

Possible Positive Feedback Loops for Climate Change

- The warming Earth increases water evaporation from the oceans, adding water vapor to the atmosphere. Water vapor is a major greenhouse gas that, as it increases, causes additional warming. If more clouds form from the increaced water vapor, and more solar radiation is reflected this would cause cooling as discussed with negative feedback above. Thus water vapor is associated with both positive and negative feedback. This makes study of clouds and global climate change complex.
- The warming Earth could melt a large amount of permafrost at high latitudes, which would in turn release the greenhouse gas methane, a by-product of decomposition of organic material in the melted permafrost layer. This would cause additional warming.
- Replacing some of the summer snowpack or glacial ice with darker vegetation and soil surfaces decreases the albedo (reflectivity) increasing the absorption of solar energy, further warming surface. This is a powerful positive feedback explaining, in part, why the Arctic is warming faster than at lower latitudes.
- In warming climates, people use more air-conditioning and thus more fossil fuels. The resulting increase in carbon dioxide could lead to additional global warming.

Since negative and positive feedback can occur simultaneously in the atmosphere, the dynamics of climate change are all the more complex. Research is ongoing to better understand negative feedback processes associated with clouds and their water vapor.

20.9 Causes of Climate Change

Not until the 19th century did scientists begin to understand that climate changed greatly over long periods and included times of continental glaciations. The realization that there had been glacial and interglacial episodes began in 1815 when a Swiss peasant, Jean-Paul Perraudin, suggested to a Swiss civil engineer, Ignaz Venetz-Sitten, that some features of mountain valleys, including the boulders and soil debris, were due to glaciers that in a previous time had extended down the slopes beyond their present limits. Impressed with these observations, Venetz-Sitten spoke before a natural history society at Lucerne in 1821 and suggested that the glaciers had at some previous time extended considerably beyond their present range.

At first, he wasn't taken seriously—in fact, the famous 19th-century geologist Louis Agassiz traveled to the Alps to refute these ideas. But once Agassiz saw the evidence, he changed his mind and formulated a theory of continental glaciation. The evidence was debris—rocks and soils—at the edges of existing mountain glaciers and the same kinds of deposits at lower elevations. Agassiz realized that only glaciers could have produced the kinds of debris now far below the ice. It was soon recognized that glaciers had covered vast areas in Great Britain, mainland Europe, and North America.[20]

This began the search for an answer to a puzzling question: Why does the climate change, and change so drastically? One of the most important insights was achieved in the 1920s by Milutin Milankovitch, a Serbian astronomer who looked at long-term climate records and began to think about what might correlate with these records. Look at Figure 20.18 and you will see that cycles of about 100,000 years are apparent; these seem to be divided as well into shorter cycles of about 20,000 to 40,000 years.

Milankovitch Cycles

Milankovitch realized that the explanation might have to do with the way the Earth revolved on its axis and rotated around the sun. Our spinning Earth is like a wobbling top following an elliptical orbit around the sun. Three kinds of changes occur.

First, the wobble means that the Earth is unable to keep its poles at a constant angle in relation to the sun (Figure 20.18a). Right now, the North Pole points to Polaris, the North Star, but this changes as the planet wobbles. The wobble makes a complete cycle in 26,000 years.

Second, the tilt of Earth's axis varies over a period of 41,000 years (Figure 20.18b).

Third, the elliptical orbit around the sun also changes. Sometimes it is a more extreme ellipse; at other times it is closer to a circle (Figure 20.18c), and this occurs over 100,000 years.

The combination of these changes leads to periodic changes in the amount and distribution of sunlight reaching the Earth. Sometimes the wobble causes the Northern Hemisphere to be tilted toward the sun (Northern Hemisphere summertime) when the Earth is closest to the sun. At other times, the opposite occurs—the Northern Hemisphere is tipped away from the sun (northern wintertime) when the Earth is closest to the sun. Milankovitch showed that these variations correlated with the major glacial and interglacial periods (Figure 20.18). They are now called Milankovitch cycles.[21]

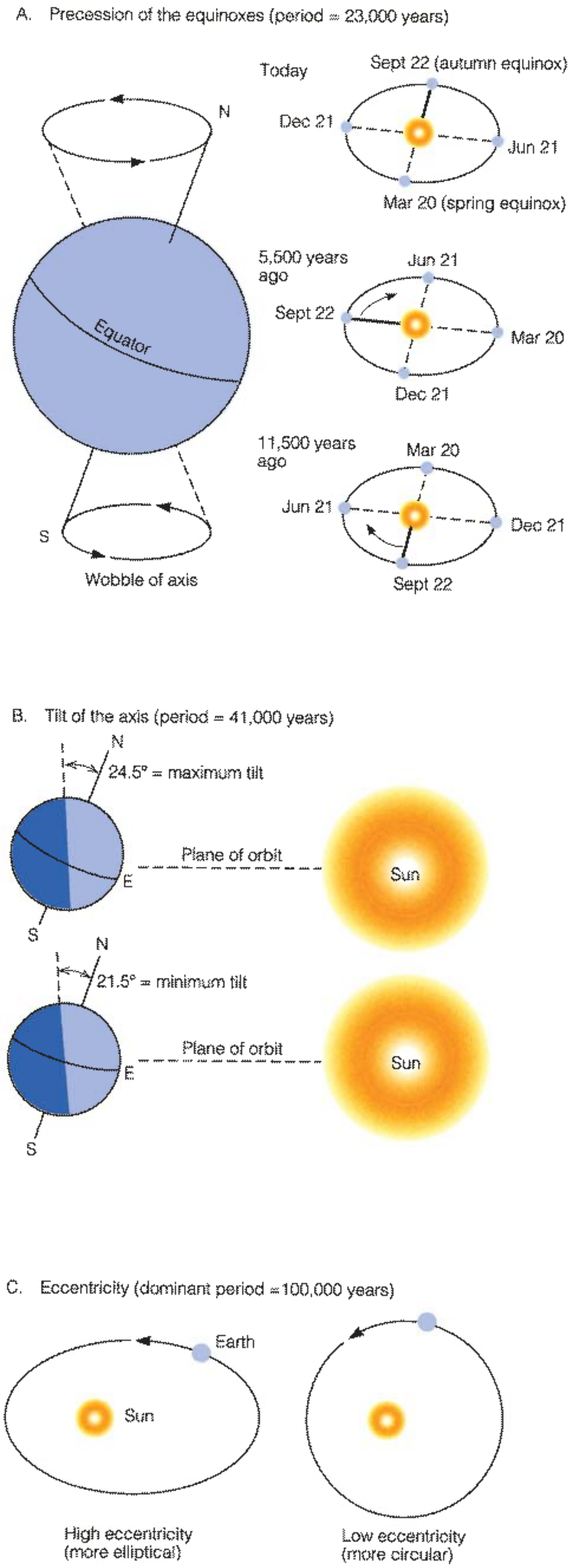


FIGURE 20.18 The Earth wobbles, changes its tilt, and has an elliptical orbit that changes as well. (*Source:* Skinner, Porter, and Botkin, *The Blue Planet* [John Wiley], 2nd edition, p. 335.)

Milankovich attempted explain ice ages through changes in solar radiation reaching Earth. His contribution is very significant. While Milankovitch cycles are consistent with the timing of variations in glacial and inter glacial change, they were not intented to not account for all the large-scale climatic variations in the geologic record. It is perhaps best to think of these cycles as response of climate to orbital variations.

Once Earth receives energy from the sun, Earth's surface features affect the climate. These earthly factors that affect, and are in turn affected by, regional and global temperature changes include warmer ice-sheet temperatures; changes in vegetation; changes in atmospheric gases, such as carbon dioxide, methane, and nitrous oxide; and particulates and aerosols. Volcanoes inject aerosols into the upper atmosphere, where they reflect sunlight and cool the Earth's surface.

Solar Cycles

As we discussed earlier, the sun goes through cycles too, sometimes growing hotter, sometimes colder. Today, solar intensity is observed directly with telescopes and other instruments. Variations in the sun's intensity in the past can be determined because hotter and cooler sun periods emit different amounts of **radionuclides**—atoms with unstable nuclei that undergo radioactive decay (such as beryllium-10 and carbon-14), which are trapped in glacial ice and can then be measured. As we mentioned earlier, evaluation of these radionuclides in ice cores from glaciers reveals that during the Medieval Warm Period, from approximately A.D. 950 to 1250, the amount of solar energy reaching Earth was relatively high, and that minimum solar activity occurred during the 14th century, coincident with the beginning of the Little Ice Age. Thus, it appears that the variability of solar energy input explains a small part of the Earth's climatic variability.[22, 23] Since about 1880 solar input has increased about 0.5% while CO_2 has increased about 33%. Solar input in the Arctic has closely followed annual surface temperature. Since 1960, CO_2 increase in the atmosphere has been about 25% in close agreement with Arctic surface temperature increase. Thus in the past 50 years CO_2 appears to be a dominant factor in increasing surface temperature in the Arctic as well as the entire Earth.[24] That is recent warming cannot be explained by solar activity.

Atmospheric Transparency Affects Climate and Weather

How transparent the atmosphere is to the radiation coming to it, from both the sun and Earth's surface, affects the temperature of the Earth. Dust and aerosols absorb light, cooling the Earth's surfaces. Volcanoes and large forest fires put dust into the atmosphere, as do various human activities, such as plowing large areas. Each gas compound has its own absorption spectrum (the electromagnetic radiation that is absorbed by a gas as it passes through the atmosphere). Thus the chemical and physical composition of the atmosphere can make things warmer or cooler.

The Surface of Earth and Albedo (reflectivity) Affects

Albedo is the reflectivity of an object that is measured as the percentage of incoming radiation that is reflected. For examples the approximate albedos are: Earth (as a whole) is 30%, clouds depending on type and thickness are 40–90%, fresh snow is 85%, glacial ice depending on soil rock cover is 20–40%, a pine forest is 10% dark rock is 5–15%, dry sand is 40%, and a grass-covered meadow is 15%.

A dark rock surface exposed near the North Pole absorbs more of the sunlight it receives than it reflects in the summer, warming the surface and the air passing over it. When a glacier spreads out and covers that rock, it reflects more of the incoming sunlight than the darker rock cooling both the surface and the air that comes in contact with it.

Vegetation also affects the climate and weather in the same way. If vegetation is a darker color than the soil, it warms the surface. If it is a lighter color than the soil, it cools the surface. Now you know why if you walk barefoot on dark asphalt on a hot day you feel the heat radiating from the surface (you may burn the bottom of your feet).

Roughness of the Earth's Surface Affects the Atmosphere

Above a completely smooth surface, air flows smoothly—a flow called "laminar." A rough surface causes air to become turbulent—to spin, rotate, reverse, and so forth. Turbulent air gives up some of the energy in its motion (its kinetic energy), and that energy is turned into heat. This affects the weather above. Forests are a much rougher surface than smooth rock or glaciers, so in this way, too, vegetation affects weather and climate.

The Chemistry of Life Affects the Atmosphere

The emission and uptake of chemicals by living things affect the weather and climate, as we will discuss in detail in the next section. Thus, a planet with water vapor, liquid water, frozen water, and living things has a much more complex energy-exchange system than a lifeless, waterless planet. This is one reason (of many) why it is difficult to forecast climate change.

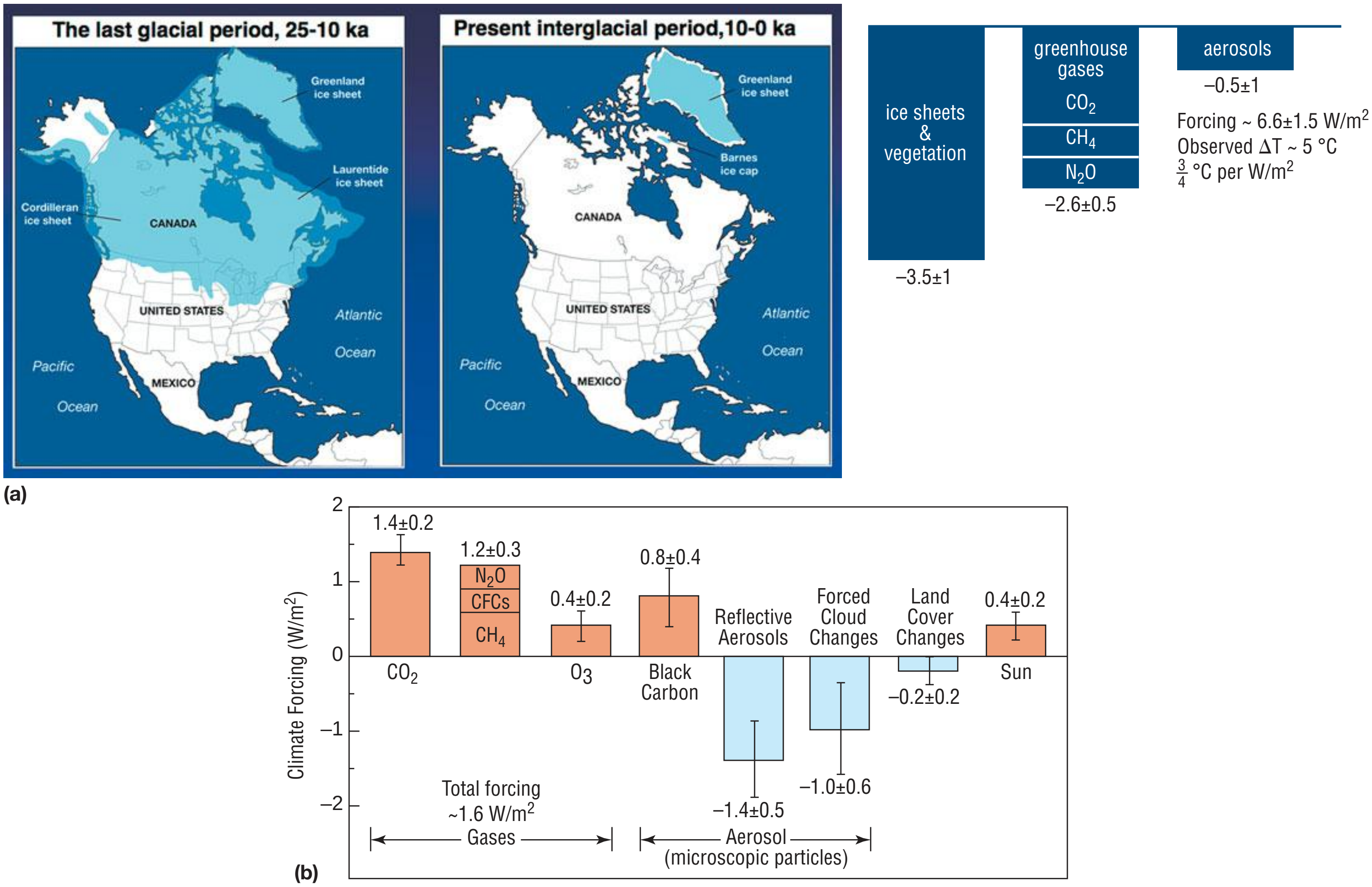
Climate Forcing

It can be helpful to view climate change in terms of ***climate forcing***—defined as an imposed perturbation of Earth's energy balance.[8] The major forcings associated with the glaciations are shown in Figure 20.19a. Factors that affect and are in turn affected by regional global temperature changes include higher ice-sheet temperatures; changes in vegetation; changes in atmospheric gases, such as carbon dioxide, methane, and nitrous oxide; and changes in sunlight intensity. Aerosols, such as those ejected by a volcano into the upper atmosphere, reflect sunlight and cool the Earth's surface. Changes in sunlight intensity are caused both by variations in sunlight brightness and by changes in Earth's orbit. Total energy forcing of the Last Glacial Maximum (LGM), around 22,000 years ago, when glaciers were at their thickest and sea levels their lowest, is calculated to have been about 6.6 ± 1.5 W/m^2. Thus, the average 5°C lowering equates to 3/4°C per W/m^2. The units are power per unit area.

Climate forcing during the industrial age is shown on Figure 20-19b. Positive forcings cause warm and negative forcings cause cooling. In recent decades human caused forcings have dominated over natural forcings. Total forcing is 1.6 ± 0.1 W/m^2, consistent with the observed rise in global surface air temperature over the past few decades.

Forcings operate by changing the properties of both the atmosphere and the surface that feed back into climate. As ice sheets grow, they reflect more incoming solar radiation, which enhances cooling. Changes in the amount of area covered by vegetation and the kinds of vegetation change reflectivity and absorption of solar energy and the uptake and release of atmospheric gases. Atmospheric gases, such as carbon dioxide, methane, and nitrous oxide, also play important roles. For now, it is more important to recognize that climate forcing is related to Earth's energy balance and as such is an important quantitative tool with which to evaluate global change in the geologic past, as well as global warming, which refers to the more recent rise in global surface air temperatures over the past few decades.[25]

As a way to visualize forcing, consider a checking account that you are free to use but earns no interest use. Assume you initially deposit $1,000, and each year you deposit $500 and write checks for $500. You do this for many years, and at the end of that time you still have $1,000 in your account. The point is that for any system, when input equals output for some material (in this case, dollars), the amount in the system remains constant. In our bank account example, if we increased the total amount in the account by only $3 per year (a 0.3% increase per year), it would double to $2,000 over a period of about 233 years. In short, a small imbalance over many years can cause significant change.



- Increases of greenhouse gases (except O_3) are known from observations and bubbles of air trapped in ice sheels. The increase of CO_2 from 285 parts per million (ppm) in 1850 to 392 in 2010 is accurate to about 5 ppm. The conversion of this gas change to a climate forcing (1.4 W/m^2), from calculation of the infrared opacity, adds about 10% to the uncertainty.
- Increase of CH_4 since 1850, including its effect on stratospheric H_2O and tropospheric O_3, causes a climate forcing about half as large as that by CO_2. Main sources of CH_4 include landfills, coal mining, leaky natural gas lines, increasing ruminant (cow) population, rice cultivation, and waste management. Growth rate of CH_4 has slowed in recent years.
- Tropospheric O_3 is increasing. The U.S. and Europe have reduced O_3 precursor emissions (hydrocarbons) in recent years, but increased emissions are occurring in the developing world.
- Block carbon ("soot"), a product of incomplete combustion, is visible in the exhaust of diesel trucks. It is also produced by biofuels and outdoor biomass burning. Black carbon aerosols are not well measured, and their climate forcing is estimated from measurements of total aerosol absorption. The forcing includes the effect of soot in reducing the reflectance of snow and ice.
- Human-made reflective aerosols include sulfates, nitrates, organic carbon, and soil dust. Sources include burning fossil fuel and agricultural activities. Uncertainty in the forcing by reflective aerosols is at least 35%.
- Indirect effects of aerosols on cloud properties are difficult to compute, but satellite measurements of the correlation of aerosol and cloud properties are consistent with the estimated net forcing of –1 W/m^2, with uncertainty of at least 50%.

FIGURE 20.19 **(a)** Climate forcing during the last major glaciations about 22,000 years ago was 6.6 ± 1.5 W/m^2, which produced a drop in global lower atmospheric temperature **(b)** climate forcing during industrial age. (*Source*: **(a)** USGS and NASA **(b)** modified from Hansen, J. 2003. *Can we defuse the global warming time bomb*? Edited version of the presentation to the Council on Environmental Quality. June 12. Washington DC, also *Natural Science* http://www.naturalscience.com)

20.10 The Oceans and Climate Change

The oceans play an important role in climate because two-thirds of the Earth is covered by water. Moreover, water has the highest heat-storage capacity of any compound, so a very large amount of heat energy can be stored in the world's oceans. There is a complex, dynamic, and ongoing relationship between the oceans and the atmosphere. If carbon dioxide increases in the atmosphere, it will also increase in the oceans, and, over time the oceans can absorb a very large quantity of CO_2. This can cause seawater to become more acidic ($H_2O + CO_2 \rightarrow H_2CO_3$) as carbonic acid increases.

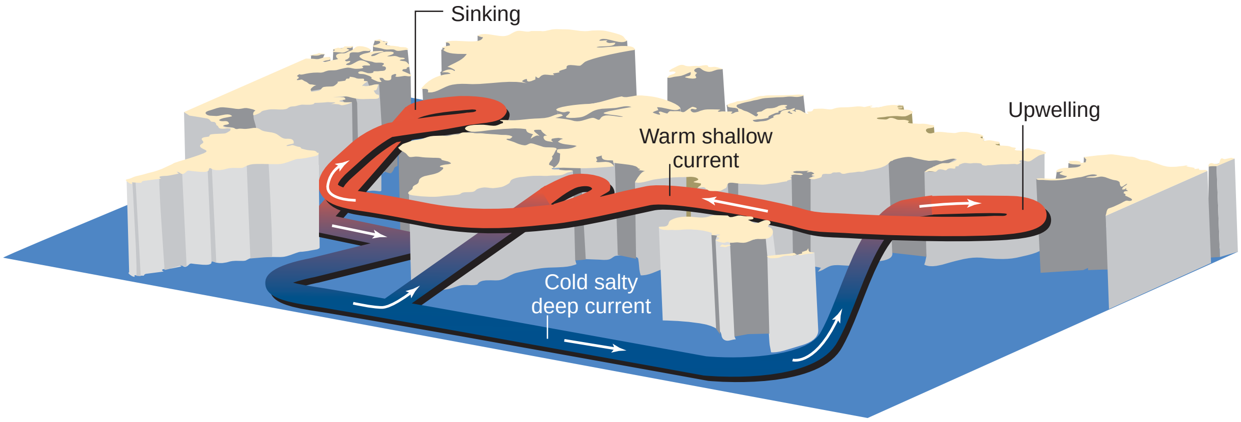


FIGURE 20.20 Idealized diagram of the oceanic conveyor belt. The actual system is more complex, but in general the warm surface water (red) is transported westward and northward (increasing in salinity because of evaporation) to near Greenland, where it cools from contact with cold Canadian air. As the surface water becomes denser, it sinks to the bottom and flows south, then east to the Pacific, then north, where upwelling occurs in the North Pacific. The masses of sinking and upwelling waters balance, and the total flow rate is about 20 million m^3/sec. The heat released to the atmosphere from the warm water keeps Northern Europe 5°C—10°C warmer than if the oceanic conveyor belt were not present. (*Source*: Modified from W. Broker, "Will Our Ride into the Greenhouse Future Be a Smooth One?" *Geology Today* 7, no. 5 [1997]:2–6.)

Part of what may drive the climate system and its changes is the "ocean conveyor belt"—a global circulation of ocean waters characterized by strong northward movement of upper warm waters of the Gulf Stream in the Atlantic Ocean. The temperature of these waters is approximately 12°–13°C when they arrive near Greenland, and they are cooled in the North Atlantic to a temperature of 2°–4°C (Figure 20.20).[25] As the water cools, it becomes saltier and denser, causing it to sink to the bottom. The cold, deep current flows southward, then eastward, and finally northward in the Pacific Ocean. Upwelling in the North Pacific starts the warm, shallow current again. The flow in this conveyor-belt current is huge—20 million m^3/sec, about equal to 100 Amazon rivers.

If the ocean conveyor belt were to shut down, some major changes might occur in the climates of some regions. Western Europe would cool but probably not experience extreme cold or icebound conditions.[26]

The ocean currents of the world have oscillations related to changes in water temperature, air pressure, storms, and weather over periods of a year or so to decades. They occur in the North Pacific, South Pacific, Indian, and North Atlantic oceans and can influence the climate. The Pacific Decadal Oscillation (PDO) for the North Pacific from 1900 to about 2010 is shown in Figure 20.21a. Natural oscillations of the ocean linked to the atmosphere can produce warmer or cooler periods of a few years to a decade or so. The effect of the oscillations can be ten times as strong (in a given year) as long-term warming that we have observed over the past century—larger, over a period of a few decades, than human-induced climate change. By comparison, the annual increase in warming due mostly to human activity is about two-hundredths of a degree Celsius per year.[27] Some scientists attribute the cool winter of 2009–2010 to natural ocean–atmosphere oscillations, and also suggest that these caused a cool year in 1911 that froze Niagara Falls. The more famous El Niño oscillations that occur in the Pacific Ocean are connected to large-scale but short-term changes in weather.

El Niño and Climate

A curious and historically important climate change linked to variations in ocean currents is the Southern Oscillation, known informally as El Niño. From the time of early Spanish settlement of the west coast of South America, people observed a strange event that occurred about every seven years. Usually starting around Christmas (hence the Spanish name El Niño, referring to the little Christ Child), the ocean waters would warm up, fishing would become poor, and seabirds would disappear.

Under normal conditions, there are strong vertical, rising currents, called upwelling, off the shore of Peru. These are caused by prevailing winds coming westward off the South American Continent, which move the surface water away from the shore and allow cold water to rise from the depths, along with important nutrients that promote the growth of algae (the base of the food chain) and thus produce lots of fish. Seabirds feed on those fish and live in great numbers, nesting on small islands just offshore.

El Niño occurs when those cold upwellings weaken or stop rising altogether. As a result, nutrients decline, algae grow poorly, and so do the fish, which either die, fail to reproduce, or move away. The seabirds, too, either leave or die. Because rainfall follows warm water eastward during El Niño years, there are high rates of precipitation and flooding in Peru, while droughts and fires are common in Australia and Indonesia. Because warm ocean water provides an atmospheric heat source, El Niño changes global atmospheric circulation, which causes changes in weather in regions that are far removed from the tropical Pacific.[28]

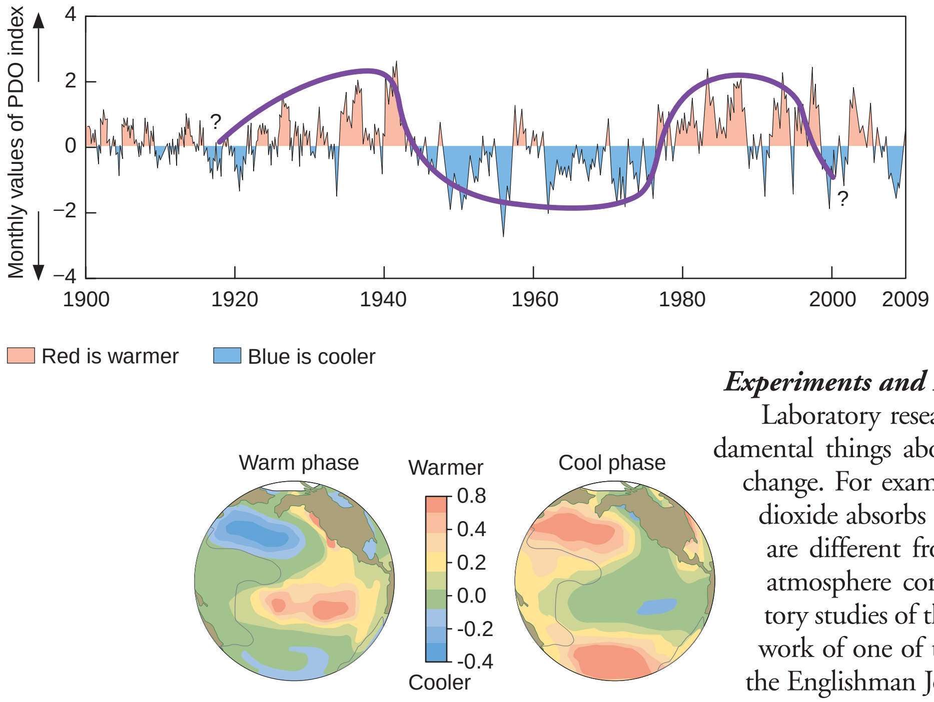


FIGURE 20.21 **(a)** The Pacific Decadal Oscillation (PDO) from 1900 to 2009. Three oscillations are clear (heavy line); **(b)** PDO warm and cool phases with characteristic changes in water temperature (°C) in the North Pacific and along the coast of the Pacific Northwest. (*Source*: Modified after http://jisao.washington.edu. Accessed March 26, 2010.)

20.11 Forecasting Climate Change

Concerns about global warming have to do with the future of the climate. This presents a problem because predicting the future has always been difficult and because people who make predictions have often been wrong. For climate and its effects on living things, there are two approaches to forecasting the future: empirical and theoretical.

Past Observations and Laboratory Research

Past Observations

We discussed this first kind of empirical approach in Section 20.5 in terms of how past climates are reconstructed. The use of empirical records is based on the idea of **uniformitarianism**—the idea that processes occurring in the past occur today and that processes occurring today occurred in the past. Therefore, the past is the key to the present and future. This leads to an "if–then" way of thinking about the future: *If* climate change in the past correlated with change of a certain factor, *then* perhaps a change in that factor will lead to a similar climate change in the future. The argument that human actions are leading to global warming is heavily based on this kind of empirical evidence, in particular measurements from the past 150 years and proxy evidence over the past few hundred years that suggest relationships between Earth's average surface temperature with both the concentations of carbon dioxide and methane in the atmosphere.[15]

Experiments and Laboratory Research

Laboratory research has taught scientists some fundamental things about the cause and effect of climate change. For example, the understanding that carbon dioxide absorbs in specific infrared wavelengths that are different from those of the other gases in the atmosphere comes from a long history of laboratory studies of the air around us, beginning with the work of one of the first modern chemical scientists, the Englishman Joseph Priestley (1733–1804). In the 1770s he did experiments with plants, mice, and candles that were in closed glass containers. He found that if a mouse was kept in a jar by itself, it soon died; but if there was a plant in the jar, the mouse lived. He also found that a plant grew better in a jar in which a mouse had died than it did when by itself. He put a mint plant and a lighted candle in a glass jar, closed the jar, and the candle soon went out. He left the closed jar for a month, and when he came back he lit the candle without opening the jar (focusing sunlight on the candle's wick) and it burned again. Obviously, the mint plant had somehow changed the air in the jar, as had the mouse.

In this way, Priestley discovered that animals and plants change the atmosphere. It wasn't long afterward that oxygen (given off, of course by the green plant) and carbon dioxide (given off by the mouse and the candle) were identified and their light-absorption spectra were determined. Without this kind of study, we wouldn't know that there were such things as greenhouse gases.[29]

Computer Simulations

Scientists have been trying to use mathematics to predict the weather since the beginning of the 20th century. They began by trying to forecast the weather a day in advance, using the formal theory of how the atmosphere functioned. The first person to try this eventually went off to fight in World War I and never completed the forecast. By the early 1970s, computers had gotten fast enough and models sophisticated enough to forecast the next day's weather in two days—not much help in practice, but a start. At least they knew whether their forecast of yesterday's weather had been right!

Computers are much faster today, and the major theoretical method used today to forecast climate change is a group of computer models called **general circulation**

models (GCMs). Mathematically, these are deterministic differential equation models. The dominant computer models of Earth's climate are all based on the general idea shown in Figure 20.22. The atmosphere is divided into rectangular solids, each a few kilometers high and several kilometers north and south. For each of these, the flux of energy and matter is calculated for each of the adjacent cells. Since there are many cells, and each cell has six sides, a huge number of calculations have to be made. Determining how well these GCMs work is a major challenge because the real test is what the future brings.

Many such computer simulations are in use around the world, but all are very similar mathematically. They all use deterministic differential equations to calculate the rate of exchange of energy and matter among the atmospheric cells. They are all steady-state models, meaning that for any given set of input information about the climate at the beginning, the result will always be the same—there is no chance or randomness involved. These models assume that the climate is in a steady state except for specific perturbations, especially those belived to be caused by human activities. Thus an assumption of these models, and a necessary outcome, is that the climate, if left to itself, will be in balance, in a steady state. This is unlike the real world's global environmental systems, which are inherently non-steady-state—always changing, as we saw at the beginning of this chapter.

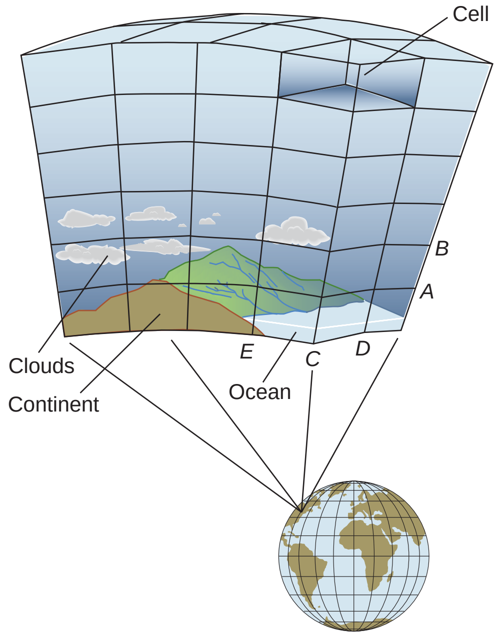


FIGURE 20.22 Idealized diagram of how the huge, general circulation models (models of the entire Earth's climate) are viewed by the computers that run the programs. The atmosphere is divided into hundreds of rectangular cells, and the flow of energy and material is calculated for the transfer between each boundary of every cell to its adjacent cells.

20.12 Potential Rates of Global Climate Change

The global average temperature since 1900 has risen by about 0.8° C (1.5°F).[31] Global surface temperature has risen about 0.2 °C (0.36° F) per decade in the past 30 years.[8] The warmest year since direct surface air temperature has been measured was 2005 (but 2005 will likely be surpassed by 2010 when all data is in). Virtually tied for second were 2002, 2003, 2006, 2007 and 2009. The decade 2001–2010 will be the warmest on record.

According to current GCMs, if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, warming of about 0.1° C per decade would be expected.[30, 31] Based on current and expected rates of CO_2 release by human activities, it is estimated that by 2030 the concentration of carbon dioxide in the atmosphere will be double the pre–Industrial Revolution level. If so, the GCMs forecast that the average global temperature will rise approximately 1°–2°C (2°–4°F), with greater increases toward the poles.[31]

In recent decades, the surface air temperature has risen more in some polar regions, in part because of positive feedback. As snow and ice melt, solar energy that used to be reflected outward by ice and snow is now absorbed by vegetation and water, resulting in enhanced warming. This is termed **polar amplification**.

20.13 Potential Environmental, Ecological, and Human Effects of Global Warming

Changes in River Flow

With a continuation of global warming, melting of glacial ice and reductions in snow cover are anticipated to accelerate throughout the twenty-first century. This is also projected to reduce water availability and hydropower potential, and change the seasonality of flows in regions supplied by meltwater from major mountain ranges (e.g., Hindu-Kush, Himalaya, Andes), where more than one-sixth of the world population currently lives.[31, 32]

California, which depends on snowmelt from the Sierra Nevada for water to irrigate one of the richest agriculture regions in the world, will have problems storing water in reservoirs if these forecasts became true. Rainfall will likely increase, but there will be less snowpack with warming. Runoff, will be more rapid than if snow slowly melts. As a result, reservoirs will fill sooner and more water will escape to the Pacific Ocean. Lower runoff is projected for much of Mexico, South America, southern Europe, India, southern Africa, and Australia.

Rise in Sea Level

The sea level reached a minimum during the most recent glacial maximum. Since then, the sea level has risen slowly. Sea level rises from two causes: (1) Liquid water expands as it warms; and (2) ice sheets on land that melt increase the amount of water in the oceans. Since the end of the last ice age, the sea level has risen approximately 23 cm (about 1 foot) per century. Climatologists forecast that global warming could about double that rate. Various models predict that the sea level may rise anywhere from 20 cm to approximately 2 m (8–80 in) in the next century; the most likely rise is probably 20–40 cm (8–16 in).[31]

About half the people on Earth live in a coastal zone, and about 50 million people each year experience flooding due to storm surges. As the sea level rises and the population increases, more and more people become vulnerable to coastal flooding. The rising sea level particularly threatens island nations (Figure 20.23) and could worsen coastal erosion on open beaches, making structures more vulnerable to damage from waves. This could lead to further investments to protect cities in the coastal zone by constructing seawalls, dikes, and other structures to control erosion. Groundwater supplies for coastal communities could also be threatened by saltwater intrusion (see Chapter 19). In short, coastal erosion is a difficult problem that is very expensive to deal with. In many cases, it is best to allow erosion to take place naturally where feasible and defend against coastal erosion only where absolutely necessary.

Glaciers and Sea Ice

The amount of ice on the Earth's surface changes in complicated ways. A major concern is whether global warming will lead to a great decline in the volume of water stored as ice, especially because melting of glacial ice raises the mean sea level and because mountain glaciers are often significant sources of water for lower-elevation ecosystems. At present, many more glaciers in North America, Europe, and other areas are retreating, than are advancing (Figure 20.24). In the Cascades of the Pacific Northwest and the Alps in Switzerland and Italy, retreats are accelerating. For example, on Mt. Baker in the Northern Cascades of Washington, all eight glaciers on the mountain were advancing in 1976. Today all eight are retreating.[32] If present trends continue, all glaciers in Glacier National Park in Montana could be gone by 2030 and most glaciers in the European Alps could be gone by the end of the century.[33]

Not all melting of glacial ice is due to global warming. For example, the study of decrease in the glacier ice on Mt. Kilimanjaro in Africa shows that the primary cause of the ice loss is not melting. The glaciers of Kilimanjaro formed during African Humid Period about 4,000 to 11,000 years ago. Although there have been wet periods since then—notably in the nineteenth century, which appears to have led to a secondary increase in ice—condition have generally been drier.[34]

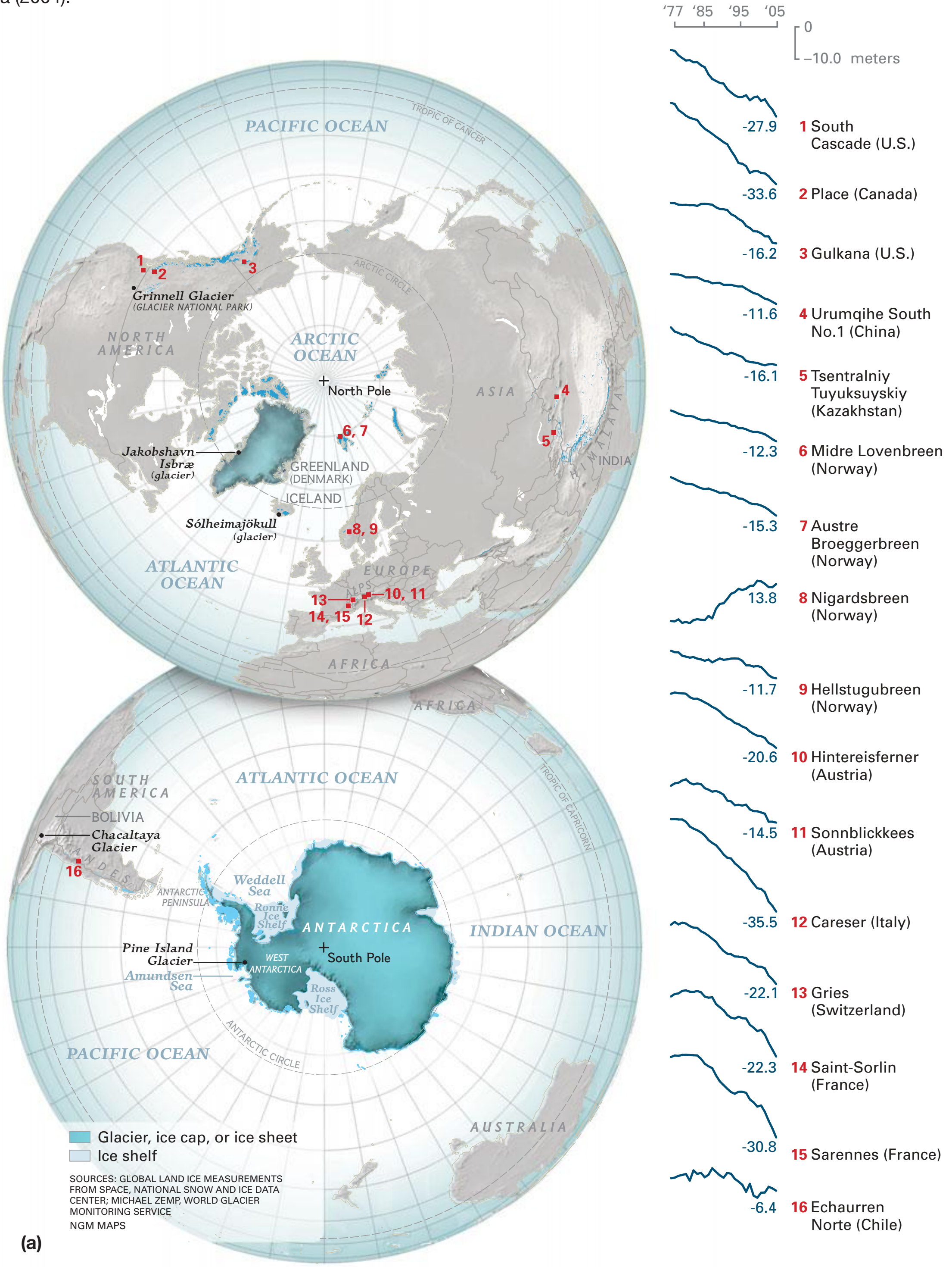
Since they were first observed in 1912, the glaciers of Kilimanjaro have decreased in area by about 80%. The ice is disappearing not from warmer temperatures at the top of the mountain, which are almost always below freezing, but because less snowfall is occurring and ice is being depleted by solar radiation and sublimation (ice is transformed from solid state to water vapor without melting). More arid conditions in the past century led to air that contained less moisture and thus favored sublimation. This may be due to land use changes from native vegetation to agriculture. Much of the ice depletion had occurred by the mid-1950s.[34]

In addition to many glaciers melting back, the Northern Hemisphere sea ice coverage in September, the time of the ice minimum, has declined an average of 10.7% per decade since satellite remote sensing became possible in the 1970s (Figure 20.25). If present trends were to continue, the Arctic Ocean might be seasonally

(a) (b)

FIGURE 20.23 The world's smallest nation, Tuvalu, may succumb to sea-level rise. Tuvalu consists of nine coral islands in the South Pacific, with a total area smaller than Manhattan, and its highest elevation above sea level is 4.5 meters. Sea levels have been rising since the end of the last ice age, a natural response. But global warming could accelerate this rise, making the 12,000 citizens of Tuvalu the world's first sea-level-rise refugees.

FIGURE 20.24 **(a)** The thinning of selected glaciers (m^2) since 1977 (National Geographic Maps); **(b)** Muir Glacier in 1941 and 2004. The glacier retreated over 12 km (7 mi) and has thinned by over 800 m (2625 ft). *Source:* National Snow and Ice Data Center W.O. Field (1941) and Molina (2004).



(a)

(b)

1941 2004

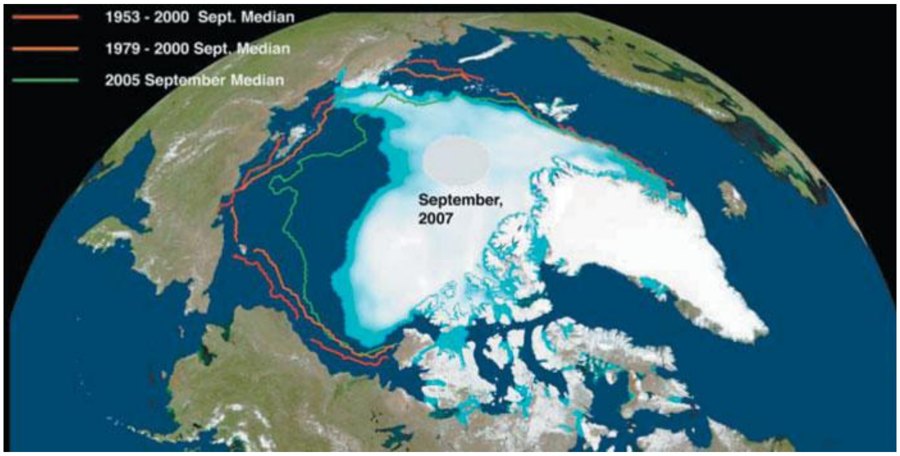


FIGURE 20.25 Satellite observations, which began in 1977, show that Arctic sea ice reached a minimum in September 2007 and has increased since then. The sea ice coverage varies greatly between summer and winter, with July marking the summer minimum. The rapid decline in 2007 was partly due to atmospheric circulation that favored melting. (*Source*: Modified after Stroever et al., 2008. EOS 89 [2] 13–14.)

A CLOSER LOOK 20.1

Some Animals and Plants in Great Britain Are Adjusting to Global Warming

Two of the longest studies of animals and plants in Great Britain show that at least some are adjusting to recent and rapid climate change. The first is a 47-year study of the bird *Parus major*. This study, one of the longest for any bird species, shows that these birds are responding behaviorally to rapid climate change. It's the case of the early bird gets the worm. A species of caterpillar that is one of the main foods of this bird during egg laying has been emerging earlier as the climate has warmed. In response, females of this bird species are laying their eggs an average of two weeks earlier (Figure 20.26). Both birds and caterpillars are doing okay so far.[39]

The second study, one of the longest experiments about how vegetation responds to temperature and rainfall, shows that long-lived small grasses and sedges are highly resistant to climate change. The authors report that changes in temperature and rainfall during the past 13 years "have had little effect on vegetation structure and physiognomy".[40]

These studies demonstrate what ecologists have known for a long time and has been one focus of their studies, as described in Chapters 5, 6, and 7: Individuals, populations, and species have evolved with, are adapted to, and adjust to environmental change, including climate change. However, as we learned from the niche concept, each species persists within a certain range of each environmental condition, so there are limits to the adjustment any one species can make over a short time. Larger changes require biological evolution, which for long-lived animals and plants can take a long time. Whether most species will be able to adjust fast enough to global warming is a hotly debated topic.

FIGURE 20.26 This pretty bird, *Parus major*, a native of Great Britain, is adjusting to rapid climate change.

ice-free by 2030.[35] On the other hand, the central ice cap on Antarctica has grown during the same time. Satellite measurement from 1992 to 2003 suggests the East Antarctica ice sheet increased in mass by about 50 billion tons per year during the period of measurement.[36] As Earth warms, more snow falls on Antarctica.

Changes in sea ice involve more than total area; also involved is the depth of the ice and the age of the ice. The newer the ice, the thinner it is, and therefore the smaller amount of water that is frozen.

The rate of melting of the Greenland ice sheet has doubled since about 1998. As melting produces surface water, it flows into the interior to the base of the ice sheet, causing the ice to flow faster, further destabilizing the ice sheet.[33] It is clear that the polar regions are complex regions on Earth. Changing patterns of ocean and atmosphere circulation in the Arctic and Antarctic regions influence everything from snowfall to melting of glacial and sea ice and movement of glacial ice.[36, 37]

Satellite observations of sea ice became possible in the 1970s . Since then, Northern Hemisphere sea ice reached an observed minimum area covered in September 2007 (Figure 20.25). However, Arctic sea ice has increased since 2007,[19] and so has the central ice cap on Antarctica. Satellite measurement from 1992 to 2003 suggests the East Antarctica ice sheet increased in mass by about 50 billion tons per year during the period of measurement.[36] Changes in sea ice involve more than total area; also involved are the depth of the ice and the age of the ice. The newer the ice, the thinner it is, and therefore the smaller amount of water that is frozen.

FIGURE 20.27 Black guillemots, medium-size birds also called sea pigeons, nest in the Far North (blue in the map above), including Cooper Island, Alaska.

Changes in Biological Diversity

Some of the greatest uncertainties about the consequence of global warming have to do with changes in biodiversity. This is because organisms are complex and so their responses to change can be complex. Warming is one change, but others—such as availability of nutrients, relations with other organisms (predator and prey), and competition for habitat and niches in ecosystems—also affect biodiversity. Because we lack adequate theoretical models to link specific climate changes to specific changes in overall biodiversity, our best insights come from empirical evidence. Surprisingly few species went extinct as a result of climate change during the past 2.5 million years, even though the amount of changes was about the same as that forecast for today and the next few decades.[38] Warming will certainly change some areas, and plants and animals will experience stress. Many will adapt, as apparently occurred during the Medieval Warm Period (see A Closer Look 20.1). For example, polar bears were undoubtedly stressed during this period but did not become extinct.

On the other hand, black guillemots, birds that nest on Cooper Island, Alaska, illustrate the concerns some scientists have about global warming and certain species (Figure 20.27). The abundance of this species has declined since ternperature increases in the 1990s caused the sea ice to recede farther from Cooper Island each spring. The parent birds feed on Arctic cod found under the sea ice and must then return to the nest to feed their chicks, who are not yet mature enough to survive on their own. For the parents to do this, the distance from feeding grounds to nest must be less than about 30 km, but in recent years the ice in the spring has been receding as much as 250 km from the island. As a result, the black guillemots on the island have lost an important source of food. The future of black guillemots on Cooper Island depends on future springtime weather. Too warm and the birds may disappear; Too cold and there may be too few snow-free days for breeding, in which case they also will disappear.

Agricultural Productivity

Globally, agricultural production will likely increase in some regions and decline in others.[19] In the Northern Hemisphere, some of the more northern areas, such as Canada and Russia, may become more productive. Although global warming might move North America's prime farming climate north from the Midwestern United States to the region of Saskatchewan, Canada, the U.S. loss would not simply be translated into a gain for Canada. Saskatchewan would have the optimum climate for growing, but Canadian soils are thinner and less fertile than the prairie-formed soils of the U.S. Midwest. Therefore, a climate shift could have serious negative effects on midlatitude food production. Meanwhile, lands in the southern part of the Northern Hemisphere may become more arid. Prolonged drought as a result of future warming as evidently occurred during the Medieval warming period (see opening case study) with loss of agricultural productivity could be one of the serious impacts of global warming.

Human Health Effects

Like other biological and ecological responses, the effects of global warrning on human health are difficult to forecast. The IPCC *Climate Change 2007: Synthesis Report* is cautious about these possible effects, stating only that one needs to be thinking about "some aspects of human health, such as excess heat-related mortality in Europe, changes in infectious disease vectors in parts of Europe, and earlier onset of and increases in seasonal production of allergenic pollen in Northern Hemisphere high and mid-latitudes."[31] Some have suggested that global warming might increase the incidence of malaria. However, this has been shown not to be the case in past and present circumstances because temperature alone is not a good correlate for malaria.[41] The same has been found for tick-borne encephalitis, another disease that some thought might increase from global warming.[42]

20.14 Adjusting to Potential Global Warming

People can adjust to the threat of global warming in two ways:

- ***Adapt***: Learn to live with future global climate change over the next 20 years because there is warming in the pipeline from greenhouse gases already emitted.
- ***Mitigate***: Work to reduce the emissions of greenhouse gases and take actions to reduce the undesirable effects of a global warming.

How can carbon dioxide emissions be reduced? Increasing energy conservation and efficiency, along with the use of alternative energy sources, can reduce emissions of carbon dioxide. Rebalancing our use of fossil fuels so that we burn more natural gas would also be helpful because natural gas releases 28% less carbon per unit of energy than does oil and 50% less than coal.[43, 44] Conservation strategies to reduce CO_2 emissions include greater use of mass transit and less use of automobiles; providing larger economic incentives to energy-efficient technology; setting higher fuel-economy standards for cars, trucks, and buses; and establishing higher standards of energy efficiency.

Because clearing forests for agriculture reduces storage of carbon dioxide, protecting the world's forests would help reduce the threat of global warming, as would reforestation.[45]

Geologic (rock) sequestration is another way to reduce the amount of carbon dioxide that would otherwise enter the atmosphere. The idea is to capture carbon dioxide from power plants and industrial smokestacks and inject it into deep subsurface geologic reservoirs. Geologic environments suitable for carbon sequestration are sedimentary rocks that contain saltwater, and sedimentary rocks at the sites of depleted oil and gas fields. To significantly mitigate the adverse effects of CO_2 emissions that result in global warming, we need to sequester approximately 2 gigatons of CO_2 per year.[46]

The process of carbon sequestration involves compressing carbon dioxide and changing it to a mixture of both liquid and gas, then injecting it deep underground. Individual injection projects can sequester approximately 1 million tons of CO_2 per year. A carbon-sequestration project is under way in Norway beneath the North Sea. The carbon dioxide from a large natural-gas production facility is injected approximately 1 km into sedimentary rocks below a natural-gas field. The project, begun in 1996, injects about 1 million tons of CO_2 every year, and it is estimated that the entire reservoir can hold up to about 600 billion tons of CO_2—about as much as is likely to be produced from all of Europe's fossil-fuel plants in the next several hundred years. Sequestering carbon dioxide beneath the North Sea is expensive, but it saves the company from paying carbon dioxide taxes for emissions into the atmosphere.

Pilot projects to demonstrate the potential of sequestering CO_2 in sedimentary rocks have been initiated in Texas beneath depleted oil fields. The storage potential at sites in Texas and Louisiana is immense: One estimate is that 200–250 billion tons of CO_2 could be sequestered in this region.[47]

International Agreements to Mitigate Global Warming

There are several approaches to seeking international agreements to limit greenhouse-gas emissions. One major approach is the international agreement in which each nation agrees to some specific limit on emissions. Another major approach is carbon trading in which a nation agrees to cap its carbon emissions at a certain total amount and then issues emission permits to its corporations and other entities, allowing each to emit a certain quantity. These permits can be traded: For example, a power company that wants to build a new fossil-fuel power plant might trade permits with a company that does reforestation, based on estimates of the amount of CO_2 the power plant would release and of an area of forest that could take up that amount. One of the most important programs of this kind is the European Climate Exchange. Carbon trading in the U.S. has come under criticism from both sides of the debate of what to do about potential global warming. That is should we use "cap and trade or not"? Those in favor argue we need to control CO_2 emissions to be proactive and reduce potential adverse inputs at global warming. Those opposed to cap and trade say the economic impact of reducing emissions and changing energy policy is too expensive and will result in economic disaster.

Attempts to establish international treaties limiting greenhouse-gas emissions began in 1988 at a major scientific conference on global warming held in Toronto, Canada. Scientists recommended a 20% reduction in carbon dioxide emissions by 2005. The meeting was a catalyst for scientists to work with politicians to initiate international agreements for reducing emissions of greenhouse gases.

In 1992, at the Earth Summit in Rio de Janeiro, Brazil, a general blueprint for reducing global emissions was suggested. Some in the United States, however, objected that the reductions in CO_2 emissions would be too costly. Agreements from the Earth Summit did not include legally binding limits. After the meetings in Rio de Janeiro, governments worked to strengthen a climate-control treaty that included specific limits on the amounts of greenhouse gases that each industrialized country could emit into the atmosphere.

Legally binding emission limits were discussed in Kyoto, Japan, in December 1997, but specific aspects of the agreement divided the delegates. The United States eventually agreed to cut emissions to about 7% below 1990 levels, but that was far short of the reductions suggested by leading global warmng scientists, who recommended reductions of 60–80% below 1990 levels. A "Kyoto Protocol" resulted from this meeting, was signed by 166 nations, and became a formal international treaty in February 2006.

In July 2008, the leaders of the G-8 nations, meeting in Japan, agreed to "consider and adopt" reductions of at least 50% in greenhouse gas emissions as part of a new U.N. treaty to be discussed in Copenhagen in 2009. This was the first time the United States agreed in principle to such a reduction (in practice, the United States has not gone along with it).

The United States, with 5% of the world's population, emits about 20% of the world's atmospheric carbon dioxide. The fast-growing economies of China and India are rapidly increasing their CO_2 emissions and are not bound by the Kyoto Protocol. California, which by itself is twelfth in the world in CO_2 emissions, passed legislation in 2006 to reduce emissions by 25% by 2020. Some have labeled the action a "job killer" but environmentalists point out that the legislation will bring opportunity and new jobs to the state. California is often a leader, and other states are considering how to control greenhouse gases. The U.S. (as a mid 2010) had not agreed to any international agreements to address climate change. New energy bills to reduce greenhouse gas emissions and turn to alternative energy to reduce our dependency on fossil fuels have been stopped in Congress. Failure to address global change will compromise our ability to be proactive and require our response to be reactive as change occurs. This is not effective environmental planning.

CRITICAL THINKING ISSUE

What Is Valid Science in the Global Warming Debate?

Modern concerns about global warming began in the 1960s with a scientific inquiry into the possibility that human activities might be able to affect the Earth's climate. But the issue touched on so many aspects of civilization, as well as the activities of individuals, that by 1990 global warming had become an intensely debated political and ideological subject

In November 2009, 1,000 e-mails and 3,000 other documents from computers at the University of East Anglia's Climatic Research Unit were hacked and released to the public. Some people claimed that the e-mails revealed efforts by IPCC scientists to exclude views of others, to withhold scientific data, and to tamper with data (a claim now refuted). In response, some defenders of the IPCC made a request to the U.S. government, under the Freedom of Information Act, to gain access to the e-mails of scientists who were said to oppose global warming. The overall result was to further transform what should have been a scientific inquiry into an even more highly politicized and ideological debate.

In Chapter 2 we discussed the scientific method. It may have seemed somewhat academic at the beginning of this book, but with the current chapter's topic you can see that understanding what is and what is not legitimate science—and what are and are not legitimate scientific findings—can affect many aspects of our lives, from international economics and trade to individual choices about how to travel. Therefore, it is important to think about the scientific method within the context of global warming. If you have the interest, you can investigate this topic broadly, but for our purposes consider the following:

A 2007 IPCC report stated that Himalayan glaciers were in danger of melting as soon as 2035. This report quickly gained wide acceptance. Some glaciers in the central Himalayas are in fact melting fast. The western larger glaciers, however, are growing, as warming has increased snowfall. In 2009, the IPCC withdrew the assertion after it was revealed that the source turned out not to be a peer-reviewed scientific article but a report of the World Wildlife Fund, which in turn was based on an article in a popular magazine in India, whose author later disavowed his offhand speculation.[48]

Scientific study suggest that the huge Himalayan ice fields would take more than 300 years to melt if global warming occurred over the next century as currently forecast by general circulation models. Others that feed water to places like India are melting faster and could impact water resources in less than 100 years.

Critical Thinking Questions

1. If you were in charge of IPCC, overseeing the report writing of many scientists, what precautions would you take to ensure that only the best scientific information got into the publications?
2. Give a general description of the kinds of data and other scientific analysis that could be used to determine the rate at which huge areas of mountain glaciers could melt. (You don't have to learn all about glaciers to answer this question, just consider the information in this chapter about what affects the Earth's climate.)
3. In what ways could laboratory research help you study how fast or how slowly glaciers might melt?
4. Why do you think so much of the climate change debate has moved from the scientific arena to the political arena? What are implications of this shift?

SUMMARY

- The atmosphere, a layer of gases that envelops Earth, is a dynamic system that is constantly changing. A great number of complex chemical reactions take place in the atmosphere, and atmospheric circulation takes place on a variety of scales, producing the world's weather and climates.
- Nearly all the compounds found in the atmosphere either are produced primarily by biological activity or are greatly affected by life.
- Major climate changes have occurred throughout the Earth's history. Of special interest to us is that periodic glacial and interglacial episodes have characterized the Earth since the evolution of our species.
- During the past 1,000 years, several warming and cooling trends have affected civilizations.
- During the past 100 years, the mean global surface air temperature has risen by about 0.8°C. About 0.5°C of this increase has occurred since about 1960.
- Water vapor, carbon dioxide, methane, some oxides of nitrogen, and CFCs are the major greenhouse gases. The vast majority of the greenhouse effect is produced by water vapor, a natural constituent of the atmosphere. Carbon dioxide and other greenhouse gases also occur naturally in the atmosphere. However, especially since the Industrial Revolution, human activity has added substantial amounts of carbon dioxide to the atmosphere, along with such greenhouse gases as methane and CFCs.
- Climate models suggest that a doubling of carbon dioxide concentration in the atmosphere could raise the mean global temperature 1°–2°C in the next few decades and 1.5°C–4.5°C by the end of this century.
- Many complex positive feedback and negative feedback cycles affect the atmosphere. Natural cycles, solar forcing, aerosol forcing, particulate forcing from volcanic eruptions, and El Niño events also affect the temperature of Earth.
- There are concerns based on scientific evidence that global warming is leading to changes in climate patterns, rise in sea level, melting of glaciers, and changes in the biosphere. A potential threat from future warming, as in the Medieval Warm Period, is the occurrence of prolonged drought that would compromise our food supply.
- Adjusting to global warming includes learning to live with the changes and attempting to mitigate warming by reducing emissions of greenhouse gases.

REEXAMINING THEMES AND ISSUES

Human Population

Burning of fossil fuels and trees has increased emissions of carbon dioxide into the atmosphere. As the human population increases and standards of living rise, the demand for energy increases; and, as long as fossil fuels are used, greenhouse gases will also increase.

Sustainability

Through our emissions of greenhouse gases, we are conducting global experiments, the final results of which are difficult to predict. As a result, achieving sustainability in the future will be more difficult. If we do not know in detail what the consequences or magnitude of human-induced climate change will be, then it is difficult to predict how we might achieve sustainable development for future generations.

Global Perspective

Global warming is a global problem.

Urban World

If sea levels rise as climate models forecast coastal cities will be affected by higher storm surges. Rising air temperatures can accentuate urban heat-island effects, making life in cities more unpleasant in the summer. If global warming reduces the availability of freshwater, cities will feel the impact.

People and Nature

Our ancestors adapted to natural climate change over the past million years. During that period, Earth experienced glacial and interglacial periods that were colder and warmer than today. Burning fossil fuels has led to human-induced climate changes different in scope from past human effects.

Science and Values

Responding to global warming requires choices based on value judgments. Scientific information, especially geologic data and the instrumental (historic) record along with modern computer simulations, is providing a solid foundation for the belief that global warming is happening. The extent to which scientific information of this kind is accepted involves value decisions.

KEY TERMS

atmosphere **434**
barometric pressure **435**
climate **431**
climate forcing **447**
general circulation models (GCMs) **451**
greenhouse effect **441**
greenhouse gases **433**
polar amplification **451**
radionuclides **446**
stratosphere **434**
troposphere **434**
uniformitarianism **450**
weather **431**

STUDY QUESTIONS

1. Summarize the scientific data that global warming as a result of human activity is occuring.
2. What is the composition of Earth's atmosphere, and how has life affected the atmosphere during the past several billion years?
3. What is the greenhouse effect? What is its importance to global climate?
4. What is an anthropogenic greenhouse gas? Discuss the various anthropogenic greenhouse gases in terms of their potential to cause global warming.
5. What are some of the major negative feedback cycles and positive feedback cycles that might increase or decrease global warming?
6. In terms of the effects of global warming, do you think that a change in climate patterns and storm frequency and intensity is likely to be more serious than a global rise in sea level? Illustrate your answer with specific problems and areas where the problems are likely to occur.
7. How would you refute or defend the statement that the best adjustment to global warming is to do little or nothing and learn to live with change?

FURTHER READING

Fay, J. A., and D. Golumb, *Energy and the Environment* (New York: Oxford University Press, 2002). See Chapter 10 on global warming.

IPCC, *Climate Change 2007. The Physical Science Basis* (New York: Cambridge University Press, 2007). A report by the international panel that was awarded the Nobel Prize for its work on global warming

Lovejoy, T.E., and Lee Hannah, *Climate Change and Biodiversity* (New Haven, CT: Yale University Press, 2005). Discusses, continent by continent, what has happened to biodiversity in the past when climate has changed.

Rohli, R.V., and A. J. Vega, *Climatology* (Sudbury, MA: Jones & Bartlett, 2008). An introduction to the basic science of how the atmosphere works.

Weart, S.R., *The Discovery of Global Warming* (Cambridge, MA: Harvard University Press, 2008). Tells how the possibility of global warming was discovered, and the history of the controversies about it.

CHAPTER 21

Air Pollution

Shown here is an aerial view of Dallas, Texas and the greater Kansas City metropolitan area are both participating in the new initiative called Sustainable Skylines, through the U.S. Environmental Protection Agency.

LEARNING OBJECTIVES

The atmosphere has always been a sink—a place of deposition and storage—for gaseous and particulate wastes. When the amount of waste entering an area of the atmosphere exceeds the atmosphere's ability to disperse or break down the pollutants, problems result. After reading this chapter, you should understand . . .

- The two major ways that pollution affects living things: by direct contact down here and by altering the atmosphere above us;
- Why air pollution from human activities, combined with meteorological conditions, may exceed the atmosphere's natural ability to remove wastes;
- What the major categories and sources of air pollutants are;
- How "acid rain" is produced and how its environmental impacts might be minimized;
- Why air quality standards are important;
- Why the economics of air pollution is controversial and difficult;
- What the major indoor air pollutants are, where they come from, and why they cause some of our most serious environmental health problems;
- "Green buildings" and other major strategies for controlling and minimizing indoor air pollution;
- The "ozone hole" and the science of ozone depletion.

CASE STUDY

Sustainable Skylines: Dallas and Kansas City

Sustainable Skylines is an initiative that has been launched by the Environmental Protection Agency (EPA). Its objective is to achieve sustainable air quality by reducing the six major air pollutants, as well as other toxic air pollutants and greenhouse gases. Cities that participate in the program are encouraged to integrate energy, land use, transportation, and air quality planning in order to achieve measurable improvements within a three-year period. As of 2009, two cities participated—Dallas, Texas, and Kansas City, Kansas and Missouri (the greater Kansas City metropolitan area). The EPA hopes to have ten cities invested in the program by 2010. Among the projects included in a particular sustainable Skyline venture are the following:

- Reducing emissions from landscape equipment by improved irrigation of lawns and turf management, as well as retrofitting small off-road equipment to achieve reduced emissions of air pollutants.
- Reducing vehicle emissions by increasing public transportation and reducing the distances traveled in vehicles.
- Replacing existing taxis with "green taxis" that emit far less pollution.
- Encouraging "**green buildings**" with healthier interior environments and landscaping that benefit the local external environment.
- Reducing emissions from idling vehicles and retrofitting diesel engines to reduce emissions.
- Programs to encourage planting trees in the city to develop a tree canopy in as many areas as possible.

Each city that participates in the Sustainable Skylines Program will have its own local programs and policies, developed in collaboration with the city's inhabitants and city leaders, along with public and private partners. For example, in Dallas, Texas, the description of activities has the goal of helping to reduce the urban "heat island" effect. Urban areas are often warmer than surrounding areas due to the abundance of equipment and lights, as well as surfaces that absorb heat. Cities with little vegetation also have less evaporative cooling. This is a particular problem in Dallas, which has a naturally warm climate much of the year. As a result, the goal of the Sustainable Skylines Program for Dallas is to increase the number of shaded surfaces and green vegetated surfaces of roofs and surrounding buildings in order to reduce the heat island effect and cool the city.

In the greater Kansas City area, the objectives are to encourage a variety of sustainable environmental projects with social benefits. They plan to address such issues as transportation, energy, land use, resource efficiency, green buildings, and air quality, with a focus on projects that will result in cleaner, healthier air for this large urban area.

21.1 Air Pollution in the Lower Atmosphere

A Brief Overview

As the fastest-moving fluid medium in the environment, the atmosphere has always been one of the most convenient places to dispose of unwanted materials. The atmosphere has been a sink for waste disposal ever since we first used fire, and people have long recognized the existence of atmospheric pollutants, both natural and human-induced. Leonardo da Vinci wrote in 1550 that a blue haze formed from materials emitted into the atmosphere by trees. What he had observed is a natural photochemical smog from hydrocarbons given off by living trees. This haze, whose cause is still not fully understood, gave rise to the name Smoky Mountains for the range in the southeastern United States.

The phenomenon of acid rain was first described in the 17th century, and by the 18th century it was known that plants in London were damaged by air pollution. Beginning with the Industrial Revolution in the 18th century, air pollution became more noticeable. The word *smog* was introduced by a physician at a public-health conference in 1905 to denote poor air quality resulting from a mixture of smoke and fog.

Stationary and Mobile Sources of Air Pollution

The two major categories of air pollution sources are stationary sources and mobile sources. **Stationary sources** have a relatively fixed location and include point sources, fugitive sources, and area sources.

- *Point sources*, discussed in Chapter 10, emit pollutants from one or more controllable sites, such as power-plant smokestacks (Figure 21.1).
- *Fugitive sources* generate air pollutants from open areas exposed to wind. Examples include burning for agricultural purposes (Figure 21.2), as well as dirt roads, construction sites, farmlands, storage piles, surface mines, and other exposed areas.
- *Area sources*, also discussed in Chapter 10, are well-defined areas within which are several sources of air pollutants—for example, small urban communities, areas of intense industrialization within urban complexes, and agricultural areas sprayed with herbicides and pesticides.

Mobile sources of air pollutants include automobiles, trucks, buses, aircraft, ships, trains, and anything else that pollutes as it moves from place to place.[2]

FIGURE 21.2 Burning sugarcane fields, Maui, Hawaii—an example of a fugitive source of air pollution.

General Effects of Air Pollution

Air pollution affects many aspects of our environment, including its visual qualities, vegetation, animals, soils, water quality, natural and artificial structures, and human health. Air pollutants affect visual resources by discoloring the atmosphere and by reducing visual range and atmospheric clarity. We cannot see as far in polluted air, and what we do see has less color contrast. These effects were once limited to cities but now extend to some wide-open spaces of the United States. For example, near the Four Corners, where New Mexico, Arizona, Colorado, and Utah meet, emissions from two large fossil-fuel-burning power plants have altered visibility in a region where visibility used to be 80 km (50 mi) from a mountaintop on a clear day.[1] The power plants are two of the largest pollution sources in the U.S.

FIGURE 21.1 This steel mill in Beijing, China, is a major source of air pollution.

Air pollution's numerous effects on vegetation include damage to leaves, needles, and fruit; reduced or suppressed growth; increased susceptibility to diseases, pests, and adverse weather; and disruption of reproductive processes.[1, 2]

Air pollution is a significant factor in the human death rate in many large cities. For example, it has been estimated that in Athens, Greece, the number of deaths is several times higher on days when the air is heavily polluted; and in Hungary, where air pollution has been a serious problem in recent years, it may contribute to as many as 1 in 17 deaths. The United States is certainly not immune to health problems related to air pollution. The most polluted air in the nation is in the Los Angeles urban area, where millions of people are exposed to it. An estimated 175 million people live in areas of the United States where exposure to air pollution contributes to lung disease, which causes more than 300,000 deaths per year. Air pollution in the United States is directly responsible for annual health costs of over $50 billion. In China, whose large cities have serious air pollution problems, mostly from burning coal, the health cost is now about $50 billion per year and may rise to about $100 billion per year by 2020.

Air pollutants can affect our health in several ways, depending on the dose or concentration and other factors, including individual susceptibility (see the discussion of dose–response in Chapter 10). Some of the primary effects are cancer, birth defects, eye and respiratory system irritation, greater susceptibility to heart disease, and aggravation of chronic diseases, such as asthma and emphysema. People suffering from respiratory diseases are the most likely to be affected. Healthy people tend to acclimate to pollutants, but this is a physiological tolerance; as explained in Chapter 10, it doesn't mean that the pollutants are doing no harm (Figure 21.3).

It is worth noting here that many air pollutants have *synergistic effects*—that is, the combined effects are greater than the sum of the separate effects. For example, sulfate and nitrate may attach to small particles in the air, facilitating their inhalation deep into lung tissue. There, they may do greater damage than a combination of the two pollutants would be expected to, based on their separate effects. This phenomenon has obvious health consequences; consider joggers breathing deeply and inhaling particulates as they run along the streets of a city. The effects of air pollutants on vertebrate animals in general include impairment of the respiratory system; damage to eyes, teeth, and bones; increased susceptibility to disease, parasites, and other stress-related environmental hazards; decreased availability of food sources (such as vegetation affected by air pollutants); and reduced ability for successful reproduction.[2]

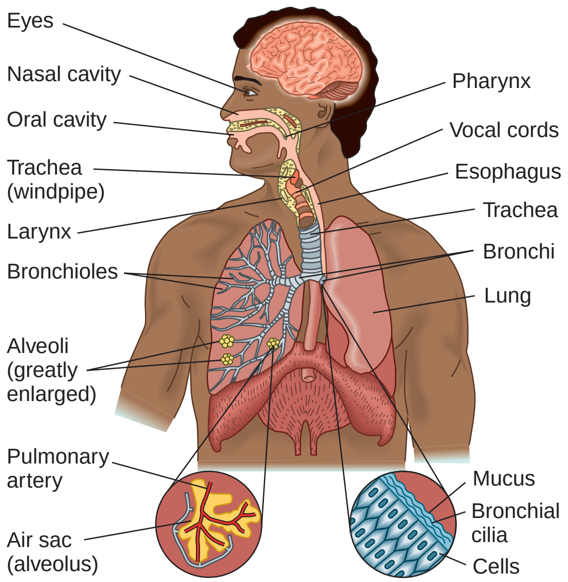


FIGURE 21.3 Idealized diagram showing some of the parts of the human body (brain, cardiovascular system, and pulmonary system) that can be damaged by common air pollutants. The most severe health risks from normal exposures are related to particulates. Other substances of concern include carbon monoxide, photochemical oxidants, sulfur dioxide, and nitrogen oxides. Toxic chemicals and tobacco smoke also can cause chronic or acute health problems.

Air-pollution deposits can also make soil and water toxic. In addition, soils may be leached of nutrients by pollutants that form acids. Air pollution's effects on manmade structures include discoloration, erosion, and decomposition of building materials (see the discussion of acid rain later in this chapter).

The Major Air Pollutants

Nearly 200 air pollutants are recognized and assessed by the EPA and listed in the Clean Air Act. They can be classified as primary or secondary. **Primary pollutants** are emitted directly into the air. They include particulates, sulfur dioxide, carbon monoxide, nitrogen oxides, and hydrocarbons. **Secondary pollutants** are produced by reactions between primary pollutants and normal atmospheric compounds. For example, ozone forms over urban areas through reactions of primary pollutants, sunlight, and natural atmospheric gases. Thus, ozone is a secondary pollutant.

The major air pollutants occur either as particulate matter (PM) or in gaseous forms. Particulates are very small particles of solid or liquid substances and may be organic or inorganic. Gaseous pollutants include sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), ozone (O_3) and volatile organic compounds (VOCs), such as hydrocarbons (compounds containing only carbon and hydrogen that include petroleum products), hydrogen sulfide (H_2S), and hydrogen fluoride (HF).

The primary pollutants that account for nearly all air-pollution problems are carbon monoxide (58%), volatile organic compounds (11%), nitrogen oxides (15%), sulfur oxides (13%), and particulates (3%). In the United States today, about 140 million metric tons of these substances enter the atmosphere from human-related processes. If these pollutants were uniformly distributed in the atmosphere, the concentration would be only a few parts per million by weight. Unfortunately, pollutants are not uniformly distributed but tend to be produced, released, and concentrated locally or regionally—for example, in large cities.

In addition to pollutants from human sources, our atmosphere contains many pollutants of natural origin, such as sulfur dioxide from volcanic eruptions; hydrogen sulfide from geysers and hot springs, as well as from biological decay in bogs and marshes; ozone in the lower atmosphere as a result of unstable meteorological conditions, such as violent thunderstorms; a variety of particles from wildfires and windstorms;[1] and natural hydrocarbon seeps, such as La Brea Tar Pits in Los Angeles.

The data in Table 21.1 suggest that, except for sulfur and nitrogen oxides, natural emissions of air pollutants exceed human-produced emissions. Nevertheless, it is the human component that is most abundant in urban areas and leads to the most severe problems for human health.

Criteria Pollutants

The six most common pollutants are called **criteria pollutants** because the EPA has set specific limits on the levels of these six and they are responsible for most of our air-pollution problems. The six are sulfur dioxide, nitrogen oxides, carbon monoxide, ozone, particulates, and lead.

Sulfur Dioxide

Sulfur dioxide (SO_2) is a colorless and odorless gas normally present at Earth's surface in low concentrations. A significant feature of SO_2 is that once emitted into the atmosphere, it can be converted into fine particulate sulfate (SO_4) and removed from the atmosphere by wet or dry deposition. The major anthropogenic (human) source of sulfur dioxide is the burning of fossil fuels, mostly coal in power plants (see Table 21.1). Another major source comprises a variety of industrial processes, ranging from petroleum refining to the production of paper, cement, and aluminum.[1-4]

Adverse effects of sulfur dioxide depend on the dose or the concentrations (see Chapter 10) and include injury or death to animals and plants, as well as corrosion of paint and metals. Crops, such as alfalfa, cotton, and barley, are especially susceptible. Sulfur dioxide can severely damage the lungs of people and other animals, especially in the sulfate form. It is also an important precursor to acid rain (see A Closer Look 21.1).[1-4]

U.S. emission rates of SO_2 from 1970 to 2007 are shown in Table 21.2. Emissions peaked at about 32 million tons in the early 1970s and since then have fallen 60%, to about 13 million tons, as a result of effective emission controls.

Nitrogen Oxides

Although nitrogen oxides (NO_x) occur in many forms in the atmosphere, they are emitted largely as nitric oxide (NO) and nitrogen dioxide (NO_2), and only these two forms are subject to emission regulations. The more important of the two is NO_2, a yellow-brown to reddish-brown gas. A major concern with NO_2 is that it may be converted by complex reactions in the atmosphere to an ion, NO_3^{2-}, within small water particulates, impairing visibility. As mentioned earlier, both NO and NO_2 are major contributors to smog, and NO_2 is also a major contributor to acid rain (see A Closer Look 21.1). Nitrogen oxides contribute to nutrient enrichment and eutrophication of water in ponds, lakes, rivers, and the ocean (see Chapter 19). Nearly all NO_2 is emitted

Table 21.1 MAJOR NATURAL AND HUMAN-PRODUCED COMPONENTS OF SELECTED AIR POLLUTANTS

AIR POLLUTANTS	EMISSIONS (% OF TOTAL) NATURAL	HUMAN-PRODUCED	MAJOR SOURCES OF HUMAN-PRODUCED COMPONENTS	PERCENT
Particulates	85	15	Fugitive (mostly dust)	85
			Industrial processes	7
			Combustion of fuels (stationary sources)	8
Sulfur oxides (SO_x)	50	50	Combustion of fuels (stationary sources, mostly coal)	84
			Industrial processes	9
Carbon monoxide (CO)	91	9	Transportation (automobiles)	54
Nitrogen dioxide (NO_2)		Nearly all	Transportation (mostly automobiles)	37
			Combustion of fuels (stationary sources, mostly natural gas and coal)	38
Ozone (O_3)	A secondary pollutant derived from reaction with sunlight NO_2, and oxygen (O_2)		Concentration present depends on reaction in lower atmosphere involving hydrocarbons and thus automobile exhaust	
Hydrocarbons (HC)	84	16	Transportation (automobiles)	27
			Industrial processes	7

Table 21.2 U.S. EMISSIONS OF CRITERIA POLLUTANTS FROM 1970–2007

	MILLIONS OF TONS PER YEAR							
	1970	1980	1985	1990	1995	2000	2005	2007
Carbon Monoxide (CO)	200	178	170	144	120	102	89	81
Lead	ND	0.074	0.023	0.005	0.004	0.002	0.003	0.002
Nitrogen Oxides (NO_x)	~27	27	26	25	25	22	19	17
Volatile Organic Compounds (VOC)	~30	30	27	23	22	17	15	15
Particulate Matter (PM)								
PM_{10}	ND	6	4	3	3	2	2	2
$PM_{2.5}$		ND	ND	2	2	2	1	1
Sulfur Dioxide (SO_2)	32	26	23	23	19	16	15	13
Totals	ND	267	250	220	191	161	141	129

Notes:

1. In 1985 and 1996 EPA refined its methods for estimating emissions. Between 1970 and 1975, EPA revised its methods for estimating PM emissions.
2. The estimates for 2002 are from 2002 NEI v2; the estimates for 2003 and beyond are preliminary and based on 2002 NEI v2.
3. No data (ND)

Source: Environmental Protection Agency, 2008.
Air Trends accessed June 10, 2008 @ www.epa.gov.

from anthropogenic sources. The two main sources are automobiles and power plants that burn fossil fuels.[1, 2]

Nitrogen oxides have various effects on people, including irritation of eyes, nose, throat, and lungs and increased susceptibility to viral infections, including influenza (which can cause bronchitis and pneumonia).[1, 2] Dissolved in water, nitrogen oxides form acids that can harm vegetation. But when the oxides are converted to nitrates, they can promote plant growth.

U.S. emission rates of NO_x from 1970 to 2007 are shown in Table 21.2. Emissions are primarily from combustion of fuels in power plants and vehicles. They have been reduced by about 30% since 1980.

Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas that, even at very low concentrations, is extremely toxic to humans and other animals. The high toxicity results from a physiological effect: Carbon monoxide and hemoglobin have a strong natural attraction for one another; if there is any carbon monoxide in the vicinity, the hemoglobin in our blood will take it up nearly 250 times faster than it will oxygen and carry mostly carbon monoxide, rather than oxygen, from the atmosphere to the internal organs. Effects range from dizziness and headaches to death. Many people have been accidentally asphyxiated by carbon monoxide from incomplete combustion of fuels in campers, tents, and houses. Carbon monoxide is particularly hazardous to people with heart disease, anemia, or respiratory disease. It may also cause birth defects, including mental retardation and impaired fetal growth. Its effects tend to be worse at higher altitudes, where oxygen levels are lower. Detectors (similar to smoke detectors) are now commonly used to warn people if CO in a building reaches a dangerous level.

Approximately 90% of the carbon monoxide in the atmosphere comes from natural sources. The other 10% comes mainly from fires, automobiles, and other sources of incomplete burning of organic compounds, but these are easily concentrated locally, especially by enclosures, so this 10% causes most of the health problems. Emissions of CO peaked in the early 1970s at about 200 million metric tons and declined 60% to about 81 million metric tons by 2007 (Table 21.2). This significant reduction stemmed largely from cleaner-burning engines despite an increased number of vehicles.

Ozone and Other Photochemical Oxidants

Photochemical oxidants are secondary pollutants arising from atmospheric interactions of nitrogen dioxide and sunlight. Ozone, of primary concern here, is a form of oxygen in which three atoms of oxygen occur together rather than the normal two. A number of other photochemical oxidants, known as PANs (peroxyacyl nitrates), occur with photochemical smog.

Ozone is relatively unstable and releases its third oxygen atom readily, so it oxidizes or burns things more readily and at lower concentrations than does normal oxygen. Released into the air or produced in the air, ozone may injure living things. However, since these include bacteria and other organisms, it is sometimes used for sterilizing purposes—for example, bubbling ozone gas through water is one way to purify water.

Ozone in the lower atmosphere is a secondary pollutant produced on bright, sunny days in areas where there is significant primary pollution. The major sources of ozone, as well as other oxidants, are automobiles and industrial processes that release nitrogen dioxide by burning fossil fuels. Because of the nature of its formation, ozone is difficult to regulate and thus is the pollutant whose health standard is most frequently exceeded in U.S. urban areas.[5, 6]

The adverse environmental effects of ozone and other oxidants, like those of other pollutants, depend in part on the dose or concentration of exposure and include damage to plants and animals, as well as to materials, such as rubber, paint, and textiles. Ozone's effects on plants can be subtle. At very low concentrations, it can slow growth without visible injury. At higher concentrations, it kills leaf tissue and, if pollutant levels remain high, whole plants. The death of white pine trees along highways in New England is believed to be due in part to ozone pollution. In animals, including people, ozone causes various kinds of damage, especially to the eyes and respiratory system. Many millions of Americans are often exposed to ozone levels that damage cell walls in lungs and airways. Tissue reddens and swells, and cellular fluids seep into the lungs. Eventually, the lungs lose elasticity and are more susceptible to bacterial infection, and scars and lesions may form in the airways. Even young, healthy people may be unable to breathe normally, and on especially polluted days breathing may be shallow and painful. Ground-level ozone decreased by 9% from 1990 to 2007.[1, 2, 6]

While too much ozone causes problems down here, too little of it has become a problem in the stratosphere. Because of the effect of sunlight on normal oxygen, ozone forms a natural layer high in the stratosphere that protects us from harmful ultraviolet radiation from the sun. However, the emission of certain chemicals in the lower atmosphere has led to serious ozone depletion in the stratosphere. We will discuss the ozone-depletion story later in the chapter. Suffice it to say here that it is becoming an environmental success story at the global level.

Particulate Matter: PM_{10}, $PM_{2.5}$, and Ultrafine Particles

Particulate matter (PM) is made up of tiny particles. The term *particulate matter* is used for varying mixtures of particles suspended in the air we breathe, but in regulations these are divided into three categories: PM_{10}, particles up to 10 micrometers (μm) in diameter; $PM_{2.5}$, particles between 2.5 and 0.18 microns; and UP, **ultrafine particles** smaller than 0.18 micrometers in diameter, released into the air by vehicles on streets and freeways. For comparison, the diameter of a human hair is about 60 to 150 μm (Figure 21.4).

Nearly all industrial processes, as well as the burning of fossil fuels, release particulates into the atmosphere. Farming, too, adds considerable particulate matter to the atmosphere, as do windstorms in areas with little vegetation and volcanic eruptions. Particles are everywhere, and high concentrations and/or specific types of particles pose a serious danger to human health, including aggravation of cardiovascular and respiratory diseases. Major particulates include asbestos (especially dangerous, discussed in detail in Chapter 10)[2] and small particles of heavy metals, such as arsenic, copper, lead, and zinc, which are usually emitted from smelters and other industrial facilities. Particulates can reduce visibility and affect climate (see Chapter 20).[2] Much particulate matter is easily visible as smoke, soot, or dust; other particulate matter is not easily visible.

Fine particles—$PM_{2.5}$ and smaller—are easily inhaled into the lungs, where they can be absorbed into the bloodstream or remain embedded for a long time. Among the most significant of these particles are sulfates and nitrates. As already explained, these are mostly secondary pollutants produced in the atmosphere by chemical reactions between normal atmospheric constituents and sulfur dioxide and nitrogen oxides. These reactions are important in the formation of sulfuric and nitric acids in the atmosphere and are further discussed when we consider acid rain.[1, 2]

Ultrafine particles (UP), released into the air by motor vehicles, are so small that they cannot be easily filtered and can enter the bloodstream. Rich in organic compounds and other reactive chemicals, they may be the most hazardous components of air pollution, especially with respect to heart disease. They evidently can contribute to inflammation (cell and tissue damage by oxidation), reducing the protective quality of "good" cholesterol and leading to plaque buildup in the arteries that can result in heart attack and stroke. Those most at risk are the young, the elderly, and individuals living near a freeway, or exercising near heavy traffic, or spending a lot of time in traffic (sitting in slow-moving traffic can roughly triple your short-term risk of a heart attack). The risk to an individual is very small, but when millions of people are exposed to a small risk, large numbers are affected. The prudent approach is to limit your exposure. For example, avoid jogging or bike riding near heavy traffic for extended periods.[3]

Particulate matter is measured as *total suspended particulates* (TSPs). Values for TSPs tend to be much higher in large cities in developing countries, such as Mexico, China, and India, than in developed countries, such as Japan and the United States.

Particulates affect human health, ecosystems, and the biosphere. In the United States, particulate air pollution is estimated to contribute to the death of 60,000 people annually.[7] Studies estimate that 2 to 9% of human mortality in cities is associated with particulate pollution, and that the mortality risk is about 15 to 25% higher in cities with the highest levels of fine particulate pollution.[8] Particulates are linked to both lung cancer and bronchitis (see Figure 21.4) and are especially hazardous to the elderly and to people who have respiratory problems, such as asthma. There is a direct relationship between particulate pollution and increased hospital admissions for respiratory distress.

Dust raised by road building and plowing not only makes breathing more difficult for animals (including humans) but also can be deposited on green plants, interfering with absorption of carbon dioxide and oxygen and release of water (transpiration). On a larger scale, particulates associated with large construction projects—such as housing developments, shopping centers, and industrial parks—may injure or kill plants and animals and damage surrounding areas, changing species composition, altering food chains, and thereby affecting ecosystems. The terrorist attacks that destroyed the Twin Towers in New York City on September 11, 2001, sent huge amounts of particles of all sizes into the air, causing serious health problems that continue even today in people who were exposed to it.

Modern industrial processes have greatly increased the total amount of suspended particulates in Earth's atmosphere. These particulates block sunlight and can cause **global dimming**, a gradual reduction in the solar energy that reaches Earth's surface. Global dimming cools the atmosphere and has lessened the global warming that has been predicted. Its effects are most apparent in the midlatitudes of the Northern Hemisphere, especially over urban regions or where jet air traffic is more common. Jet plane exhaust emits particulates high in the atmosphere. That this could affect the climate was suggested in 2001, when civil air traffic was shut down for two days after the September 11 attacks in New York. During those two days, the daily temperature range over the United States was about 1°C higher than usual.[9] Of course, this may have been just a coincidence.

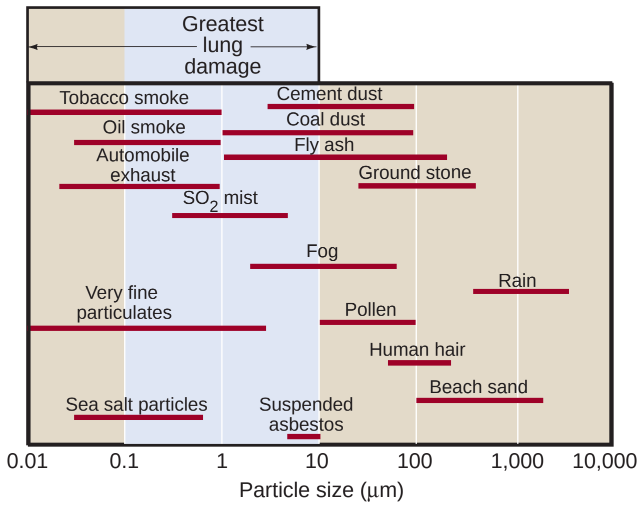


FIGURE 21.4 Sizes of selected particulates. The shaded area shows the size range that produces the greatest lung damage. (*Source:* Modified from Fig. 7–8, p. 244 in *Chemistry, Man and Environmental Change: An Integrated Approach*, by J. Calvin Giddings. Copyright © 1973 by J. Calvin Giddings. Reprinted by permission of Harper Collins Publishers, Inc.).

Table 21.2 shows that anthropogenic emissions of PM_{10} in the United States from 1970 to 2007 declined by about two-thirds (66%).

Lead

Lead (a heavy metal) is an important constituent of automobile batteries and many other industrial products. Leaded gasoline (still used in some countries) helps protect engines and promotes more effective fuel consumption. However, the lead is emitted into the air with the exhaust and has thereby been spread widely around the world, reaching high levels in soils and waters along roadways. Once released, lead can be transported through the air as particulates to be taken up by plants through the soil or deposited directly on their leaves. Thus, it enters terrestrial food chains. When lead is carried by streams and rivers, deposited in quiet waters, or transported to oceans or lakes, it is taken up by aquatic organisms and enters aquatic food chains. Lead is toxic to wildlife and people. It can damage the nervous system, impair learning, and reduce IQ and memory. In children it can also contribute to behavioral problems. (Recall that this is the subject of the Critical Thinking section in Chapter 10.) In adults it can contribute to cardiovascular and kidney disease, as well as anemia.[1, 2]

Lead reaches Greenland as airborne particulates and in seawater and is stored in glacial ice. The concentration of lead in Greenland glaciers was essentially zero in A.D. 800 and reached measurable levels with the beginning of the Industrial Revolution in the mid-18th century. The lead content of the glacial ice increased steadily from 1750 until about 1950, when there was a sudden upsurge in the rate of lead accumulation, reflecting rapid growth in the use of leaded gasoline. The accumulation of lead in Greenland's ice illustrates that our use of heavy metals in the 20th century reached the point of affecting the entire biosphere.

Lead has now been removed from nearly all gasoline in the United States, Canada, and much of Europe. In the United States, lead emissions have declined about 98% since the early 1980s (Table 21.2). The reduction and eventual elimination of lead in gasoline are a good start in reducing levels of anthropogenic lead in the biosphere.

A CLOSER LOOK 21.1

Acid Rain

Acid rain is precipitation in which the pH is below 5.6. The pH, a measure of acidity and alkalinity, is the negative logarithm of the concentration of the hydrogen ion (H^+). Because the pH scale is logarithmic, a pH value of 3 is 10 times more acidic than a pH value of 4 and 100 times more acidic than a pH value of 5. Automobile battery acid has a pH value of 1. Many people are surprised to learn that all rainfall is slightly acidic; water reacts with atmospheric carbon dioxide to produce weak carbonic acid. Thus, pure rainfall has a pH of about 5.6, where 1 is highly acidic and 7 is neutral (see Figure 21.5). (Natural rainfall in tropical rain forests has been observed in some instances to have a pH of less than 5.6; this is probably related to acid precursors emitted by the trees.)

Acid rain includes both wet (rain, snow, fog) and dry (particulate) acidic depositions. The depositions occur near and downwind of areas where the burning of fossil fuels produces major emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Although these oxides are the primary contributors to acid rain, other acids are also involved. An example is hydrochloric acid emitted from coal-fired power plants.

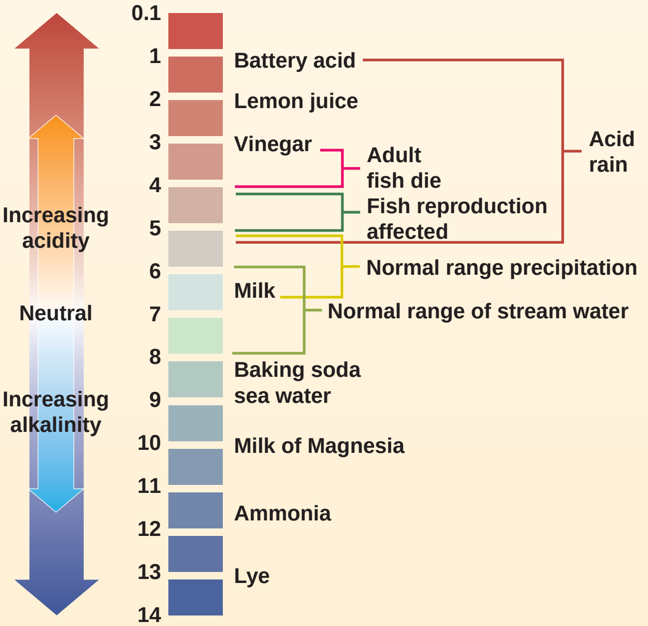


FIGURE 21.5 The pH scale shows the levels of acidity in various fluids. The scale ranges from less than 1 to 14, with 7 being neutral: pHs lower than 7 are acidic; pHs greater than 7 are alkaline (basic). Acid rain can be very acidic and harmful to the environment. (*Source:* http:/ga.water.usgs.gov/edu/phdiagram.html. Accessed August 12, 2005.)

Acid rain has likely been a problem at least since the beginning of the Industrial Revolution. In recent decades, however, it has gained more and more attention, and today it is a major, global environmental problem affecting all industrial countries. In the United States, nearly all of the eastern states are affected, as well as West Coast urban centers, such as Seattle, San Francisco, and Los Angeles. The problem is also of great concern in Canada, Germany, Scandinavia, and Great Britain. Developing countries that rely heavily on coal, such as China, are facing serious acid rain problems as well.

Causes of Acid Rain

As we have said, sulfur dioxide and nitrogen oxides are the major contributors to acid rain. Amounts of these substances emitted into the environment in the United States are shown in Table 21.1. As shown earlier in Table 21.2, emissions of SO_2 peaked in the 1970s and declined to about 13 million metric tons per year by 2007; and nitrogen oxides leveled off at about 25 million metric tons per year in the mid-1980s and had dropped to 17 million metric tons by 2007.

In the atmosphere, reactions with oxygen and water vapor transform SO_2 NO_x into sulfuric and nitric acids, which may travel long distances with prevailing winds and be deposited as acid precipitation—rainfall, snow, or fog (Figure 21.6). Sulfate and nitrate particles may also be deposited directly on the surface of the land as dry deposition and later be activated by moisture to become sulfuric and nitric acids.

Again, sulfur dioxide is emitted primarily by stationary sources, such as power plants that burn fossil fuels, whereas nitrogen oxides are emitted by both stationary and mobile sources, such as automobiles. Approximately 80% of sulfur dioxide and 65% of nitrogen oxides in the United States come from states east of the Mississippi River.

Sensitivity to Acid Rain

Geology, climate, vegetation, and soil help determine the effects of acid rain, because these differ widely in their "buffers"—chemicals that can neutralize acids. Sensitive areas are those in which the type of bedrock (such as granite) or soils (such as those consisting largely of sand) cannot buffer acid input. Limestone bedrock provides the best buffering because it is made up mainly of calcium carbonate ($CaCO_3$), the mineral known as calcite. Calcium carbonate reacts with the hydrogen in the water and neutralizes the acid.

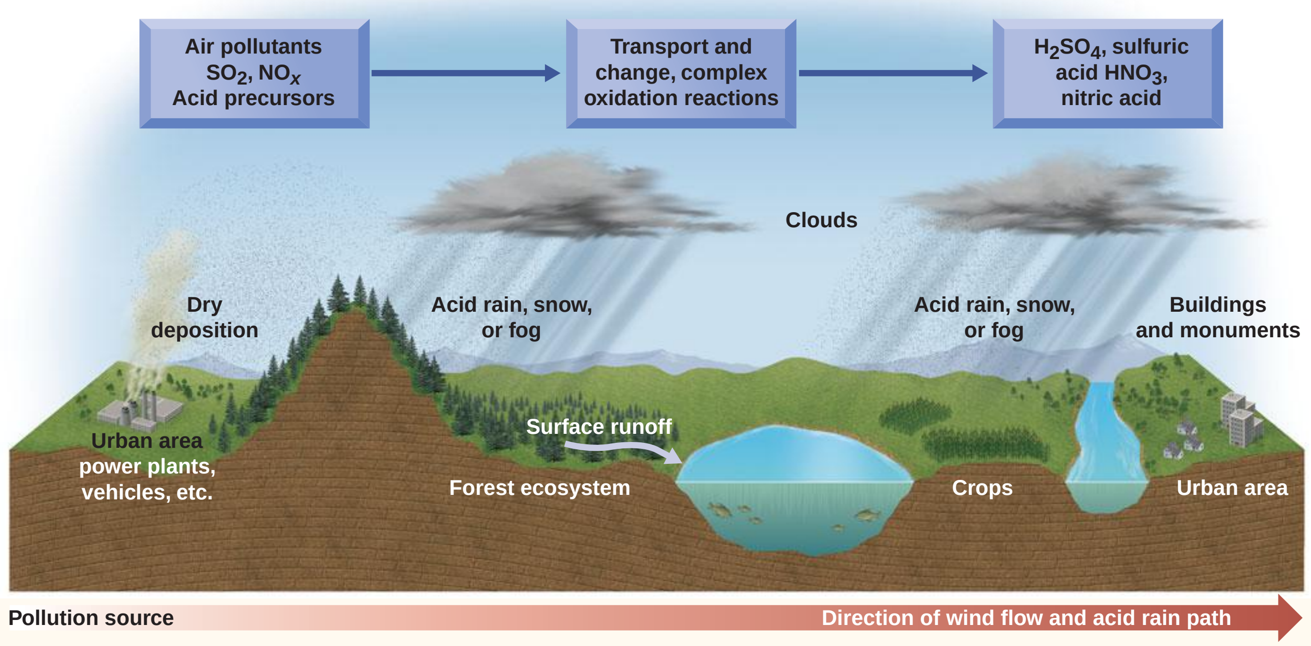


FIGURE 21.6 Idealized diagram showing selected aspects of acid rain formation and paths.

Soils may lose their fertility when exposed to acid rain, either because nutrients are leached out by acid water or because the acid in the soil releases elements that are toxic to plants.

Acid Rain's Effects on Forest Ecosystems

It has long been suspected that acid precipitation damages trees. Studies in Germany led scientists to cite acid rain and other air pollution as the cause of death for thousands of acres of evergreen trees in Bavaria. Similar studies in the Appalachian Mountains of Vermont (where many soils are naturally acidic) suggest that in some locations half the red spruce trees have died in recent years. Some high-elevation forests of the Appalachian Mountains, including the Great Smoky Mountains and Shenandoah National Park, have been impacted by acid rain, acid fog, and dry deposition of acid. Symptoms include slowed tree growth, leaves and needles that turn brown and fall off, and in extreme cases the death of trees. The acid rain does not directly kill trees; rather, it weakens them as essential nutrients are leached from soils or stripped from leaves by acid fog. Acidic rainfall also may release toxic chemicals, such as aluminum, that damage trees.[10]

Acid Rain's Effects on Lake Ecosystems

Records from Scandinavian lakes show an increase in acidity accompanied by a decrease in fish. The increased acidity has been traced to acid rain caused by industrial processes in other countries, particularly Germany and Great Britain. Thousands of lakes, ponds, and streams in the eastern United States are sensitive to acidification, including the Adirondacks and Catskill Mountains of New York State and others in the Midwest and in the mountains of the Western U.S. Little Echo Pond in Franklin, New York, is one of the most acidic lakes, with a measured pH of 4.2.[10]

Acid rain affects lake ecosystems in three ways. First, it damages aquatic species (fish, amphibians, and crayfish) directly by disrupting their life processes in ways that limit growth or cause death. For example, crayfish produce fewer eggs in acidic water, and the eggs produced often grow into malformed larvae.

Second, acid rain dissolves chemical elements necessary for life in the lake. Once in solution, the necessary elements leave the lake with water outflow. Thus, elements that once cycled in the lake are lost. Without these nutrients, algae do not grow, animals that feed on the algae have little to eat, and animals that feed on these animals also have less food.[10, 11]

Third, acid rain leaches metals, such as aluminum, lead, mercury, and calcium, from the soils and rocks in a drainage basin and discharges them into rivers and lakes. Elevated concentrations of aluminum are particularly damaging to fish because the metal can clog the gills and cause suffocation. The heavy metals may pose health hazards to people, too, because the metals may become concentrated in fish and then be passed on to people, mammals, and birds that eat the fish. Drinking water from acidic lakes may also have high concentrations of toxic metals.

Not all lakes are vulnerable to acidification. Acid is neutralized in waters with a high carbonate content (in the form of the ion HCO_3). Therefore, lakes on limestone or other rocks rich in calcium or magnesium carbonates can readily buffer river and lake water against acids. Lakes with high concentrations of such elements are called hard water lakes. Lakes on sand or igneous rocks, such as granite, tend to lack sufficient buffering to neutralize acids and are more susceptible to acidification.[12]

Acid Rain's Effects on Human Society

Acid rain damages not only our forests and lakes but also many building materials, including steel, galvanized steel, paint, plastics, cement, masonry, and several types of rock, especially limestone, sandstone, and marble. Classical buildings on the Acropolis in Athens and in other cities show considerable decay (chemical weathering) that accelerated in the 20th century as a result of air pollution. The problem has grown to such an extent that buildings require restoration, and the protective coatings on statues and other monuments must be replaced quite frequently, at a cost of billions of dollars a year. Particularly important statues in Greece and other areas have been removed and placed in protective glass containers, leaving replicas standing in their former outdoor locations for tourists to view.[11]

Stone decays about twice as rapidly in cities as it does in less urban areas. The damage comes mainly from acid rain and humidity in the atmosphere, as well as from corrosive groundwater.[15] This implies that measuring rates of stone decay will tell us something about changes in the acidity of rain and groundwater in different regions and ages. It is now possible, where the ages of stone buildings and other structures are known, to determine whether the acid rain problem has changed over time.

Control of Acid Rain

We know what causes acid precipitation—the solution is what we are struggling with. One solution to lake acidification is rehabilitation by the periodic addition of lime, as has been done in New York State, Sweden, and Ontario. This solution is not satisfactory over a long period, however, because the continuing effort is expensive. A better approach is to target the components of acid rain, the emissions of sulfur dioxide and nitrogen oxides. As noted, sulfur dioxide emissions in the United States are down about 60% since 1970—a big improvement that is significantly reducing acid rain. Emissions were lowered by a market-based SO_2 cap-and-trade program of the U.S. Environmental Protection Agency's Acid Rain Program, by which utilities receive pollution allowances that they can trade or sell if they lower emissions from their power plants (see Chapter 7 for a discussion of cap and trade).[14]

Air Toxics

Toxic air pollutants, or **air toxics**, are among those pollutants known or suspected to cause cancer and other serious health problems after either long-term or short-term exposure. The most serious exposure to air toxics occurs in California and New York, with Oregon, Washington, DC, and New Jersey making up the rest of the top five. States with the cleanest air include Montana, Wyoming, and South Dakota.

Air toxics include gases, metals, and organic chemicals that are emitted in relatively small volumes. They cause respiratory, neurological, reproductive, or immune diseases, and some may be carcinogenic. A 2006 EPA report estimated that the average risk of cancer from exposure to air toxics is about 1 in 21,000. The assessment concluded that benzene poses the most significant risk for cancer, accounting for 25% of the average individual cancer risk from all air toxics. Again, the effect on an individual's health depends on a number of factors, including duration and frequency of exposure, toxicity of the chemical, concentration of the pollutant the individual is exposed to, and method of exposure, as well as an individual's general health.[15]

Among the more than 150 known toxic air pollutants are hydrogen sulfide, hydrogen fluoride, various chlorine gases, benzene, methanol, and ammonia. In 2006 the EPA released an assessment of the national health risk from air toxics. It focused on exposure from breathing the pollutants; it did not address other ways people are exposed to them.

Standards and regulations established for more than 150 air toxics are expected to reduce annual emissions from 1990 levels. Even though vehicle miles will likely increase significantly by 2020, emissions of gaseous air toxics (such as benzene) from vehicles on highways are projected to decline about 80% from 1990 levels. Following are several examples of air toxics.

Hydrogen Sulfide

Hydrogen sulfide (H_2S) is a highly toxic corrosive gas, easily identified by its rotten-egg odor. Hydrogen sulfide is produced from natural sources, such as geysers, swamps, and bogs, and from human sources, such as petroleum refineries and metal smelters. The potential effects of hydrogen sulfide include functional damage to plants and health problems ranging from toxicity to death for humans and other animals.[4]

Hydrogen Fluoride

Hydrogen fluoride (HF) is a gas released by some industrial activities, such as aluminum production, coal gasification, and burning of coal in power plants. Hydrogen fluoride is extremely toxic; even a small concentration (as low as 1 ppb) may cause problems for plants and animals. It is potentially dangerous to grazing animals because some forage plants can become toxic when exposed to this gas.[1]

Mercury

Mercury is a heavy metal released into the atmosphere by coal-burning power plants, other industrial processes, and mining. Natural processes—such as volcanic eruptions and evaporation from soil, wetlands, and oceans—also release mercury into the air. Its toxicity to people is well documented and includes neurological and development damage, as well as damage to the brain, liver, and kidneys. Mercury from the atmosphere may be deposited in rivers, ponds, lakes, and the ocean, where it accumulates through biomagnification and both wildlife and people are exposed to it.[2]

Volatile Organic Compounds

Volatile organic compounds (VOCs) include a variety of organic compounds. Some of these compounds are used as solvents in industrial processes, such as dry cleaning, degreasing, and graphic arts. Hydrocarbons (compounds of hydrogen and carbon) comprise one group of VOCs. Thousands of hydrocarbons exist, including natural gas, or methane (CH_4); butane (C_4H_{10}); and propane (C_3H_8). Analysis of urban air has identified many hydrocarbons, and their potential adverse effects are numerous. Some are toxic to plants and animals, and others may be converted to harmful compounds through complex chemical changes that occur in the atmosphere. Some react with sunlight to produce photochemical smog.

Globally, our activities produce only about 15% of hydrocarbon emissions. In the United States, however, nearly half the hydrocarbons entering the atmosphere are emitted from anthropogenic sources. The largest of these sources in the United States is automobiles. Anthropogenic sources are particularly abundant in urban regions. However, in some southeastern U.S. cities, such as Atlanta, Georgia, natural emissions (in Atlanta's case, apparently from trees) probably exceed those from automobiles and other human sources.[3]

Like emissions of sulfur dioxide and nitrogen oxide, VOCs peaked in the 1970s and have been reduced by 50% (Table 21.2) thanks to effective government-mandated emission controls for automobiles.

Methyl Isocyanate

Some chemicals are so toxic that extreme care must be taken to ensure they do not enter the environment. This was demonstrated on December 3, 1984, when a toxic liquid from a pesticide plant leaked, vaporized, and formed a deadly cloud of gas that settled over a 64 km^2 area of Bhopal, India. The gas leak lasted less than an hour; yet more than 2,000 people were killed and more than 15,000 injured. The colorless gas that resulted from the leak was methyl isocyanate (C_2H_3NO), which causes severe irritation (burns on contact) to eyes, nose, throat, and lungs. Breathing the gas in concentrations of only a few parts per million (ppm) causes violent coughing, swelling of the lungs, bleeding, and death. Less exposure can cause a variety of problems, including blindness.

Methyl isocyanate is an ingredient of a common pesticide known in the United States as Sevin, as well as two other insecticides used in India. An industrial plant in West Virginia also makes the chemical. Small leaks not leading to major accidents occurred there both before and after the catastrophe in Bhopal.

Clearly, chemicals that can cause widespread injury and death should not be stored near large population centers. In addition, chemical plants should have reliable accident-prevention equipment, as well as personnel trained to control and prevent problems.

Benzene

Benzene (C_6H_6) is a gasoline additive and an important industrial solvent. Generally, it is produced when carbon-rich materials, such as oil and gasoline, undergo incomplete combustion. It is also a component of cigarette smoke. Automobiles, trucks, airplanes, trains, and farm machinery are major sources of environmental benzene.[15]

Acrolein

Acrolein (CH_2CHCHO) is a volatile hydrocarbon that is extremely irritating to the eyes, nose, and respiratory system in general. It is produced by manufacturing processes that involve combustion of petroleum fuels and is a component of cigarette smoke.[15]

Variability of Air Pollution

Pollution problems vary greatly among the different regions of the world and even within just the United States. For example, as noted earlier, in the Los Angeles basin and many U.S. cities, nitrogen oxides and hydrocarbons are particularly troublesome because they combine in the presence of sunlight to form photochemical smog. Most of the nitrogen oxides and hydrocarbons are emitted from automobiles and other mobile sources. In other U.S. regions, such as Ohio and the Great Lakes region, air quality also suffers from emissions of sulfur dioxide and particulates from industry and from coal-burning power plants, which are point sources.

Air pollution also varies with the time of year. For example, smog is usually a problem in the summer, when there is a lot of sunlight. Particulates are a problem in dry months, when wildfires are likely, and during months when the wind blows across the desert. For example, drought and heat in August of 2010 resulted in wildfires in Russia that produced a thick hazardous smoke and resulting very poor air quality in Moscow. The combination of heat and air pollution at the height of the pollution event killed about 700 people per day in Moscow.

Pollution from particulates is a problem in arid regions, where there is little vegetation and the wind easily picks up and transports fine dust. Las Vegas, Nevada, the fastest-growing urban area in the United States in the 1990s, now has some of the most polluted air in the southwestern United States. The brown haze over Las Vegas is due mostly to the nearly 80,000 metric tons of PM_{10} that enter the air in that region from the desert environment. About 60% of the dust comes from new construction sites, dirt roads, and vacant land. The rest is natural windblown dust. Las Vegas also has a carbon monoxide problem from vehicles, but it is the particulates that are causing concern, possibly leading to future EPA sanctions and growth restrictions.

Haze from Afar

Air pollution has become global and is not limited to urban areas. One example of this is Alaska's North Slope, a vast strip of land approximately 200 km (125 mi) wide that many consider to be one of the few unspoiled wilderness areas left on Earth. It seems logical to assume that air quality in the Arctic environments of Alaska would be pristine, except perhaps near areas where petroleum is being vigorously developed. However, ongoing studies suggest that the North Slope has an air-pollution problem that originates in Eastern Europe and Eurasia.

It is suspected that pollutants from burning fossil fuels in Eurasia are transported via the jet stream, at speeds that may exceed 400 km/hr (250 mi/hr), northeast over the North Pole to the North Slope of Alaska. There, they slow, stagnate, and produce a reddish-brown air mass known as "Arctic haze." The concentrations of air pollutants, including oxides of sulfur and nitrogen, are comparable to those of some eastern U.S. cities, such as Boston. Air quality problems in remote areas, such as Alaska, have significance as we try to understand air pollution at the global level.[16]

A curious global event occurred in the spring of 2001 when a white haze consisting of dust from Mongolia and industrial particulate pollutants arrived in North America. The haze affected one-fourth of the United States and could be seen from Canada to Mexico. In the United States, pollution levels from the haze alone were as high as two-thirds of federal health limits and caused respiratory problems. The haze demonstrates that pollution from Asia is carried by winds across the Pacific Ocean. Today we know from satellite observation that air pollutants transported by winds from East Asia to North America account for about 15% of the total pollutants originating from the United States and Canada.[17]

Urban Air Pollution: Chemical and Atmospheric Processes

Now that we have introduced and discussed the various types of air pollutants. This preparation allows for a more detailed discussion of the processes and chemistry of urban **smog**.

There are two major types of urban smog: photochemical smog, sometimes called L.A.-type smog or brown air; and sulfurous smog, sometimes referred to as London-type smog, gray air, or industrial smog. **Sulfurous smog** is produced primarily by the burning of coal or oil at large power plants. Sulfur oxides and particulates combine under certain conditions to produce a concentrated sulfurous smog. **Photochemical smog** is directly related to automobile use.

Figure 21.7 shows a characteristic pattern in the way nitrogen oxides, hydrocarbons, and oxidants (mostly ozone) vary during a typically smoggy day in Southern California. Early in the morning, when commuter traffic begins to build up, concentrations of nitrogen oxide (NO) and hydrocarbons begin to increase. At the same time, nitrogen dioxide (NO_2) may decrease because sunlight breaks it down to produce NO plus atomic oxygen (NO + O). The atomic oxygen (O) is then free to combine with molecular oxygen (O_2) to form ozone (O_3). As a result, the concentration of ozone also increases after sunrise. Shortly thereafter, oxidized hydrocarbons react with NO to increase the concentration of NO_2 by midmorning. This causes the NO concentration to decrease and allows ozone to build up, producing a midday peak in ozone and a minimum in NO. As the smog develops, visibility may be greatly reduced as light is scattered by the pollutants. Figure 21.8 shows Los Angeles on a clear day, in sharp contrast to the way the city looks on a smoggy day.

What are the chances that a deadly smog will occur somewhere in the world? Unfortunately, the answer is all too good, given the amount of air pollution in some large cities. Beijing, for example, might be a candidate; the city uses an immense amount of coal, and coughing is so pervasive that residents often refer to it as the "Beijing cough." Another likely candidate is Mexico City, which has one of the worst air-pollution problems anywhere in the world today.

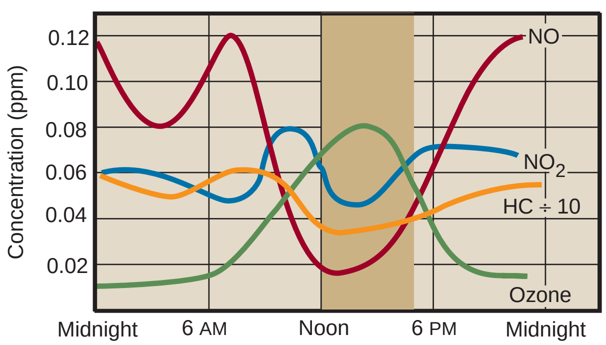


FIGURE 21.7 Development of photochemical smog over the Los Angeles area on a typical warm day.

(a) (b)

FIGURE 21.8 The city of Los Angeles on **(a)** a clear day and **(b)** a smoggy day.

Wherever multiple sources emit air pollutants over a wide area, air pollution can develop. Whether it does or not depends on topography and meteorological conditions, which can determine whether air pollution is a nuisance or a major health problem. The primary adverse effects are damage to green plants and aggravation of chronic illnesses. Most of these effects are due to relatively low concentrations of pollutants over a long period. Periods of pollution generally do not directly cause numerous deaths. Serious pollution events (disasters) can develop over a period of days and lead to increases in illnesses and deaths.

In the lower atmosphere, restricted circulation associated with an atmospheric inversion may lead to pollution events. An **atmospheric inversion** occurs when warmer air lies above cooler air and there is little wind. The air stays still both vertically and horizontally, so any pollutant emissions stay there and build up. Figure 21.9 shows two types of atmospheric inversion that may contribute to air-pollution problems. In the upper diagram, which is somewhat analogous to the situation in the Los Angeles area, descending warm air forms a semipermanent inversion layer. Because the mountains act as a barrier to the pollution, polluted air moving in response to the sea breeze

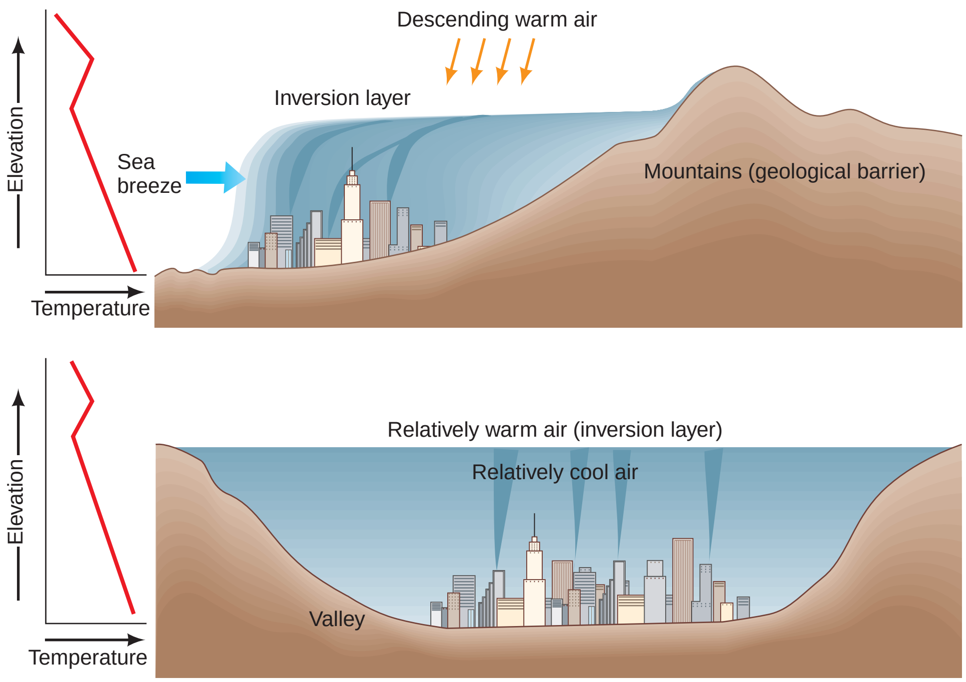


FIGURE 21.9 Two causes of the development of atmospheric inversion, which may aggravate air-pollution problems.

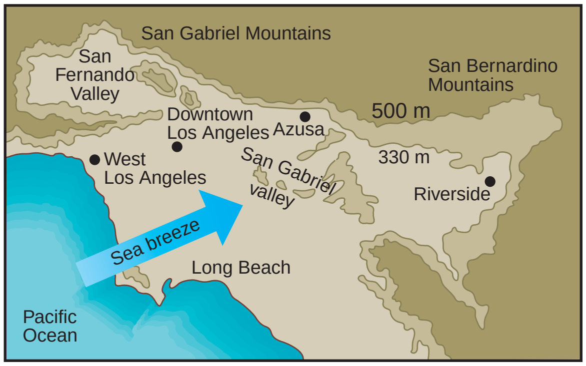


FIGURE 21.10 Part of Southern California showing the Los Angeles basin (south coast air basin). (*Source*: Modified from S.J. Williamson, *Fundamentals of Air Pollution* [Reading, MA: Addison-Wesley, 1973].)

and other processes tends to move up canyons, where it is trapped. The air pollution that develops occurs primarily in summer and fall.

The lower part of Figure 21.9 shows a valley with relatively cool air overlain by warm air. This type of inversion can occur when cloud cover associated with a stagnant air mass develops over an urban area. Incoming solar radiation is blocked by the clouds, which reflect and absorb some of the solar energy and are warmed. On the ground or near Earth's surface, the air cools. If there is moisture in the air (humidity), then, as the air cools, the dew point (the temperature at which water vapor condenses) is reached, and fog may form. Because the air is cold, people burn more fuel to heat their homes and factories, so more pollutants are delivered into the atmosphere. As long as the stagnant conditions exist, the pollutants will build up. It was this mechanism that caused the deadly 1952 London smog that killed about 4,000 people over a one week period December 4 to 10.

Cities in a valley or topographic bowl surrounded by mountains are more susceptible to smog problems than are cities in open plains. Surrounding mountains and the occurrence of temperature inversions prevent pollutants from being dispersed by winds and weather systems. The production of air pollution is particularly well documented for Los Angeles, which has mountains surrounding part of the urban area and lies within a region where the air lingers, allowing pollutants to build up (Figure 21.10).

In sum, the potential for air pollution in urban areas is determined by the following:

- The rate of emission of pollutants per unit area.
- The distance that an air mass moves downwind through a city.
- The average speed of the wind.
- The elevation to which potential pollutants can be thoroughly mixed by naturally moving air in the lower atmosphere (Figure 21.11).[18]

The concentration of air pollutants is directly proportional to the first two factors: As either the emission rate or downwind travel distance through an urban area increases, so will the concentration of pollutants in the air. Again, the Los Angeles basin is a good example (see Figure 21.10). If there is a wind from the ocean, as is generally the case, coastal areas will experience much less air pollution than inland areas. Assuming a constant rate of emission of air pollutants, the air mass will collect more and more pollutants as it moves through the urban area; the inversion layer acts as a lid for the pollutants. However, near a geological barrier, such as a mountain, there may be a chimney effect in which the pollutants spill over the top of the mountain (see Figures 21.10 and 21.11). This has been noticed in the Los Angeles basin, where pollutants may climb several thousand meters, damaging mountain pines and other vegetation and spoiling the air of mountain valleys.

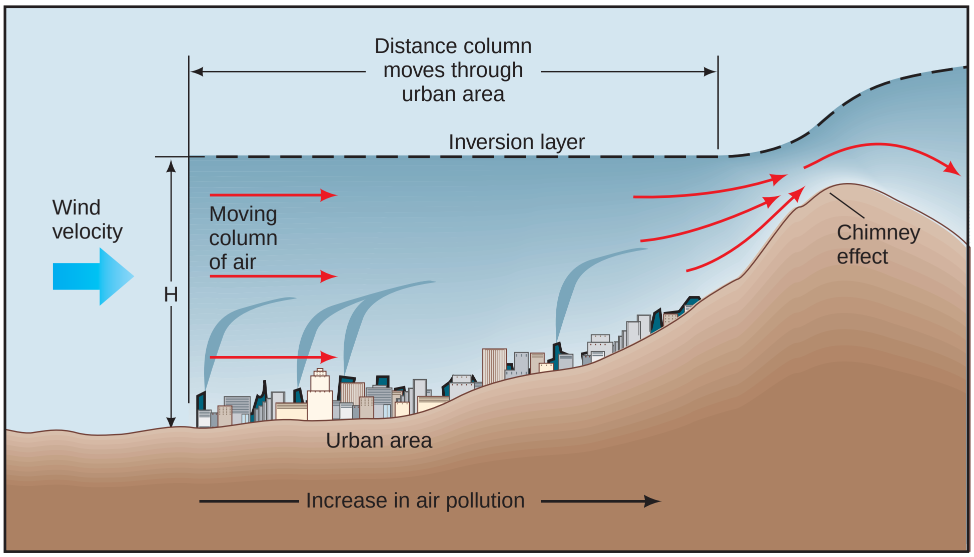


FIGURE 21.11 The higher the wind velocity and the thicker the mixing layer (shown here as H), the less air pollution. The greater the emission rate and the longer the downwind length of the city, the more air pollution. The chimney effect allows polluted air to move over a mountain and down into an adjacent valley.

City air pollution diminishes with increases in the third and fourth factors, which are meteorological: the wind velocity and the height of mixing. The stronger the wind and the higher the mixing layer, the lower the pollution.

Future Trends for Urban Air Pollution

The United States

What does the future hold for U.S. urban areas with respect to air pollution? The optimistic view is that urban air quality will continue to improve as it has in the past 40 years because we know so much about the sources of air pollution and have developed effective ways to reduce it (see Table 21.2). In recent years, as the U.S. population, gross domestic product, and energy consumption have increased, emissions of the major pollutants have decreased (Figure 21.12).[2]

Despite improvements, air pollution in the United States remains a serious problem in many parts of the country. The Los Angeles urban area, for example, still has the worst air quality in the United States. Southern California is coming to grips with the problem, and the people studying air pollution there understand that further pollution abatement will require massive efforts. There are encouraging signs of improvement. For example, from the 1950s to the present, the peak level of ozone (considered one of the best indicators of air pollution) has declined, even though the population nearly tripled and the number of motor vehicles quadrupled during this period. Nevertheless, exposure to ozone in Southern California remains the nation's worst. Even if all the aforementioned controls in urban areas are implemented, air quality will continue to be a significant problem in coming decades, particularly if the urban population continues to increase.

We have focused on air pollution in Southern California because its air quality is especially poor. However, most large and not-so-large U.S. cities have poor air quality for a significant part of the year. With the exception of the Pacific Northwest, no U.S. region is free from air pollution and its health effects.[6]

Developing Countries

The pessimistic view is that population pressures and environmentally unsound policies and practices will dictate what happens in many developing parts of the world, and the result will be poorer air quality. They often don't have the financial base necessary to fight air pollution and are more concerned with finding ways to house and feed their growing populations.

Consider Mexico City. With a population of about 25 million, Mexico City is one of the four largest urban areas in the world. Cars, buses, industry, and power plants in the city emit hundreds of thousands of metric

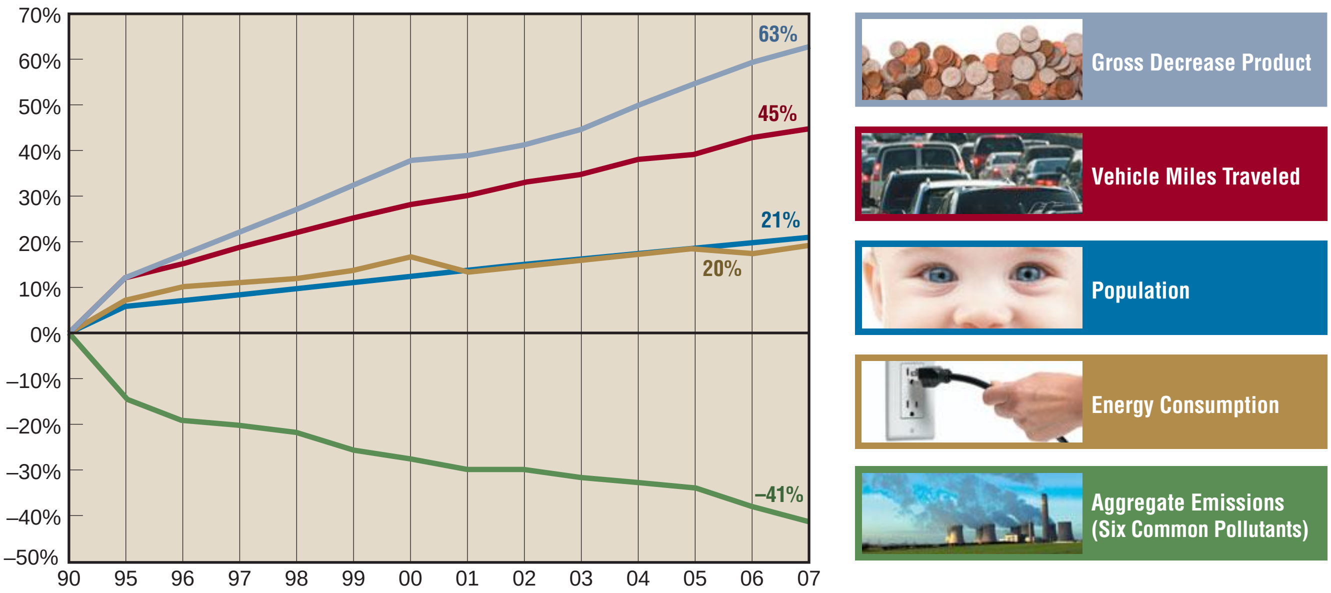


FIGURE 21.12 Change in United States population, gross domestic product, energy consumption, and aggregate emission of the six common air pollutants (ground-level ozone, particulates, lead, nitrogen dioxide, sulfur dioxide, and carbon monoxide) from 1990 to 2007. (*Source*: U.S. Environmental Protection Agency, 2008, air quality trends through 2007. www.epa.gov.

tons of pollutants into the atmosphere each year. The city is at an elevation of about 2,255 m (7,400 ft) in a natural basin surrounded by mountains, a perfect situation for a severe air pollution problem. It is becoming a rare day in Mexico City when the mountains can be seen. Headaches, irritated eyes, and sore throats are common when the pollution settles in, and physicians report a steady increase in respiratory diseases. They advise parents to take their children out of the city permanently. The people in Mexico City do not need to be told they have an air-pollution problem; it is all too apparent. However, developing a successful strategy to improve the quality of the air is difficult.[19]

21.2 Controlling Common Pollutants of the Lower Atmosphere

The most reasonable ways to control the most common air pollutants in our cities include reducing emissions, capturing them before they reach the atmosphere, and removing them from the atmosphere. From an environmental viewpoint, reducing emissions through energy efficiency and conservation (such as burning less fuel) is the preferred strategy, with clear advantages over all other approaches (see Chapters 14 to 16). Here, we discuss control of selected air pollutants.

Particulates

Particulates emitted from fugitive, point, or area stationary sources are much easier to control than the very small particulates of primary or secondary origin released from mobile sources, such as automobiles. As we learn more about these very small particles, we will have to devise new methods to control them.

A variety of "settling chambers" or collectors are used to control emissions of coarse particulates from power plants and industrial sites (point or area sources) by providing a mechanism that causes particles in gases to settle out in a location where they can be collected for disposal in landfills. In recent decades, we have made great strides in controlling particulates, such as ash, from power plants and industry.

Automobiles

Controlling such pollutants as carbon monoxide, nitrogen oxides, and hydrocarbons in urban areas is best achieved by pollution-control measures for automobiles. Control of these materials will also limit ozone formation in the lower atmosphere, since, as you have learned, ozone forms through reactions with nitrogen oxides and hydrocarbons in the presence of sunlight.

Nitrogen oxides from automobile exhausts are controlled by recirculating exhaust gas and diluting the air-to-fuel mixture burned in the engine. Dilution lowers the temperature of combustion and decreases the oxygen concentration in the burning mixture so that it produces fewer nitrogen oxides. Unfortunately, the same process increases hydrocarbon emissions. Nevertheless, exhaust recirculation to reduce nitrogen oxide emissions has been common practice in the United States for more than 20 years.[20]

The exhaust system's catalytic converter is the device most commonly used to reduce carbon monoxide and hydrocarbon emissions from automobiles. In the converter, oxygen from outside air is introduced, and exhaust gases from the engine are passed over a catalyst, typically platinum or palladium. Two important chemical reactions occur: Carbon monoxide is converted to carbon dioxide; and hydrocarbons are converted to carbon dioxide and water.

Other approaches to reducing air pollution from vehicles include reducing the number and types of cars on roads; developing cleaner fuels through use of fuel additives and reformulation; and requiring more fuel-efficient motor vehicles, such as those with electric engines and hybrid cars that have both an electric engine and an internal combustion engine.

Sulfur Dioxide

Sulfur dioxide emissions have been reduced by using abatement measures before, during, or after combustion. Technology to clean up coal so that it will burn more cleanly is already available. Although removing the sulfur makes fuel more expensive, the expense must be balanced against the long-term consequences of burning high-sulfur coal. Switching from high-sulfur coal to low-sulfur coal seems an obvious way to reduce emissions of sulfur dioxide, and in some regions this will work. Unfortunately, however, most of the naturally low-sulfur coal in the United States is in the western part of the country, whereas most coal is burned in the East, so transportation is an issue and using low-sulfur coal is a solution only in cases where it is economically feasible.

Sulfur emissions can also be reduced by washing coal. When finely ground coal is washed with water, iron sulfide (mineral pyrite) settles out because of its relatively high density. But this is ineffective for removing organic sulfur bound up with carbonaceous material, and it is expensive.

Another option is *coal gasification*, which converts relatively high-sulfur coal to a gas in order to remove the sulfur.

The gas is quite clean and can be transported relatively easily, augmenting supplies of natural gas. True, it is still fairly expensive compared with gas from other sources, but its price may become more competitive in the future.

Desulfurization, or **scrubbing** (Figure 21.13), removes sulfur from stationary sources such as power plants. This technology was developed in the 1970s in the United States in response to passage of the Clean Air Act. However, the technology was not initially implemented in the United States; instead, regulators chose to allow plants to disperse pollutants through very tall smokestacks. This worsened the regional acid-rain problem.

Nearly all scrubbers (90%) used at coal-burning power plants in the United States are wet scrubbers that use a lot of water and produce a wet end product. Wet scrubbing is done after coal is burned. The SO_2 rich gases are treated with a slurry (a watery mixture) of lime (calcium oxide, CaO) or limestone (calcium carbonate, $CaCO_3$). The sulfur oxides react with the calcium to form calcium sulfite, which is collected and then usually disposed of in a landfill.[21]

In West Virginia, a coal mine, power plant, and synthetic gypsum plant located close to each other joined forces in 2008 to produce electric energy, recover sulfur dioxide, and produce high-quality wallboard (sheetrock) for the construction industry. The power plant benefits by selling the raw gypsum (from scrubbers) rather than paying to dispose of it in a landfill. The wallboard plant is right next to the power plant and uses gypsum that does not have to be mined from earth.[22]

Air Pollution Legislation and Standards

Clean Air Act Amendments of 1990

The Clean Air Act Amendments of 1990 are comprehensive regulations enacted by the U.S. Congress that address the problems of acid rain, toxic emissions, ozone depletion, and automobile exhaust. In dealing with acid rain, the amendments establish limits on the maximum permissible emissions of sulfur dioxide from utility companies burning coal. The goal of the legislation—to reduce such emissions by about 50%, to 10 million tons a year, by 2000—was more than achieved (refer back to Table 21.2).

An innovative aspect of the legislation is the incentives it offers to utility companies to reduce emissions of sulfur dioxide. As explained earlier here and discussed in detail in Chapter 7, the incentives are marketable permits (allowances) that allow companies to buy and sell the right to pollute[23] (see A Closer Look 21.1). The 1990 amendments also call for reducing emissions of nitrogen dioxides by approximately 2 million tons from the 1980 level. The actual reduction has been 10 million tons—an air- pollution success story!

Ambient Air Quality Standards

Air quality standards are important because they are tied to emission standards that attempt to control the concentrations of various pollutants in the atmosphere. The many countries that have developed air quality standards include France, Japan, Israel, Italy, Canada, Germany, Norway, and the United States. National Ambient Air Quality Standards (NAAQS) for the United States, defined to comply with the Clean Air Act, are shown in Table 21.3. Tougher standards were set for ozone and $PM_{2.5}$ in recent years to reduce adverse health effects on children and elderly people, who are most susceptible to air pollution. The new standards are saving the lives of thousands and improving the health of hundreds of thousands of children. The ozone standard was significantly strengthened in

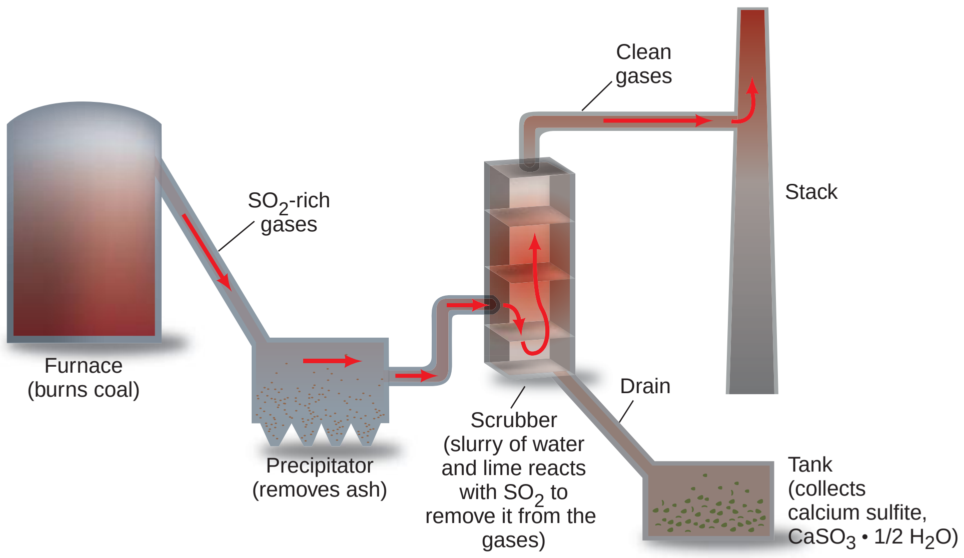


FIGURE 21.13 Scrubber used to remove sulfur oxides from the gases emitted by tall stacks.

2008. The change is expected to result in health benefits of more than $15 billion per year.

Air Quality Index

In the United States, the Air Quality Index (AQI) (Table 21.4) is used to describe air pollution on a given day. For example, air quality in urban areas is often reported as good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, or hazardous, corresponding to a color code of the Air Quality Index. The AQI is determined by measuring the concentration of five major pollutants: particulate matter, sulfur dioxide, carbon monoxide, ozone, and nitrogen dioxide. An AQI value greater than 100 is unhealthy. In most U.S. cities, AQI values range between 0 and 100. Values above 100 are generally recorded for a particular city only a few times a year, but some cities with serious air-pollution problems may exceed an AQI of 100 many times a year. In a typical year, AQI values above 200 (for all U.S. sites) are rare, and those above 300 are very rare. In large cities outside the United States with dense human populations and numerous uncontrolled sources of pollution, AQIs greater than 200 are frequent.

The Cost of Controlling Outdoor Air Pollution

The cost of outdoor air pollution control varies widely from one industry to another. For example, the cost for incremental control in a fossil-fuel-burning utility is a few hundred dollars per additional ton of particulates removed. For an aluminum refinery, the cost to remove an additional ton of particulates may be as much as several thousand dollars. Some economists would argue that it is wise to raise the standards for utilities and relax them, or at least not raise them, for aluminum plants. This would lead to more cost-efficient pollution control while maintaining good air quality. However, the geographic distribution of various facilities will determine the trade-offs possible.[23, 24]

Economic analysis of air pollution is not simple. There are many variables, some of which are hard to quantify. We do know the following:

- With increasing air pollution controls, the capital cost for technology to control air pollution increases.
- As the controls for air pollution increase, the loss from pollution damages decreases.

Table 21.3 U.S. NATIONAL AMBIENT AIR QUALITY STANDARDS (NAAQS)

POLLUTANT	STANDARD VALUE[a]		STANDARD TYPE
Carbon monoxide (CO)			
8-hour average	9 ppm	(10 mg/m^3)	Primary[c]
1-hour average	35 ppm	(40 mg/m^3)	Primary
Nitrogen dioxide (NO_2)			
Annual arithmetic mean	0.053 ppm	(100 μg/m^3)	Primary and secondary[d]
Ozone (O_3)			
8-hour average	0.075 ppm	(147 μg/m^3)	Primary and secondary
Lead (Pb)			
Quarterly average	1.5 μg/m^3		Primary and secondary
Particulate (PM 10) *Particles with diameters of 10 micrometers or less*			
Annual arithmetic mean	50 μg/m^3		Primary and secondary
24-hour average	150 μg/m^3		Primary and secondary
Particulate (PM 2.5)[b] *Particles with diameters of 2.5 micrometers or less*			
Annual arithmetic mean	15 μg/m^3		Primary and secondary
24-hour average	65 μg/m^3		Primary and secondary
Sulfur dioxide (SO_2)			
Annual arithmetic mean	0.03 ppm	(80 μg/m^3)	Primary
24-hour average	0.14 ppm	(365 μg/m^3)	Primary
3-hour average	0.50 ppm	(1300 μg/m^3)	Secondary

[a] Parenthetical value is an approximately equivalent concentration.

[b] The ozone 8-hour standard and the PM 2.5 standards are included for information only. A 1999 federal court ruling blocked implementation of these standards, which the EPA proposed in 1997. EPA has asked the U.S. Supreme Court to reconsider that decision. (Note: In March 2001, the Court ruled in favor of the EPA, and the new standards are expected to take effect within a few years.)

[c] Primary standards set limits to protect public health, including the health of sensitive populations such as asthmatics, children, and the elderly.

[d] Secondary standards set limits to protect public welfare, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

Source: U.S. Environmental Protection Agency.

Table 21.4 AIR QUALITY INDEX (AQI) AND HEALTH CONDITIONS

INDEX VALUES	DESCRIPTOR	CAUTIONARY STATEMENT	GENERAL ADVERSE HEALTH EFFECTS	ACTION LEVEL (AQI)[a]
0–50	Good	None	None	None
51–100	Moderate	Unusually sensitive people should consider limiting prolonged outdoor exertion.	Very few symptoms[b] for the most susceptible people[c]	None
101–150	Unhealthy for sensitive groups	Active children and adults, and people with respiratory disease, such as asthma, should limit prolonged outdoor exertion.	Mild aggravation of symptoms in susceptible people, few symptoms for healthy people	None
151–199	Unhealthy	Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else, especially children, should limit prolonged outdoor exertion.	Mild aggravation of symptoms in susceptible people, irritation symptoms for healthy people	None
200–300	Very unhealthy	Active children and adults, and people with respiratory disease, such as asthma, should avoid outdoor exertion; everyone else, especially children, should limit outdoor exertion.	Significant aggravation of symptoms in susceptible people, widespread symptoms in healthy people	Alert (200+)
Over 300	Hazardous	*Everyone* should avoid outdoor exertion.	300–400: Widespread symptoms in healthy people 400–500: Premature onset of some diseases Over 500: Premature death of ill and elderly people; healthy people experience symptoms that affect normal activity	Warning (300+) Emergency (400+)

[a] Triggers preventative action by state or local officials.

[b] Symptoms include eye, nose, and throat irritation; chest pain; breathing difficulty.

[c] Susceptible people are young, old, and ill people and people with lung or heart disease.

AQI 51–100	Health advisories for susceptible individuals.
AQI 101–150	Health advisories for all.
AQI 151–200	Health advisories for all.
AQI 200+	Health advisories for all; triggers an alert; activities that cause pollution might be restricted.
AQI 300	Health advisories to all; triggers a warning; probably would require power plant operations to be reduced and carpooling to be used.
AQI 400+	Health advisories for all; triggers an emergency; cessation of most industrial and commercial activities, including power plants; nearly all private use of vehicles prohibited.

Source: U.S. Environmental Protection Agency.

- The total cost of air pollution is the cost of pollution control plus the environmental damages of the pollution.

Although the cost of pollution-abatement technology is fairly well known, it is difficult to accurately determine the loss from pollution damages, particularly when considering health problems and damage to vegetation, including food crops. For example, exposure to air pollution may cause or aggravate chronic respiratory diseases in people, at a very high cost. A recent study of the health benefits of cleaning up the air quality in the Los Angeles basin estimated that the annual cost of air pollution in the basin is 1,600 lives and about $10 billion.[25] Air pollution also leads to loss of revenue from people who choose not to visit some areas, such as Los Angeles and Mexico City, because of known air-pollution problems.[26, 27]

With our discussion of the more traditional outdoor air pollutants behind us, we turn now to ozone depletion in the stratosphere. This will be followed by a discussion of indoor air pollution, which has emerged as a serious environmental problem.

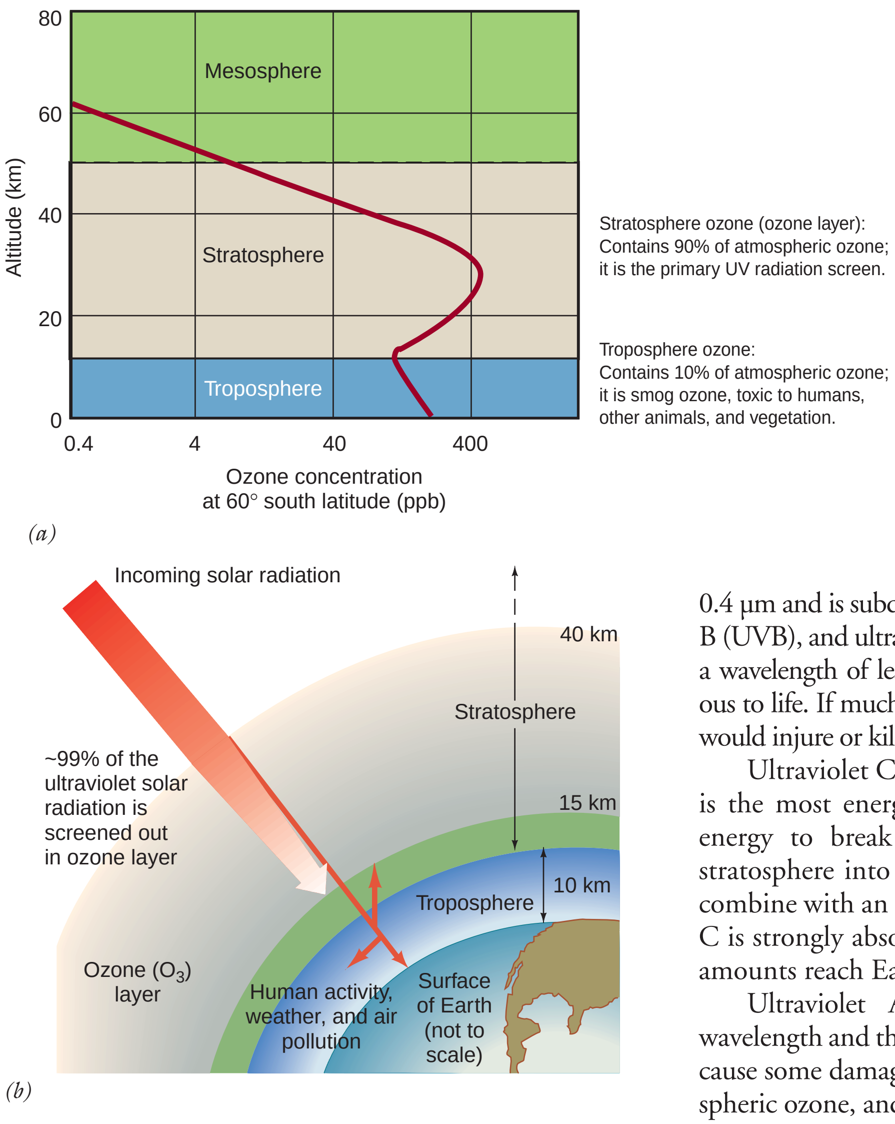


FIGURE 21.14 **(a)** Structure of the atmosphere and ozone concentration. **(b)** Reduction of the potentially most biologically damaging ultraviolet radiation by ozone in the stratosphere. (*Source:* Ozone concentrations modified from R.T. Watson, "Atmospheric Ozone," in J.G. Titus, ed., *Effects of Change in Stratospheric Ozone and Global Climate*, vol. 1, *Overview*, p. 70 (U.S. Environmental Protection Agency).

21.3 High-Altitude (Stratospheric) Ozone Depletion

The serious problem of ozone depletion in the stratosphere (about 9 to 25 km above Earth's surface) starts down here in the lower atmosphere.

About 21% of the air we breathe at sea level is *diatomic* oxygen (O_2), which is two oxygen atoms bonded together. **Ozone (O_3)** is a *triatomic* form of oxygen in which three atoms of oxygen are bonded. Ozone is a strong oxidant and reacts chemically with many materials in the atmosphere. In the lower atmosphere, as we have discussed, ozone is a pollutant produced by photochemical reactions involving sunlight, nitrogen oxides, hydrocarbons, and diatomic oxygen. In the stratosphere, however, ozone plays an entirely different role, protecting us from ultraviolet radiation.

Ultraviolet Radiation and Ozone

The ozone layer in the stratosphere is often called the **ozone shield** because it absorbs most of the potentially hazardous ultraviolet radiation that enters Earth's atmosphere from the sun. Ultraviolet radiation has wavelengths between 0.1 and 0.4 μm and is subdivided into ultraviolet A (UVA), ultraviolet B (UVB), and ultraviolet C (UVC). Ultraviolet radiation with a wavelength of less than about 0.3 μm can be very hazardous to life. If much of this radiation reached Earth's surface, it would injure or kill most living things.[28, 29]

Ultraviolet C (UVC) has the shortest wavelength and is the most energetic of the three types. It has enough energy to break down diatomic oxygen (O_2) in the stratosphere into two oxygen atoms, each of which may combine with an O_2 molecule to create ozone. Ultraviolet C is strongly absorbed in the stratosphere, and negligible amounts reach Earth's surface.[28,29]

Ultraviolet A (UVA) radiation has the longest wavelength and the least energy of the three types. UVA can cause some damage to living cells, is not affected by stratospheric ozone, and is transmitted to the surface of Earth.[28]

Ultraviolet B (UVB) radiation is energetic and strongly absorbed by stratospheric ozone. In fact, ozone is the only known gas that absorbs UVB. Thus, depletion of ozone in the stratosphere allows more UVB to reach the Earth. Because UVB radiation is known to be hazardous to living things,[28-30] this increase in UVB is the hazard we are talking about when we discuss the problem of ozone depletion in the stratosphere.

The structure of the atmosphere and concentrations of ozone are shown in Figure 21.14. Approximately 90% of the ozone in the atmosphere is in the stratosphere, ranging from about 15 km to 40 km (9 to 25 mi) in altitude, with peak concentrations of about 400 ppb. The altitude of peak concentration varies from about 30 km (19 mi) near the equator to about 15 km (9 mi) in polar regions.[28]

Processes that produce ozone in the stratosphere are illustrated in Figure 21.15. The first step in ozone production is *photodissociation*—intense ultraviolet radiation (UVC) breaks an oxygen molecule (O_2) into two oxygen atoms. These atoms then react with another oxygen molecule to form two ozone molecules. Ozone, once produced, may absorb UVC radiation, which breaks the ozone molecule into an oxygen molecule and an oxygen atom. This is followed by the recombination of the oxygen atom with another oxygen molecule to re-form into ozone. As part of this process, UVC radiation is converted to heat energy in the stratosphere. Natural conditions that prevail in the stratosphere result in a dynamic balance between the creation and destruction of ozone.

In sum, approximately 99% of all ultraviolet solar radiation (all UVC and most UVB) is absorbed or screened out in the ozone layer. The absorption of ultraviolet radiation by ozone is a natural service function of the ozone shield and protects us from the potentially harmful effects of ultraviolet radiation.

Measuring Stratospheric Ozone

Scientists first measured the concentration of atmospheric ozone in the 1920s from the ground, using an instrument known as a Dobson ultraviolet spectrometer. The Dobson unit (DU) is still commonly used to measure the ozone concentrations; 1 DU equals a concentration of 1 ppb O_3. Today, we have a record of ozone concentrations spanning about 50 years. Most of the measurement stations are in the midlatitudes, and the accuracy of the data varies with the levels of quality control.[28] Satellite measurements of atmospheric ozone concentrations began in 1970 and continue today.

Ground-based measurements first identified ozone depletion over the Antarctic. Members of the British Antarctic Survey began to measure ozone in 1957, and in 1985 they published the first data that suggested significant ozone depletion over Antarctica. The data are taken during October of each year—the Antarctic spring—and show that the concentration of ozone hovered around 300 DU from 1957 to about 1970, and then dropped sharply, to approximately 140 DU by 1986. Despite the variations, the direction of

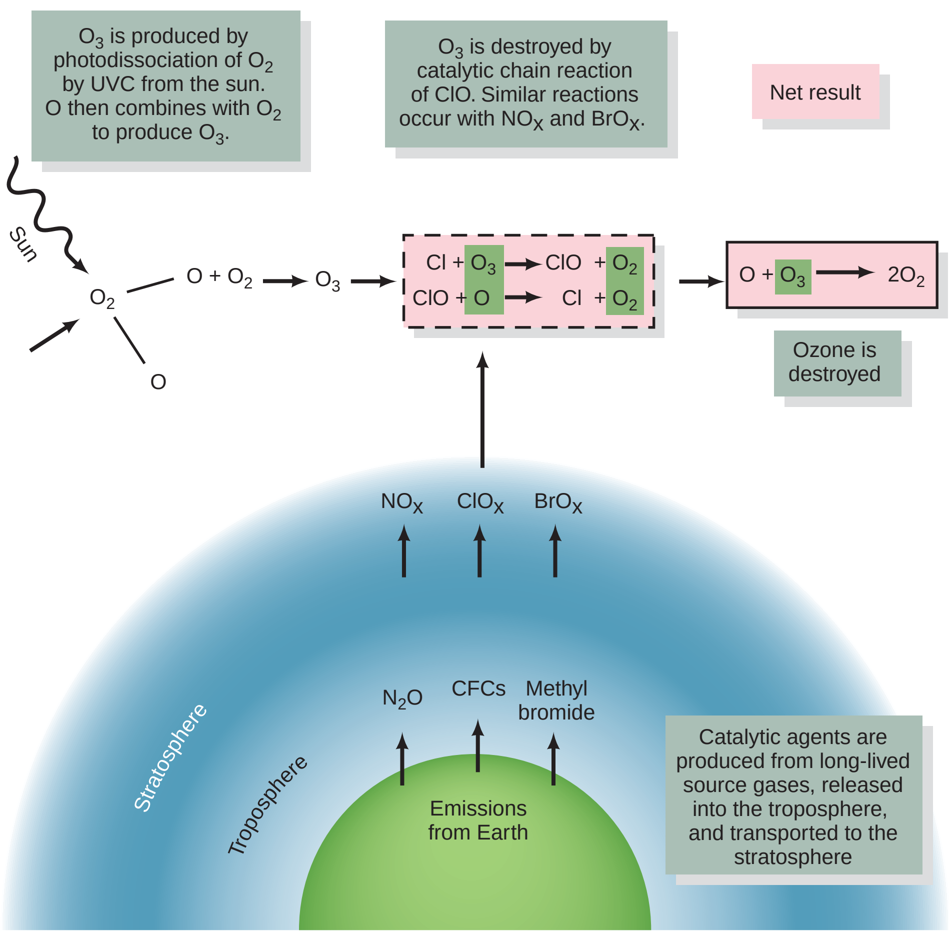


FIGURE 21.15 Processes of natural formation of ozone and destruction by CFCs, N_2O, and methyl bromide. (*Source:* Modified from NASA-GSFC, "Stratospheric Ozone," accessed August 22, 2000, at http://see.gsfc.nasa.gov.)

change, with minor exceptions, is clear: Ozone concentrations in the stratosphere during the Antarctic spring have been decreasing since the mid-1970s.[31-34] The depletion in ozone was dubbed the *ozone hole*. There is no actual hole in the ozone shield where all the ozone is depleted; rather, the term describes a relative depletion in the concentration of ozone that occurs during the Antarctic spring.

Ozone Depletion and CFCs

The hypothesis that ozone in the stratosphere is being depleted by **chlorofluorocarbons (CFCs)** was first suggested in 1974 by Mario Molina and F. Sherwood Rowland.[34] This hypothesis, based mostly on physical and chemical properties of CFCs and knowledge about atmospheric conditions, was immediately controversial and vigorously debated by scientists, companies producing CFCs, and other interested parties.[35-36] The major features of the Molina and Rowland hypothesis are as follows:[28, 29]

- CFCs emitted in the lower atmosphere by human activity are very stable and nonreactive in the lower atmosphere and therefore have a very long residence time (about 100 years). No significant sinks for CFCs are known, with the possible exception of soils, which evidently do remove an unknown amount of CFCs from the atmosphere at Earth's surface.[36]
- Because of their long residence time in the lower atmosphere, and because the lower atmosphere is very fluid, the CFCs eventually disperse, wander upward, and enter the stratosphere. Once they reach altitudes above most of the stratospheric ozone, they may be destroyed by the highly energetic solar ultraviolet radiation. This releases chlorine, a highly reactive atom.
- The reactive chlorine may then enter into reactions that deplete ozone in the stratosphere.
- Ozone depletion allows an increased amount of UVB radiation to reach Earth. Ultraviolet B is a cause of human skin cancers and is also believed to be harmful to the human immune system.

Simplified Stratospheric Chlorine Chemistry

CFCs are considered responsible for most of the ozone depletion. Let us look more closely at how this occurs.

Earlier, we noted that there are no tropospheric sinks for CFCs. That is, the processes that remove most chemicals in the lower atmosphere—destruction by sunlight, rain-out, and oxidation—do not break down CFCs because CFCs are transparent to sunlight, are essentially insoluble, and are nonreactive in the oxygen-rich lower atmosphere.[37] Indeed, the fact that CFCs are nonreactive in the lower atmosphere was one reason they were attractive for use as propellants.

When CFCs wander to the upper part of the stratosphere, however, reactions do occur. Highly energetic ultraviolet radiation (UVC) splits up the CFC, releasing chlorine. When this happens, the following two reactions can take place:[37]

$$(1)\ Cl + O_3 \rightarrow ClO + O_2$$
$$(2)\ ClO + O \rightarrow Cl + O_2$$

These two equations define a chemical cycle that can deplete ozone (Figure 21.15). In the first reaction, chlorine combines with ozone to produce chlorine monoxide. which, in the second reaction, combines with monatomic oxygen to produce chlorine again. The chlorine can then enter another reaction with ozone and cause additional ozone depletion. This series of reactions is what is known as a *catalytic chain reaction*. Because the chlorine is not removed but reappears as a product of the second reaction, the process may be repeated over and over again. It has been estimated that each chlorine atom may destroy approximately 100,000 molecules of ozone in one or two years before the chlorine is finally removed from the stratosphere through other chemical reactions and rain-out.[37] The significance of these reactions is apparent when we realize how many metric tons of CFCs have been emitted into the atmosphere.

It should be noted that what actually happens chemically in the stratosphere is considerably more complex than the two equations shown here. The atmosphere is essentially a chemical soup in which a variety of processes related to aerosols and clouds take place (some of these are addressed in the discussion of the ozone hole). Nevertheless, these equations show us the basic chemical chain reaction that occurs in the stratosphere to deplete ozone.

The catalytic chain reaction just described can be interrupted through storage of chlorine in other compounds in the stratosphere. Two possibilities are as follows:

1. Ultraviolet light breaks down CFCs to release chlorine, which combines with ozone to form chlorine monoxide (ClO), as already described. This is the first reaction discussed. The chlorine monoxide may then react with nitrogen dioxide (NO_2) to form a chlorine nitrate ($ClONO_2$). If this reaction occurs, ozone depletion is minimal. The chlorine nitrate, however, is only a temporary reservoir for chlorine. The compound may be destroyed, and the chlorine released again.
2. Chlorine released from CFCs combine with methane (CH_4) to form hydrochloric acid (HCl). The hydrochloric acid may then diffuse downward. If it enters the troposphere, rain may remove it, thus removing the chlorine from the ozone-destroying chain reaction. This is the ultimate end for most chlorine atoms in the stratosphere. However, while the hydrochloric acid molecule is in the stratosphere, it may be destroyed by incoming solar radiation, releasing the chlorine for additional ozone depletion.

It has been estimated that the chlorine chain reaction that destroys ozone may be interrupted by the processes just described as many as 200 times while a chlorine atom is in the stratosphere.[28, 38]

It is important to remember that for the Southern Hemisphere and under natural conditions, the highest concentration of ozone is in the polar regions (about 60° south latitude) and the lowest near the equator. At first this may seem strange because ozone is produced in the stratosphere by solar energy, and there is more solar energy near the equator. But although much of the world's ozone is produced near the equator, the ozone in the stratosphere moves from the equator toward the poles with global air-circulation patterns.[32]

In part as a result of ozone depletion, concentrations of ozone have declined in both northern and southern temperate latitudes. While remaining relatively constant at the equator, ozone has been significantly reduced in the Antarctic since the 1970s. Massive destruction of ozone in the Antarctic constitutes the "ozone hole."[28]

The Antarctic Ozone Hole

Since the Antarctic ozone hole was first reported in 1985, it has captured the interest of many people around the world. Every year since then, ozone depletion has been observed in the Antarctic in October, the spring season there. Because the thickness of the ozone layer above the Antarctic in springtime has been declining since the mid-1970s, the geographic area covered by the ozone hole has grown from a million or so square kilometers in the late 1970s and early 1980s to about 29 million square kilometers by 1995—about the size of North America in 2000. It has since stabilized as the ozone concentration has ceased its steep decline.[31, 39]

Polar Stratospheric Clouds

The minimum concentration of ozone in the Antarctic since 1980 has varied from about 50% to 70% of that in the 1970s. Polar stratospheric clouds over the Antarctic appear to be one of the causes of this variation. Observed for at least the past hundred years about 20 km (12 mi) above the polar regions, the clouds have an eerie beauty and an iridescent glow, reminiscent of mother-of-pearl.[38] They form during the polar winter (called the polar night because the tilt of Earth's axis limits sunlight). During the polar winter, the Antarctic air mass is isolated from the rest of the atmosphere and circulates about the pole in what is known as the Antarctic *polar vortex*. The vortex forms as the isolated air mass cools, condenses, and descends.[31,32]

Clouds form in the vortex when the air mass reaches a temperature between 195 K and 190 K (–78° to –83°C; –108° to –117°F). At these very low temperatures, small sulfuric acid particles (approximately 01. μm) freeze and serve as seed particles for nitric acid (HNO_3). These clouds are called Type I polar stratospheric clouds. If temperatures drop below 190 K (–83°C; –117°F), water vapor condenses around some of the earlier-formed Type I cloud particles, forming Type II polar stratospheric clouds, which contain larger particles. Type II polar stratospheric clouds are the ones with the mother-of-pearl color.

During the formation of polar stratospheric clouds, nearly all the nitrogen oxides in the air mass are converted to the clouds as nitric acid particles, which grow heavy and descend below the stratosphere, leaving very little nitrogen oxide in the vicinity of the clouds.[28, 38, 39] This facilitates ozone-depleting reactions that may ultimately reduce stratospheric ozone in the polar vortex by as much as 1% to 2% per day in the early spring, when sunlight returns to the polar region (Figure 21.16).

An idealized diagram of the polar vortex that forms over Antarctica is shown in Figure 21.16*a*. The Ozone-depleting reactions within the vortex are illustrated in Figure 21.16*b*. As shown, in the dark Antarctic winter almost all available nitrogen oxides are tied up on the edges of particles in the polar stratospheric clouds or have settled out. Hydrochloric acid and chlorine nitrate (the two important sinks of chlorine) act on particles of polar stratospheric clouds to form dimolecular chlorine (Cl_2) and nitric acid through the following reaction:[40]

$$HCl + ClONO_2 \rightarrow Cl_2 + HNO_3$$

In the spring, when sunlight returns and breaks apart chlorine (Cl_2), the ozone-depleting reactions discussed earlier occur. Nitrogen oxides are absent from the Antarctic stratosphere in the spring, so the chlorine cannot be sequestered to form chlorine nitrate, one of its major sinks, and remains free to destroy ozone. In the early Antarctic spring, these ozone-depleting reactions can be rapid, producing the 50% reduction in ozone observed in recent years. Ozone depletion in the Antarctic vortex ceases later in spring as the environment warms and the polar stratospheric clouds disappear, releasing nitrogen back into the atmosphere, where it can combine with chlorine and thus be removed from ozone-depleting reactions. Stratospheric ozone concentrations then increase as ozone-rich air masses again migrate to the polar region.

A weaker, shorter polar vortex forms over the North Pole area and can lead to ozone depletion of as much as 30–40%. When the vortex breaks up, it can send ozone-deficient air masses southward to drift over areas of Europe and North America.[41]

Environmental Effects of Ozone Depletion

Ozone depletion damages some food chains on land and in the oceans and is dangerous to people, increasing the incidence of skin cancers and cataracts and suppressing immune systems.[41, 42] A 1% decrease

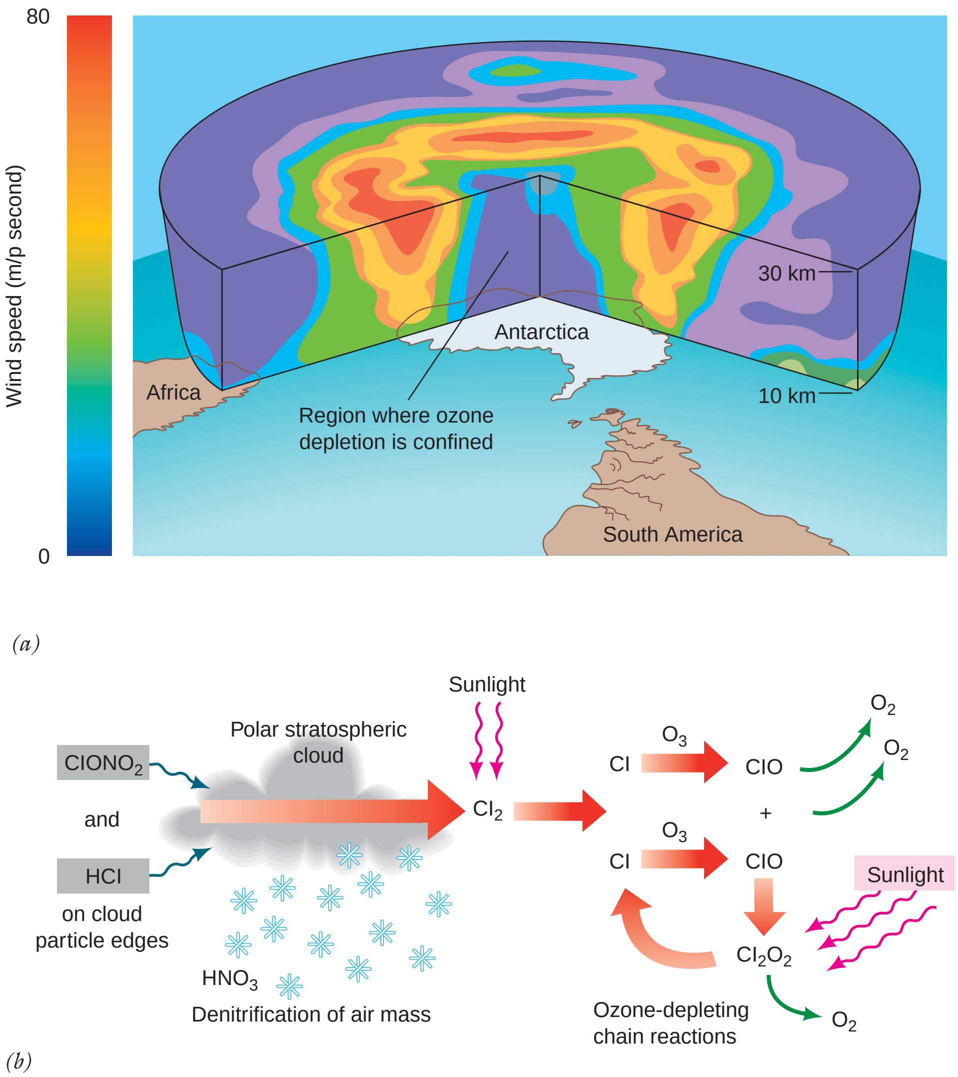


FIGURE 21.16 **(a)** Idealized diagram of the Antarctic polar vortex and **(b)** the role of polar stratospheric clouds in the ozone-depletion chain reaction. (*Source*: Based on O.B. Toon and R.P. Turco, "Polar Stratospheric Clouds and Ozone Depletion," *Scientific American*, 264, no. 6 [1991]: 68–74.)

in ozone can cause a 1–2% increase in UVB radiation and a 2% increase in skin cancer.[43] Because skin cancers have increased globally, health-conscious people today are replacing tanning oils with sunblocks and hats, and newspapers in the United States now provide the **Ultraviolet (UV) Index** (Table 21.5). Developed by the National Weather Service and EPA, the index predicts UV intensity on a scale from 1 to 11+. Some news agencies also use the index to recommend the level of sunblock. It is speculated that the incidence of skin cancer due to ozone depletion will rise until about 2060 and then decline as the ozone shield recovers as a result of controls on CFC emissions.[44, 45]

You can lower your risk of skin cancer and other skin damage from UV exposure by taking a few simple precautions:

- Limit exposure to the sun between 10 A.M. and 4 P.M., the hours of intense solar radiation, and stay in the shade when possible.
- Use a sunscreen with an SPF of at least 30 (but remember that protection diminishes with increased exposure), or use clothing to cover up.
- Wear UV-protective sunglasses.
- Avoid tanning salons and sun lamps.
- Consult the UV Index before going out.

A simple guideline: If your shadow is longer than you are, such as in the evening or early morning, UV exposure is relatively low. If your shadow is shorter than you are, you are in the part of the day with highest UV exposure.

Table 21.5 ULTRAVIOLET (UV) INDEX FOR HUMAN EXPOSURE

EXPOSURE CATEGORY	UV INDEX	COMMENT
Low	< 2	Sunblock recommended for all exposure
Moderate	3 to 5	Sunburn can occur quickly
High	6 to 7	Potentially hazardous
Very high	8 to 10	Potentially very hazardous
Extreme	11	Potentially very hazardous

Note: At moderate exposure to UV, sunburn can occur quickly, at high exposure, fair-skinned people may burn in 10 minutes or less of exposure.

Source: Modified after U.S. Environmental Protection Agency 2004 (with the National Weather Service). Accessed June 16, 2004 at www.epa.gov.

The Future of Ozone Depletion

The signing of the Montreal Protocol in September 1987 was an important diplomatic achievement: 27 nations signed the agreement originally, and an additional 119 signed later. The protocol outlined a plan to eventually reduce global emissions of CFCs to 50% of 1986 emissions. It originally called for eliminating production of CFCs by 1999, but the period was shortened because of scientific evidence that stratospheric ozone was being depleted faster than predicted. An eventual phase-out of all CFC consumption is part of the Montreal Protocol. Stratospheric concentrations of CFCs are expected to return to pre-1980 levels by about 2050, and the rate of increase of CFC emissions has already been reduced.[31, 46, 47] Of primary importance is developing substitutes for CFCs that are both safe and effective. Hydrofluorocarbons (HFCs) are the long-term substitute for CFCs because they do not contain chlorine.

However, a troubling aspect of ozone depletion is that if the manufacture, use, and emission of all ozone-depleting chemicals were to stop today, the problem would not go away—because millions of metric tons of those chemicals are now in the lower atmosphere, working their way up to the stratosphere. Several CFCs have atmospheric lifetimes of 75–140 years. Thus, an estimated 35% of the CFC-12 molecules in the atmosphere will likely still be there in 2100, and approximately 15% in 2200.[28] In addition, some 10–15% of the CFC molecules manufactured in recent years have not yet been admitted to the atmosphere because they remain in foam insulation, air-conditioning units, and refrigerators.[28] Nevertheless, indicators suggest that growth in the concentrations of CFCs has been slowed and in some cases reversed, and recovery of ozone should be noticeable by 2020 or later.[31]

Today by necessity, we are adapting to ozone depletion by learning to live with higher levels of exposure to ultraviolet radiation. (For example using sunblock, wearing hats and avoiding direct mid day solar radiation.) In the long term, achieving a sustainable level of stratospheric ozone will require management of man-made ozone-depleting chemicals.

21.4 Indoor Air Pollution

We have discussed air pollution in the lower atmosphere and the depletion of stratospheric ozone by chemical emissions that rise from the lower atmosphere to cause depletion of O_3 in the stratosphere that produces a hazard from exposure to ultravioleted radiation from the sun. We turn next to air pollution in our homes, schools, and other buildings that we spend time in.

Indoor air pollution from fires for cooking and heating has affected human health for thousands of years. A detailed autopsy of a 4th-century Native American woman, frozen shortly after death, revealed that she suffered from **black lung disease** from breathing very polluted air over many years. The pollutants included hazardous particles from lamps that burned seal and whale blubber.[48] This same disease has long been recognized as a major health hazard for underground coal miners and has been called “coal miners’ disease.” As recently as the mid-1970s, black lung disease was estimated to be responsible for about 4,000 deaths each year in the United States.[49]

People today spend between 70% and 90% of their time in enclosed places—homes, workplaces, automobiles, restaurants, and so forth—but only recently have we begun to fully study the indoor environment and how pollution of that environment affects our health. The World Health Organization has estimated that as many as one in three people may be working in a building that causes them to become sick, and as many as 20% of public schools in the United States have problems related to indoor air quality. The EPA considers indoor air pollution one of the most significant environmental health hazards people face in the modern workplace.[50]

Hurricane Katrina in 2005 (see Chapter 22) left a great number of people homeless. In response, the Federal Emergency Management Agency (FEMA) provided thousands of trailers for people to live in. That sounded like a great idea until complaints started to come in about health problems of people living in the trailers. A study by the Centers for Disease Control and Prevention (CDC) confirmed that the mobile homes suffered from indoor air pollution by formaldehyde in their construction materials. Formaldehyde is a chemical widely used in the manufacture of building materials, as well as a number of other products. It is considered a probable human carcinogen (a substance that causes or promotes cancer). Common symptoms of exposure to formaldehyde include irritation of the skin, nose, throat, and eyes. People with asthma may be more sensitive to the chemical, and their symptoms may be worse. Since discovery of the high levels of formaldehyde in mobile homes in late 2007, plans have gone forward to remove the remaining people, particularly those experiencing symptoms of formaldehyde toxicity.[51, 52]

The history of formaldehyde in the mobile homes provided to Katrina victims is a sad legacy of the entire way our federal government responded to Hurricane Katrina and its aftermath. It is also important because it brings to the public consciousness the potential problems of indoor air pollution, which is often more significant than outdoor air pollution.

Sources of Indoor Air Pollution

The sources of indoor air pollution are incredibly varied (Figure 21.17) and can arise from both human activities and natural processes. Two common pollutants are shown in Figure 21.18. Other common indoor air pollutants, together with guidelines for allowable exposure, are listed in Table 21.6.

1. Heating, ventilation, and air-conditioning systems may be sources of indoor air pollutants, including molds and bacteria, if filters and equipment are not maintained properly. Gas and oil furnaces release carbon monoxide, nitrogen dioxide, and particles.
2. Restrooms may have a variety of indoor air pollutants, including secondhand smoke, and also molds and fungi due to humid conditions.
3. Furniture and carpets often contain toxic chemicals (formaldehyde, organic solvents, asbestos) that may be released over time in buildings.
4. Coffee machines, fax machines, computers, and printers can release particles and chemicals, including ozone (O_3), which is highly oxidizing.
5. Pesticides can contaminate buildings with cancer-causing chemicals.
6. Fresh-air intake that is poorly located—for example, above a loading dock or first-floor restaurant exhaust fan—can bring in air pollutants.
7. People who smoke indoors, perhaps in restaurants or offices, pollute the indoor environment, and even people who smoke outside buildings, particularly near open or revolving doors, may cause pollution as the smoke (secondhand smoke) is drawn into and up through the building by the chimney effect.
8. Remodeling, painting, and other such activities often bring a variety of chemicals and materials into a building. Fumes from such activities may enter the building's heating, ventilation, and air-conditioning system, causing widespread pollution.
9. A variety of cleaning products and solvents used in offices and other parts of buildings contain harmful chemicals whose fumes may circulate throughout a building.
10. People can increase carbon dioxide levels; they can emit bioeffluents and spread bacterial and viral contaminants.
11. Loading docks can be sources of organics from garbage containers, of particulates, and of carbon monoxide from vehicles.
12. Radon gas can seep into a building from soil; rising damp (water), which facilitates the growth of molds, can enter foundations and rise up walls.
13. Dust mites and molds can live in carpets and other indoor places.
14. Pollen can come from inside and outside sources.

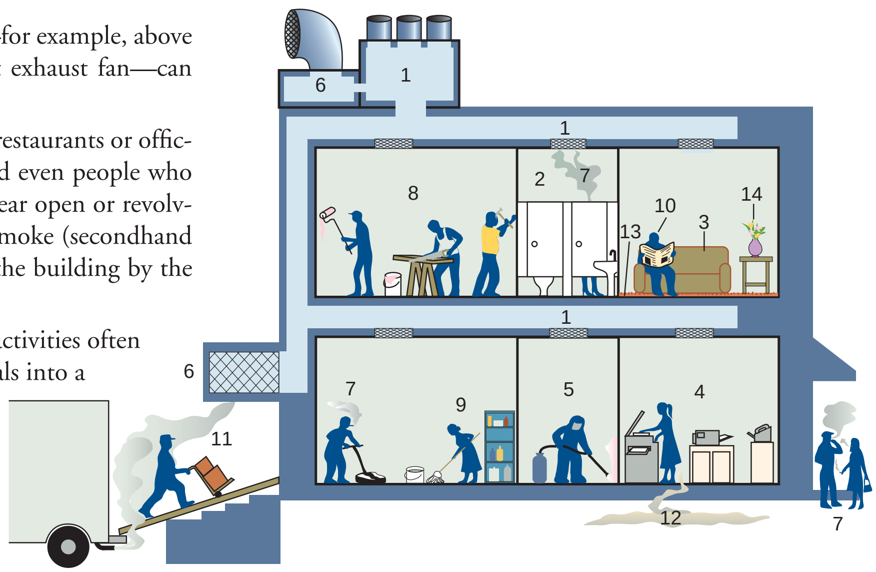


FIGURE 21.17 Some potential sources of indoor air pollution.

Table 21.6 SOURCES, CONCENTRATIONS, OCCURRENCES, AND POSSIBLE HEALTH EFFECTS OF INDOOR AIR POLLUTANTS

POLLUTANT	SOURCE	GUIDELINES (DOSE OR CONCENTRATIONS)	POSSIBLE HEALTH EFFECTS
Asbestos	Fireproofing; insulation, vinyl floor, and cement products; vehicle brake linings	0.2 fibers/mL for fibers larger than 5 μm	Skin irritation, lung cancer
Biological aerosols/ microorganisms	Infectious agents, bacteria in heating, ventilation, and air-conditioning systems: allergens	None available	Diseases, weakened immunity
Carbon dioxide	Motor vehicles, gas appliances, smoking	1,0000 ppm	Dizziness, headaches, nausea
Carbon monoxide	Motor vehicles, kerosene and gas space heaters, gas and wood stoves, fireplaces; smoking	10,000 $\mu g/m^2$ for 8 hours; 40,000 $\mu g/m^3$ for 1 hour	Dizziness, headaches, nausea, death
Formaldehyde	Foam insulation; plywood, particleboard, ceiling tile, paneling, and other construction materials	120 $\mu g/m^3$	Skin irritant, carcinogen
Inhalable particulates	Smoking, fireplaces, dust, combustion sources (wildfires, burning trash, etc.)	55-110 $\mu g/m^3$ annual; 350 $\mu g/m^2$ for 1 hour	Respiratory and mucous irritant, carcinogen
Inorganic particulates			
Nitrates	Outdoor air	None available	
Sulfates	Outdoor air	4 $\mu g/m^3$ annual; 12 $\mu g/m^3$ for 24 hours	
Metal particulates			
Arsenic	Smoking, pesticides, rodent poisons	None available	Toxic, carcinogen
Cadmium	Smoking, fungicides	2 $\mu g/m^3$ for 24 hours	
Lead	Automobile exhaust	1.5 $\mu g/m^3$ for 3 months	
Mercury	Old fungicides; fossil fuel combustion	2 $\mu g/m^3$ for 24 hours	
Nitrogen dioxide	Gas and kerosene space heaters, gas stoves, vehicular exhaust	100 $\mu g/m^3$ annual	Respiratory and mucous irritant
Ozone	Photocopying machines, electrostatic air cleaners, outdoor air	235 $\mu g/m^3$ for 1 hour	Respiratory irritant causes fatigue
Pesticides and other semivolatile organics	Sprays and strips, outdoor air	5 $\mu g/m^3$ for chlordane	Possible carcinogens
Radon	Soil gas that enters buildings, construction materials, groundwater	4pCi/L	Lung cancer
Sulfur dioxide	Coal and oil combustion, kerosene space heaters, outside air	80 $\mu g/m^3$ annual; 365 $\mu g/m^3$ for 24 hours	Respiratory and mucous irritant
Volatile organics	Smoking, cooking, solvents, paints, varnishes, cleaning sprays, carpets, furniture, draperies, clothing	None available	Possibe carcinogens

Source: N. L. Nagda, H. E. Rector, and M. D. Koontz, 1987; M. C. Baechler et al., 1991; E. J. Bardana Jr. and A. Montaro (eds.), 1997; M. Meeker,1996; D. W. Moffatt, 1997.

(a) (b)

FIGURE 21.18 **(a)** This dust mite (magnified about 140 times) is an eight-legged relative of spiders. It feeds on human skin in household dust and lives in materials such as fabrics on furniture. Dead dust mites and their excrement can cause allergic reactions and asthma attacks in some people. **(b)** Microscopic pollen grains that in large amounts may be visible as a brown or yellow powder. The pollen shown here is from dandelions and horse chestnuts.

Many products and processes used in our homes and workplaces are sources of pollution. Other air pollutants—such as carbon monoxide, particulates, nitrogen dioxide, radon, and carbon dioxide—may enter a building by infiltration, either through cracks and other openings in the foundations and walls or by way of ventilation systems, and are generally found in much higher concentrations indoors than outdoors (see Figure 21.19). The reason is somewhat ironic: The steps we have taken to make our homes and offices energy-efficient often trap pollutants inside. Two of the best ways to conserve energy in homes and other buildings are to increase insulation and decrease infiltration of outside air. But windows that don't open and extensive caulking and weather stripping, while reducing energy consumption, also reduce natural ventilation. With less natural ventilation, we must depend more on the ventilation systems that are part of heating and air-conditioning systems.

Pathways, Processes, and Driving Forces

Both natural and human processes create differential pressures that move air and contaminants from one area of a building to another. Areas of high pressure may develop on the windward side of a building, whereas pressure is lower on the leeward, or protected, side. As a result, air is drawn into a building from the windward side. Opening and closing doors produces pressure differentials that cause air to move within buildings. Wind, too, can affect the movement of air in a building, particularly if the structure is leaky.[53]

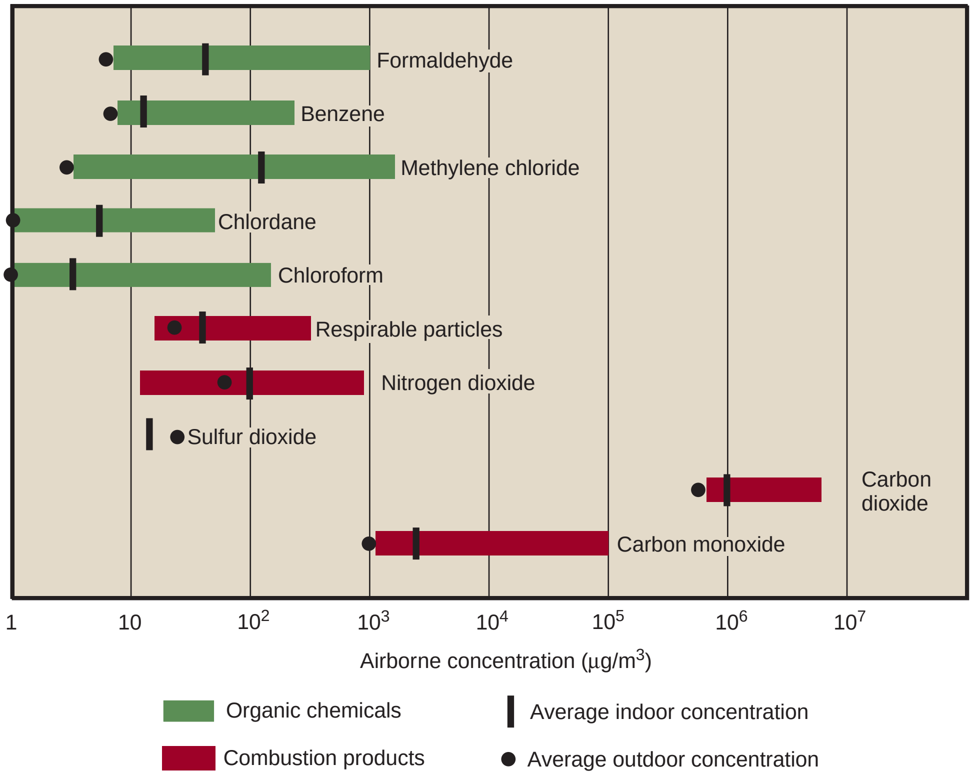


FIGURE 21.19 Concentrations of common indoor air pollutants compared with outdoor concentrations plotted on a log scale, that is, $10^2 = 100$; $10^3 = 1{,}000$, $10^4 = 10{,}000$, etc. (*Source*: A.V. Nero Jr., "Controlling Indoor Air Pollution," *Scientific American*, 258, no. 5 [1998]: 42–48.)

A **chimney effect (or stack effect)** occurs when the indoor and outdoor temperatures differ. Warm air rises within a building. If the indoor air is warmer than the outdoor air, then as the warmer air rises to the building's upper levels, it is replaced in the lower levels by outdoor air drawn in through various openings—windows, doors, cracks in the foundations and walls. Because air is so fluid, the possible interactions between the driving forces and the building are complex, and the distribution of potential air contaminants and pollutants can be extensive. One outcome is that people in various parts of a building may complain about the air quality even if they are widely separated from each other and from potential sources of pollution.[53]

Heating, Ventilation, and Air-Conditioning Systems

Heating, ventilation, and air-conditioning systems are designed to provide a comfortable indoor environment. Their design depends on a number of variables, including the activity of people in the building, air temperature and humidity, and air quality. If the heating, ventilation, and air-conditioning system is designed correctly and functions properly, it will maintain a comfortable temperature and adequate ventilation (using outdoor air), and also remove common air pollutants via exhaust fans and filters.[53]

Regardless of the type of system used in a home or other building, its effectiveness depends on the proper design of the equipment for that building, proper installation, and correct maintenance and operating procedures. Indoor air pollution may result if any one of these factors concentrates pollutants from the many possible sources. Filters plugged or contaminated with fungi, bacteria, or other potentially infectious agents can cause serious problems. In addition, as we see later in this chapter, ventilation systems are not generally designed to reduce some types of indoor pollution.[53, 54]

Environmental Tobacco Smoke

Environmental tobacco smoke (ETS), also known as *secondhand smoke*, comes from two sources: smoke exhaled by smokers and smoke emitted from burning tobacco in cigarettes, cigars, or pipes. People exposed to ETS are referred to as *passive smokers*.[55]

ETS is the most widely known hazardous indoor air pollutant. It is hazardous for the following reasons:[55, 56]

- Tobacco smoke contains several thousand chemicals, many of which are irritants. Examples include NOx, CO, hydrogen cyanide, and about 40 carcinogenic chemicals.
- Studies of nonsmoking workers exposed to ETS found that they have impaired airway functions comparable to that caused by smoking up to ten cigarettes a day. They suffer more illnesses, such as coughs, eye irritation, and colds, and lose more work time than those not exposed to ETS.
- In the United States, about 3,000 deaths from lung cancer and 40,000 deaths from heart disease a year are thought to be associated with ETS.

The number of smokers in the United States has declined, but there are still about 40 million. The rate is higher in the developing world, where health warnings are few or nonexistent. Smoking is extremely addictive because tobacco contains nicotine, a highly addictive substance. Nevertheless, education and social pressure have persuaded some thoughtful people to quit smoking and to encourage others to keep trying.

Radon Gas

It has become apparent over the past few decades that radon gas—colorless, odorless, and tasteless—may be a significant environmental health problem in the United States.[57, 58] **Radon** comes from natural processes, not from human activities. It is a naturally occurring radioactive gas that is a product of the radioactive-decay chain from uranium to stable lead. Radon-222, which has a half-life of 3.8 days, is emitted during the radioactive decay of radium-226. Radon decays with emission of an alpha particle to polonium-218, which has a half-life of approximately 3 minutes. (The discussion of radiation, radiation units, radiation doses, and health problems related to radiation in Chapter 17 will help you understand the following discussion.)

Geology and radon gas. The concentration of radon gas that reaches the surface of the Earth and thus can enter our dwellings is related to the concentration of radon in the rocks and soil, as well as the efficiency of the transfer processes from the rocks or soil to the surface. Some regions in the United States contain bedrock with an above-average natural concentration of uranium. A large area that includes parts of Pennsylvania, New Jersey, and New York—an area known as the Reading Prong—has many homes with elevated radon concentrations.[57] Such areas have also been identified in a number of other states, including Florida, Illinois, New Mexico, South Dakota, North Dakota, Washington, and California.

How dangerous is radon gas? Many people today are worried about radon in their homes because studies indicate that exposure to elevated concentrations increases the risk of lung cancer, and that the risk increases with the level and duration of exposure and also certain habits, such as smoking.[58] Radon, combined with smoking, is thought to produce a synergistic effect that is particularly hazardous. One estimate is that the combination of exposure to radon gas and tobacco smoke is 10 to 20 times more hazardous than exposure to either pollutant by itself.[58]

The Environmental Protection Agency (EPA) estimates that 14,000 lung cancer deaths per year in the United States are related to exposure to radon and its daughter products (products that result from its radioactive decay), primarily polonium-218. (The estimate actually ranges from 7,000 to 30,000.) By comparison, approximately 140,000 people die of lung cancer in the United States each year. If these estimates are correct—and they are controversial—approximately 10% of the lung cancer deaths in the United States can be attributed to radon. Exposure to radon has also been linked to other forms of cancer, such as melanoma (a deadly skin cancer) and leukemia, but, again, such linkages are highly controversial.[59, 60] The link between radon and cancer is mostly based on studies of uranium miners, a group of people exposed to high concentrations of radon in mines.

If the estimated risks from radon are anywhere close to the actual risk, then the hazard is a large one. The U.S. Surgeon General has stated that "indoor radon gas is a national health problem." The risks posed by radon are thought to be hundreds of times higher than risks from outdoor pollutants in air and water. Such pollutants are generally regulated to reduce the risk of premature death and disease to less than 0.001%. Risks from some indoor pollutants, such as organic chemicals, may be as high as 0.1%.[61] These risks still are very small compared with the risk for radon. For example, people who live in homes for about 20 years with an average concentration of radon of about 25 pCi/L are estimated to have a 1 to 2% chance of contracting lung cancer.[58, 61]

How does radon enter homes and other buildings? Radon enters homes and other buildings in three main ways: (1) It migrates up from soil and rock into basements and lower floors; (2) dissolved in groundwater, it is pumped into wells and then into homes; and (3) radon-contaminated materials, such as building blocks, are used in construction. It is difficult to estimate how many homes in the United States may have elevated concentrations of radon. The EPA estimates that about 7% have elevated radon levels and recommends that all homes and schools be tested. The test is simple and inexpensive.

Symptoms of Indoor Air Pollution

People living or working in particular indoor environments may react to pollutants in different ways: Some are particularly susceptible to indoor air pollution; some report different symptoms from the same pollutant; and some report symptoms that turn out not to stem from air pollution.

A wide variety of symptoms can result from exposure to indoor air pollutants (see Table 21.7). Some chemical pollutants can cause nosebleeds, chronic sinus infections, headaches, and irritation of the skin or eyes, nose, and throat. More-serious problems include loss of balance and memory, chronic fatigue, difficulty in speaking, and allergic reactions, including asthma.

Sick Buildings

An entire building can be considered "sick" because of environmental problems. There are two types of "sick" buildings:

- Buildings with identifiable problems, such as toxic molds or bacteria known to cause disease. The diseases are known as *building-related illnesses* (BRI).
- Buildings with **sick building syndrome (SBS)**, where the symptoms people report cannot be traced to any known cause.

A sick building's indoor environment appears to be unhealthy in that a number of people in the building report adverse health effects that they believe are related to the amount of time they spend in the building. Their complaints may range from funny odors to more-serious symptoms, such as headaches, dizziness, nausea, and so forth. In addition, an unusual number of people in the building may feel sick, or may have contracted a serious disease, such as cancer.[62-64]

In many cases, it is difficult to establish what may be causing the sick building syndrome. It has sometimes been found to be related to poor management and low worker morale, rather than to toxins in the building. When the occupants of a building report adverse health effects and a study does not detect the cause, a number of other things may be happening:[53]

21.5 Controlling Indoor Air Pollution

As much as $250 billion per year might be saved by decreasing illnesses and increasing productivity through improving the work environment.[50] A good starting point would be environmental legislation requiring certain indoor air quality standards. At a minimum, these should include increasing the inflow of fresh air through ventilation. In Europe, systems of filters and pumps in many office buildings circulate air three times as frequently as is typical in the United States. Many building codes in Europe require that workers have access to fresh air (windows) and natural light. Unfortunately, no similar codes

Table 21.7 SOME SYMPTOMS OF INDOOR AIR POLLUTION

SYMPTOMS	ETS[a]	COMBUSTION PRODUCTS[b]	BIOLOGIC POLLUTANTS[c]	VOCS[d]	HEAVY METALS[e]	SBS[f]
Respiratory						
Inflammation of mucous membranes of the nose, nasal congestion	Yes	Yes	Yes	Yes	No	Yes
Nosebleed	No	No	No	Yes	No	Yes
Cough	Yes	Yes	Yes	Yes	No	Yes
Wheezing, worsening asthma	Yes	Yes	No	Yes	No	Yes
Labored breathing	Yes	No	Yes	No	No	Yes
Severe lung disease	Yes	Yes	Yes	No	No	Yes
Other						
Irritation of mucous membranes of eyes	Yes	Yes	Yes	Yes	No	Yes
Headache or dizziness	Yes	Yes	Yes	Yes	Yes	Yes
Lethargy, fatigue, malaise	No	Yes	Yes	Yes	Yes	Yes
Nausea, vomiting, anorexia	No	Yes	Yes	Yes	Yes	No
Cognitive impairment, personality change	No	Yes	No	Yes	Yes	Yes
Rashes	No	No	Yes	Yes	Yes	No
Fever, chills	No	No	Yes	No	Yes	No
Abnormal heartbeat	Yes	Yes	No	No	Yes	No
Retinal hemorrhage	No	Yes	No	No	No	No
Muscle pain, cramps	No	No	No	Yes	No	Yes
Hearing loss	No	No	No	Yes	No	No

[a] Environmental tobacco smoke.

[b] Combustion products Include particles, NO_x, CO, and CO_2 .

[c] Biologic pollutants include molds, dust mites, pollen, bacteria, and viruses.

[d] Volatile organic compounds, including formaldehyde and solvents.

[e] Heavy metals include lead and mercury.

[f] Sick building syndrome.

Source: Modified from American Lung Association, Environmental Protection Agency, and American Medical Association, “Indoor Air Pollution—An introduction for Health Professionals,” 523-217/81322 (Washington, D.C.: GPO, 1994).

exist for U.S. workers, and many buildings use central air-conditioning with windows permanently sealed.[50]

You might think that heating, ventilating, and air-conditioning systems, operating properly and well maintained, will ensure good indoor air quality, but in fact these systems are not designed to maintain all aspects of air quality. For example, commonly used ventilation systems do not generally reduce radon gas. Other strategies include source removal, source modification, and air cleaning.[62]

Education also plays an important role in developing strategies to reduce indoor air pollution; it enables people to make informed decisions about exposure to chemicals, such as paints and solvents, and about strategies to avoid potentially hazardous conditions in the home and workplace.[62] At one level, this may involve deciding not to install unvented or poorly vented appliances. A surprising (and tragic) number of people are killed each year by carbon monoxide poisoning due to poor ventilation in homes, campers, and tents. Educated people are also more aware of their legal rights with respect to product liability and safety.

Making Homes and Other Buildings Radon Resistant

Protecting new homes from potential radon problems is straightforward and relatively inexpensive. It is also easy to upgrade an older home to reduce radon. The techniques vary according to the type of foundation the structure has. The basic strategy is to prevent radon from entering a home (usually sealing entry points) and ensure that radon is removed from the site (this generally involves designing a ventilation system).[65, 66]

Designing Buildings to Minimize Indoor Air Pollution

There is a movement under way in the United States and the world to create buildings specifically designed to provide a healthful indoor environment for their occupants. The basic objectives of the design are to minimize indoor air pollutants; ensure that fresh air is supplied and circulated; manage moisture to avoid problems such as mold; reduce energy use; use materials whose origin is environmentally benign and can be recycled, as much as possible; create as pleasing a working environment as possible; use vegetation planted on roofs and wherever else possible to take up carbon dioxide, release oxygen, and add to the general pleasantness of the working environment.

CRITICAL THINKING ISSUE

Should Carbon Dioxide Be Regulated along with Other Major Air Pollutants?

The six common pollutants, sometimes called the *criteria pollutants*, are ozone, particulate matter, lead, nitrogen dioxide, carbon monoxide, and sulfur dioxide. These pollutants have a long history with the EPA, and major efforts have been made to reduce them in the lower atmosphere over the United States. This effort has been largely successful—all of them have been significantly reduced since 1990.

In 2009, the EPA suggested that we add carbon dioxide to this list. Two years earlier, the U.S. Supreme Court had ordered the EPA to make a scientific review of carbon dioxide as an air pollutant that could possibly endanger public health and welfare. Following that review, the EPA announced that greenhouse gases pose a threat to public health and welfare. This proclamation makes it possible that greenhouse gases, especially carbon dioxide, will be regulated by the Clean Air Act, which regulates most other serious air pollutants. The EPA's conclusion that greenhouse gases harm or endanger public health and welfare is based primarily on the role these gases play in climate change. The analysis states that the impacts include, but are not limited to, increased drought that will impact agricultural productivity; more intense rainfall, leading to a greater flood hazard; and increased frequency of heat waves that affect human health.

The next step in adding carbon dioxide and other greenhouse gasses, such as methane, to the list of pollutants regulated by the EPA will be a series of public hearings and feedback from a variety of people and agencies. Some people oppose listing carbon dioxide as an air pollutant because, first of all, it is a nutrient and stimulates plant growth; and, second, it does not directly affect human health in most cases (the exception being carbon dioxide emitted by volcanic eruption and other volcanic activity, which can be extremely toxic).

Critical Thinking Questions

After going over the information concerning global climate change and the role of carbon dioxide in causing change, consider the following questions:

1. Do you think carbon dioxide, along with other greenhouse gases, should be controlled under the Clean Air Act? Why? Why not?
2. Assuming carbon dioxide and other greenhouse gases are to be controlled under the Clean Air Act, what sorts of programs might be used for such control? For example, the control of sulfur dioxide was primarily through a cap-and-trade program where the total amount of emissions were set, and companies bought and sold shares of allowed pollution up to the cap.
3. If the United States can curtail emissions of carbon dioxide under the Clean Air Act, how effective will this be in, say, reducing the global concentration of carbon dioxide to about 350 parts per million given what other countries are likely to do in the future with respect to emissions and given that the concentration today is about 390 parts per million?

SUMMARY

- There are two main kinds of air pollutants: primary and secondary. Primary pollutants are emitted directly into the air: particulates, sulfur dioxide, carbon monoxide, nitrogen oxides, and hydrocarbons. Secondary pollutants are produced through reactions between primary pollutants and other atmospheric compounds. Ozone is a secondary pollutant that forms over urban areas through photochemical reactions between primary pollutants and natural atmospheric gases.
- There are also two kinds of sources: stationary and mobile. Stationary sources have a relatively fixed position and include point sources, area sources, and fugitive sources.
- Meteorological conditions—in particular, restricted circulation in the lower atmosphere due to temperature inversion—greatly determine whether or not polluted air is a problem in an urban area.
- Pollution-control methods are tailored to specific pollution sources and types and vary from settling chambers for particulates to scrubbers that remove sulfur before it enters the atmosphere.
- Emissions of air pollutants in the United States are decreasing, but in large urban areas of developing countries it remains a serious problem.
- The concentration of atmospheric ozone has been measured for more than 70 years. Concentrations in the stratosphere have declined since the mid-1970s, allowing more ultraviolet radiation to reach the lower atmosphere, where it can damage living things.
- In 1974, Mario Molina and F. Sherwood Rowland hypothesized that stratospheric ozone might be depleted by emissions of chlorofluorocarbons (CFCs) into the lower atmosphere. Major features of the hypothesis are that CFCs are very stable and have a long residence time in the atmosphere. Eventually they reach the stratosphere, where they may be destroyed by solar ultraviolet radiation, releasing chlorine. The chlorine may then enter into a catalytic chain reaction that depletes ozone in the stratosphere.
- Banning chemicals that deplete stratospheric ozone is a step in the right direction. However, millions of tons of these are now in the lower atmosphere and working their way up, so even if all production, use, and emission of these chemicals stopped today, the problem would continue for a long time. The good news is that concentrations of CFCs in the atmosphere have apparently peaked and are now static or in slow decline.
- Possible sources of indoor air pollution are construction materials, furnishings, types of equipment used for heating and cooling, as well as natural processes that allow gases to seep into buildings.
- Indoor concentrations of air pollutants are generally greater than outdoor concentrations of the same pollutants.
- Ventilation is commonly used to control indoor air pollution, but tighter construction impedes ventilation, and many popular ventilation systems do not reduce certain types of indoor air pollutants.
- The most common natural process that affects interior air quality is the "chimney" or "stack effect" that occurs when the indoor and outdoor environments differ in temperature.
- People react to indoor air pollution in different ways, and so reported symptoms may vary.
- In some cases, reported symptoms have nothing to do with air pollution.
- Controlling indoor air pollution involves several strategies, including ventilation, source removal, source modification, and air-cleaning equipment, as well as education.

REEXAMINING THEMES AND ISSUES

Human Population

Population growth will exacerbate air pollution problems. As the number of people increases, so does the use of resources, many of which are related to emissions of air pollutants. This may be partially offset in developed countries, where the per capita emissions of air pollutants have been reduced in recent years.

Sustainability

Ensuring that future generations inherit a quality environment is an important objective of sustainability. Thus, it is vital that we develop technology that minimizes air pollution.

Global Perspective

Atmospheric processes and atmospheric pollution occur on regional and global scales. Pollutants emitted into the atmosphere at a particular site may join the global circulation pattern and spread throughout the world, and pollutants emitted from urban or agricultural areas may be dispersed to pristine areas far removed from human activities. Therefore, an understanding of global atmospheric processes is critical to finding solutions to many air pollution problems, including acid deposition.

Urban World

Cities and urban corridors are sites of intense human activity, and many of these activities contribute to air pollution. Some large cities have such severe air pollution problems that the health and lives of people are being affected.

People and Nature

Although we think of nature as unspoiled, in reality nature can be toxic. This is especially true with regard to air pollution—for example, the vast majority of particulates and carbon monoxide are generated by volcanic eruption and wildfire. Even hydrocarbons have local sources, such as seeps, which, in areas such as offshore Goleta, California, emit a significant amount of hydrocarbons that contribute to smog.

Science and Values

The science and technology necessary to reduce air pollution are well known; what we do with these tools involves a value judgment. It is clear that people value a high-quality environment, and clean air is at the top of the list. The developed countries have an obligation to take a leadership role in finding ways to use resources while minimizing air pollution. Of particular importance is finding methods and technologies that will allow for reducing air pollution while stimulating economies. What is considered waste in one part of the urban-industrial complex may be used as resources in another part. This idea is at the heart of what is sometimes called industrial ecology. The discovery, understanding, and management of ozone-depleting chemicals is an environmental success, reflecting the value of the environment.

KEY TERMS

STUDY QUESTIONS

1. Since the amount of pollution emitted into the air is a very small fraction of the total material in the atmosphere, why do we have air-pollution problems?
2. What are the differences between primary and secondary pollutants?
3. Carefully examine Figure 21.11, which shows a column of air moving through an urban area, and Figure 21.7, which shows relative concentrations of pollutants that develop on a typical warm day in Los Angeles. What linkages between the information in these two figures might be important in trying to identify and learn more about potential air pollution in an area?
4. Why is acid deposition a major environmental problem, and how can it be minimized?
5. Why will air-pollution abatement strategies in developed countries probably be much different in terms of methods, process, and results than air-pollution abatement strategies in developing countries?
6. In a highly technological society, is it possible to have 100% clean air? Is it likely?
7. Study Figure 21.14 carefully and discuss how the information in parts (a) and (b) are linked and related to the chapter in general. Apply Critical Thinking skills.
8. Discuss the processes responsible for stratospheric ozone depletion. Which are most significant? Where? Why?
9. What are some of the common sources of indoor air pollutants where you live, work, or attend classes?
10. Develop a research plan to complete an audit of the indoor air quality in your local library. How might that research plan differ from a similar audit for the science buildings on your campus?
11. What do you think about the concept of sick building syndrome? If you were working for a large corporation and a number of employees said they were getting sick and listed a series of symptoms and problems, how would you react? What could you do? Play the role of the administrator and develop a plan to look at the potential problem.
12. Suppose that next year our understanding of ozone depletion is changed by the discovery that concentrations of stratospheric ozone have natural cycles and that lower concentrations in recent years have resulted not from our activities but from natural processes. How would you put all the information in this chapter into perspective? Would you think science had let you down?

FURTHER READING

Boubel, R.W., D.L. Fox, D.B. Turner, and A.C. Stern, *Fundamentals of Air Pollution,* 4th ed. (New York: Academic, 2008). A thorough book covering the sources, mechanisms, effects, and control of air pollution.

Brenner, D.J., *Radon: Risk and Remedy* (New York: Freeman, 1989). A wonderful book about the hazard of radon gas. It covers everything from the history of the problem to what was happening in 1989, as well as solutions.

Christie, M., *The Ozone Layer: A Philosophy of Science Perspective* (Cambridge: Cambridge University Press, 2000). A complete look at the history of the ozone hole, from the first discovery of its existence to more recent studies of the hole over Antarctica.

Hamill, P., and O.B. Toon. "Polar Stratospheric Clouds and the Ozone Hole," *Physics Today* 44, no. 12 (1991): 34–42. A good review of the ozone problem and important chemical and physical processes related to ozone depletion.

Reid, S., *Ozone and Climate Change: A Beginner's Guide* (Amsterdam: Gordon & Breach Science Publishers, 2000). A look at the science behind the ozone hole and future predictions, written for a general audience to make the science understandable.

Rowland, F.S. "Stratospheric Ozone Depletion by Chlorofluorocarbons."*AMBIO*19, no. 6–7 (1990):281–292. An excellent summary of stratospheric ozone depletion, it discusses some of the major issues.

Wang, L.,"Paving out Pollution," *Scientific American,* February 2002, p. 20. Discussion of an innovative approach to reducing air pollution.

CHAPTER 22

Urban Environments

New Orleans suffering right after Hurricane Katrina.

LEARNING OBJECTIVES

Because the world is becoming increasingly urbanized, it is important to learn how to improve urban environments—to make cities more pleasant and healthier places to live, and reduce undesirable effects on the environment. After reading this chapter, you should understand . . .

- How to view a city from an ecosystem perspective;
- How location and site conditions determine the success, importance, and longevity of a city;
- How cities have changed with changes in technology and in ideas about city planning;
- How a city changes its own environment and affects the environment of surrounding areas, and how we can plan cities to minimize some of these effects;
- How trees and other vegetation not only beautify cities but also provide habitats for animals, and how we can alter the urban environment to encourage wildlife and discourage pests;
- How cities can be designed to promote biological conservation and become pleasant environments for people;
- The fundamental choices we face in deciding what kind of future we want and what the role of cities will be in that future.

CASE STUDY

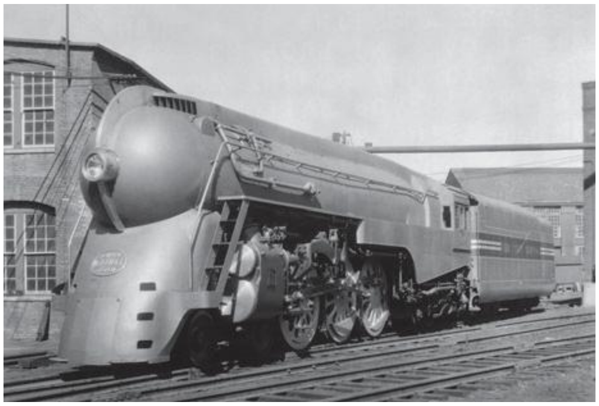
New York's High Line Park in the Sky

From the late 19th century to the 1930s, trains ran on street level in New York City, carrying goods such as meat to the meatpacking district near the Hudson River. This was dangerous and caused accidents. In the 1930s, a public–private project built an elevated railroad 30 feet above the streets, making the streets safer, if darker and less attractive.

By the 1980s the economy had changed, and the trains were no longer needed and so stopped running. The elevated rail line that had served Manhattan's meatpacking district near the Hudson River was just another urban eyesore. Although the narrow, rusty steel stairs that led up to them were closed off and hard to find, a few New Yorkers did manage to climb up and discovered that nature was taking over—the open ground between and along the tracks was undergoing secondary succession, with trees, shrubs, tall grasses, and flowering plants growing wild. Following the rails above the city streets, you could get a secret taste of what Henry David Thoreau would have called "wildness"—the feeling of nature—even within one of the world's largest cities.

Some people proposed tearing down the useless rail line to let more light reach the streets beneath, but another group of citizens had a different idea: to turn it into a park. They formed "Friends of the High Line" in 1999 and got city approval. In 2009 the eagerly anticipated first section of the High Line Park opened, carefully planned by professional landscape designers who strove to keep the natural, uncultivated look by using many of the same plant species that had been growing wild on their own.

Although New York City has many parks, including the very large Central Park, its millions of residents need more places to relax, stroll, sit, and enjoy nature. The park will ultimately be a mile and a half long, and as soon as the first section opened, it was filled with people (Figure 22.1), strolling, enjoying the views of the city on one side and the river on the other, relaxing on wheeled wooden lounges mounted on the tracks. A lot of imagination had helped bring nature to the city, and city people to nature.[1]



(a)

(b)

(c)

FIGURE 22.1 A portion of the newly opened first section of New York City's High Line **(a)** as originally designed for use as an elevated freight railway within Manhattan and **(b)** as it is today, an urban park, ultimately a mile and a half long when completed, planted with many of the species that grew wild after the railway was abandoned **(c)** the HighLine as an elevated with Field.

22.1 City Life

In the past, the emphasis of environmental action has most often been on wilderness, wildlife, endangered species, and the impact of pollution on natural landscapes outside cities. Now it is time to turn more of our attention to city environments. In the development of the modern environmental movement in the 1960s and 1970s, it was fashionable to consider everything about cities bad and everything about wilderness good. Cities were viewed as polluted, dirty, lacking in wildlife and native plants, and artificial—therefore bad. Wilderness was viewed as unpolluted, clean, teeming with wildlife and native plants, and natural—therefore good.

Although it was fashionable to disdain cities, many people live in urban environments and have suffered directly from their decline. According to the United Nations Environment Program, in 1950 fewer than a third of the people of the world lived in a town or city, while today almost half of the world's population is urban, and the forecasts are that in just 20 years—by 2030—almost two-thirds of the people will live in cities and towns.[2] (See Chapter 4.)

In the United States, about 75% of the population live in urban areas and about 25% in rural areas. Perhaps even more striking, half of all Americans live in one of the 39 cities with populations over 1 million.[3] However, in the past decade more people have moved out of the largest cities in the United States than have moved into them. The New York, Los Angeles, Chicago, and San Francisco/Oakland metropolitan areas each averaged a net loss of more than 60,000 people a year. Chicago's Cook County lost a half million people between 2000 and 2004.[4, 5, 6, 7] Today approximately 45% of the world's population live in cities, and it is projected that 62% of the population will live in cities by the year 2025.[6] Economic development leads to urbanization; 75% of people in developed countries live in cities, but only 38% of people in the poorest of the developing countries are city dwellers.[7]

Megacities—huge metropolitan areas with more than 8 million residents—are cropping up more and more. In 1950 the world had only two: the New York City and nearby urban New Jersey metropolitan area (12.2 million residents altogether) and greater London (12.4 million). By 1975, Mexico City, Los Angeles, Tokyo, Shanghai, and São Paulo, Brazil, had joined this list. By 2002, the most recent date for which data are available, 30 urban areas had more than 8 million people.[5]

Yet comparatively little public concern has focused on urban ecology. Many urban people see environmental issues as outside their realm, but the reality is just the opposite: City dwellers are at the center of some of the most important environmental issues. People are realizing that city and wilderness are inextricably connected. We cannot fiddle in the wilderness while our Romes burn from sulfur dioxide and nitrogen oxide pollution. Fortunately, we are experiencing a rebirth of interest in urban environments and urban ecology. The National Science Foundation has added two urban areas, Baltimore and Phoenix, to its Long-Term Ecological Research Program, a program that supports research on, and long-term monitoring of, specific ecosystems and regions.

In the future, most people will live in cities. In most nations, most urban residents will live in the country's single largest city. For most people, living in an environment of good quality will mean living in a city that is managed carefully to maintain that environmental quality.

22.2 The City as a System

We need to analyze a city as the ecological system that it is—but of a special kind. Like any other life-supporting system, a city must maintain a flow of energy, provide necessary material resources, and have ways of removing wastes. These ecosystem functions are maintained in a city by transportation and communication with outlying areas. A city is not a self-contained ecosystem; it depends on other cities and rural areas. A city takes in raw materials from the surrounding countryside: food, water, wood, energy, mineral ores—everything that a human society uses. In turn, the city produces and exports material goods and, if it is a truly great city, also exports ideas, innovations, inventions, arts, and the spirit of civilization. A city cannot exist without a countryside to support it. As was said half a century ago, city and country, urban and rural, are one thing—one connected system of energy and material flows—not two things (see Figure 22.2).

As a consequence, if the environment of a city declines, almost certainly the environment of its surroundings will also decline. The reverse is also true: If the environment around a city declines, the city itself will be threatened. Some people suggest, for example, that the ancient Native American settlement in Chaco Canyon, Arizona, declined after the environment surrounding it either lost soil fertility from poor farming practices or suffered a decline in rainfall.

Cities also export waste products to the countryside, including polluted water, air, and solids. The average city resident in an industrial nation annually uses (directly or indirectly) about 208,000 kg (229 tons) of water, 660 kg (0.8 ton) of food, and 3,146 kg (3.5 tons) of fossil fuels and produces 1,660,000 kg (1,826 tons) of sewage, 660 kg (0.8 ton) of solid wastes, and 200 kg (440 lb) of air pollutants. If these are exported without care, they pollute the countryside, reducing its ability to provide necessary resources for the city and making life in the surroundings less healthy and less pleasant.

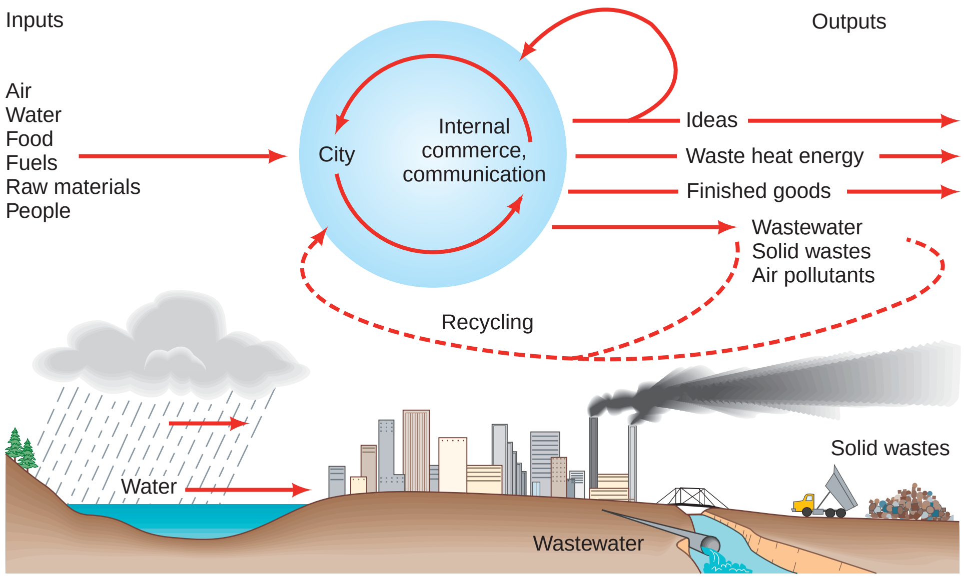


FIGURE 22.2 The city as a system with flows of energy and materials. A city must function as part of a city–countryside ecosystem, with an input of energy and materials, internal cycling, and an output of waste heat energy and material wastes. As in any natural ecosystem, recycling of materials can reduce the need for input and the net output of wastes.

Given such dependencies and interactions between city and surroundings, it's no wonder that relationships between people in cities and in the countryside have often been strained. Why, country dwellers want to know, should they have to deal with the wastes of those in the city? The answer is that many of our serious environmental problems occur at the interface between urban and rural areas. People who live outside but near a city have a vested interest in maintaining both a good environment for that city and maintaining a good system for managing the city's resources. The more concentrated the human population, the more land is available for other uses, including wilderness, recreation, conservation of biological diversity, and production of renewable resources. So cities benefit wilderness, rural areas, and so forth.

With the growing human population, we can imagine two futures. In one, cities are pleasing and livable, use resources from outside the city in a sustainable way, minimize pollution of the surrounding countryside, and allow room for wilderness, agriculture, and forestry. In the other future, cities continue to be seen as environmental negatives and are allowed to decay from the inside. People flee to grander and more expansive suburbs that occupy much land, and the poor who remain in the city live in an unhealthy and unpleasant environment. Without care for the city, its technological structure declines and it pollutes even more than in the past. Trends in both directions appear to be occurring.

In light of all these concerns, this chapter describes how a city can fit within, use, and avoid destroying the ecological systems on which it depends, and how the city itself can serve human needs and desires as well as environmental functions. With this information, you will have the foundation for making decisions, based on science and on what you value, about what kind of urban-rural landscape you believe will provide the most benefits for people and nature.

22.3 The Location of Cities: Site and Situation

Here is an idea that our modern life, with its rapid transportation and its many electronic tools, obscures: Cities are not located at random but develop mainly because of local conditions and regional benefits. In most cases they grow up at crucial transportation locations—an aspect of what is called the city's situation—and at a good site, one that can be readily defended, with good building locations, water supplies, and access to resources. The primary exceptions are cities that have been located primarily for political reasons. Washington, DC, for example, was located to be near the geographic center of the area of the original 13 states; but the site was primarily swampland, and nearby Baltimore provided the major harbor of the region.

The Importance of Site and Situation

The location of a city is influenced primarily by the **site**, which is the summation of all the environmental features of that location; and the **situation**, which is the placement of the city with respect to other areas. A good site includes a geologic substrate suitable for buildings, such as a firm rock base and well-drained soils that are above the water table; nearby supplies of drinkable water; nearby lands suitable for agriculture; and forests. Sometimes, however, other factors—such as the importance of creating a port city—can compensate for a poor geological site, as long as people are able to build an artificial foundation for the city and maintain that foundation despite nature's attempts to overwhelm it.

Cities influence and are influenced by their environment. The environment of a city affects its growth, success, and importance—and can also provide the seeds of its destruction. All cities are so influenced, and those who plan, manage, and live in cities must be aware of all aspects of the urban environment.

The environmental situation is especially important with respect to transportation and defense. Waterways, for example, are important for transportation. Before railroads, automobiles, and airplanes, cities depended on water for transportation, so most early cities—including all the important cities of the Roman Empire—were on or near waterways. Waterways continue to influence the locations of cities; most major cities of the eastern United States are situated either at major ocean harbors, like New Orleans (see A Closer Look 22.1), or at the fall line on major rivers.

A **fall line** on a river occurs where there is an abrupt drop in elevation of the land, creating waterfalls (Figure 22.3), typically where streams pass from harder, more erosion-resistant rocks to softer rocks. In eastern North America the major fall line occurs at the transition from the granitic and metamorphic bedrock that forms the Appalachian Mountains to the softer, more easily eroded and more recent sedimentary rocks. In general, the transition from major mountain range bedrock to another bedrock forms the primary fall line on continents.

Cities have frequently been established at fall lines, especially the major continental fall lines, for a number

FIGURE 22.3 **The fall line.** Most major cities of the eastern and southern United States lie either at the sites of harbors or along a fall line (shown by the dashed line in the figure), which marks locations of waterfalls and rapids on major rivers. This is one way the location of cities is influenced by the characteristics of the environment. (*Source*: C.B. Hunt, *Natural Regions of the United States and Canada* [San Francisco: Freeman, 1974]. Copyright 1974 by W.H. Freeman & Co.)

of reasons. Fall lines provide waterpower, an important source of energy in the 18th and 19th centuries, when the major eastern cities of the United States were established or rose to importance. At that time, the fall line was the farthest inland that larger ships could navigate; and just above the fall line was the farthest downstream that the river could be easily bridged. Not until the development of steel bridges in the late 19th century did it become practical to span the wider regions of a river below the fall line. The proximity of a city to a river has another advantage: River valleys have rich, water-deposited soils that are good for agriculture. In early times, rivers also provided an important means of waste disposal, which today has become a serious problem.

Cities also are often founded at other kinds of crucial locations, growing up around a market, a river crossing, or a fort. Newcastle, England, and Budapest, Hungary, are located at the lowest bridging points on their rivers. Other cities, such as Geneva, are located where a river enters or leaves a major lake. Some well-known cities are at the confluence of major rivers: Saint Louis lies at the confluence of the Missouri and Mississippi rivers; Manaus (Brazil), Pittsburgh (Pennsylvania), Koblenz (Germany), and Khartoum (Sudan) are at the confluence of several rivers. Many famous cities are at crucial defensive locations, such as on or adjacent to easily defended rock outcrops. Examples include Edinburgh, Athens, and Salzburg. Other cities and municipalities are situated on peninsulas—for example, Istanbul and Monaco. Cities also frequently arise close to a mineral resource, such as salt (Salzburg, Austria), metals (Kalgoorlie, Australia), or medicated waters and thermal springs (Spa, Belgium; Bath, Great Britain; Vichy, France; and Saratoga Springs, New York).

When a successful city grows and spreads over surrounding terrain, its original purpose may be obscured. Its original market or fort may have evolved into a square or a historical curiosity. In most cases, though, cities originated where the situation provided a natural meeting point for people.

An ideal location for a city has both a good site and a good situation, but such a place is difficult to find. Paris is perhaps one of the best examples of a perfect location for a city—one with both a good site and a good situation. Paris began on an island more than 2,000 years ago, the situation providing a natural moat for defense and waterways for transportation. Surrounding countryside, a fertile lowland called the Paris basin, affords good

(a)

(b)

FIGURE 22.4 **(a)** Geologic, topographic, and hydrologic conditions greatly influence how successful the city can be. If these conditions, known collectively as the city's site, are poor, much time and effort are necessary to create a livable environment. New Orleans has a poor site but an important situation. **(b)** In contrast, New York City's Manhattan is a bedrock island rising above the surrounding waters, providing a strong base for buildings and a soil that is sufficiently above the water table so that flooding and mosquitoes are much less of a problem.

A CLOSER LOOK 22.1

Should We Try to Restore New Orleans?

On August 29, 2005, Hurricane Katrina roared, slammed, and battered its way into New Orleans with 192 km/hr (120 mph) winds. Its massive storm surges breached the levees that had protected many of the city's residents from the Gulf Coast's waters, flooding 80% of the city and an estimated 40% of the houses (opening photo). With so many people suddenly homeless and such major damage (Figure 22.5), the New Orleans mayor, Ray Nagin, ordered a first-time-ever complete evacuation of the city, an evacuation that became its own disaster. Some estimates claimed that 80% of the 1.3 million residents of the greater New Orleans metropolitan area evacuated.

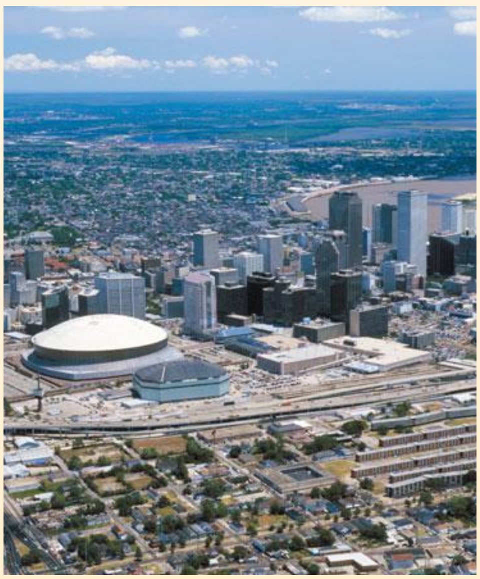
By the time it was over, Katrina was the most costly hurricane in the history of the United States—between $75 billion and $100 billion, in addition to an estimated $200 billion in lost business revenue. A year after the hurricane, much of the damage remained, and even today much of New Orleans is not yet restored. Citizens remain frustrated by the lack of progress on many fronts.[8] An estimated 50,000 homes will have to be demolished. Many former residents are still living elsewhere, scattered across the nation. The storm affected the casino and entertainment industry, as many of the Gulf Coast's casinos were destroyed or sustained considerable damage. New Orleans also was home to roughly 115,000 small businesses, many of which will likely never reopen.

The problem with New Orleans is that it is built in the wetlands at the mouth of the Mississippi River, and much of it is below sea level (Figure 22.6). Although a port at the mouth of the Mississippi River has always been an important location for a city, there just wasn't a great place to build that city. The original development, the French Quarter, was just barely above sea level, about the best that could be found.

Hurricane Katrina was rated a Category 3 hurricane, but discussions about protecting the city from future storms focus on an even worse scenario, a Category 5 hurricane with winds up to 249 km/hr (155 mph). As of 2009, 68,000 homes remained abandoned.[9] Clearly, New Orleans requires an expensive improvement in its site if it is to survive at all. And if it does, will it be restored to its former glory and importance? Will it continue in any fashion, even as a mere shadow of its former self? Fortunately, the city has many residents who love it and are working hard to restore it.

To know how to rebuild the city, to decide whether this is worth doing, and to forecast whether such a restoration is likely, we have to understand the ecology of cities, how cities fit into the environment, the complex interplay between a city and its surroundings, and how a city acts as an environment for its residents.

(a)



(b)

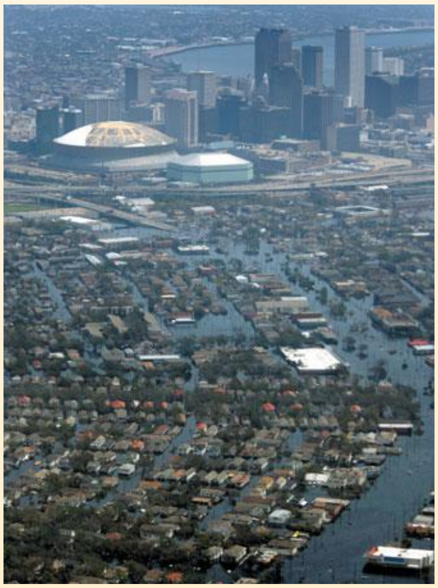


FIGURE 22.5 **(a)** Aerial photograph of New Orleans skyline before Hurricane Katrina struck. The Super Dome is near the center left. **(b)** A similar view of New Orleans, but after Hurricane Katrina struck on August 31, 2005. The widespread flooding of the city from the hurricane is visible.

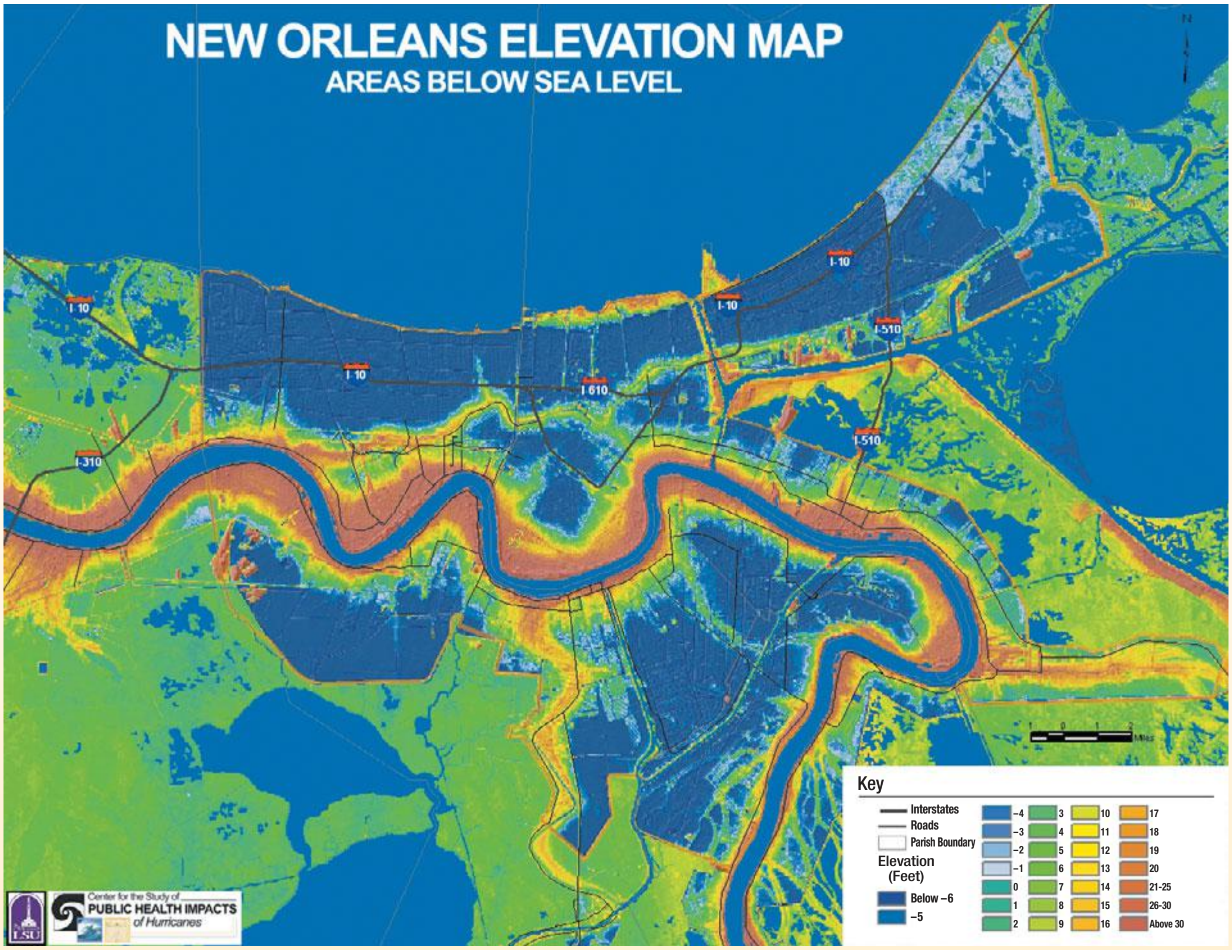


FIGURE 22.6 Map of New Orleans showing how much of the city is below sea level. The city began with the French Quarter, which is above sea level. As the population grew and expanded, levees were built to keep the water out, and the city became an accident waiting to happen. (*Source*: Tim Vasquez/Weather Graphics)

local agricultural land and other natural resources. New Orleans on the other hand, is an example of a city with an important situation but, as Hurricane Katrina made abundantly clear, a poor site (Figure 22.4).

Site Modification

Site is provided by the environment, but technology and environmental change can alter a site for better or worse. People can improve the site of a city and have done so when the situation of the city made it important and when its citizens could afford large projects. An excellent situation can sometimes compensate for a poor site. However, improvements are almost always required to the site so the city can persist.

Changes in a site over time can have adverse effects on a city. For example, Bruges, Belgium, developed as an important center for commerce in the 13th century because its harbor on the English Channel permitted trade with England and other European nations. By the 15th century, however, the harbor had seriously silted in, and the limited technology of the time did not make dredging possible (Figure 22.7). This problem, combined with political events, led to a decline in the importance of Bruges—a decline from which it never recovered. Nevertheless, today, Bruges still lives, a beautiful city with many fine examples of medieval architecture. Ironically, that these buildings were never replaced with modern ones makes Bruges a modern tourist destination.

Ghent, Belgium, and Ravenna, Italy, are other examples of cities whose harbors silted in. As human effects on the environment bring about global change, there may be rapid, serious changes in the sites of many cities.

FIGURE 22.7 Bruges, Belgium, was once an important seaport, but over the years sand that the ocean deposited in the harbor left the city far inland. Today, Bruges is a beautiful historic city, though no longer important for commerce.

22.4 An Environmental History of Cities

The Rise of Towns

The first cities emerged on the landscape thousands of years ago, during the New Stone Age, with the development of agriculture, which provided enough food to sustain a city.[8] In this first stage, the number of city dwellers per square kilometer was much higher than the number of people in the surrounding countryside, but the density was still too low to cause rapid, serious disturbance to the land. In fact, the waste from city dwellers and their animals was an important fertilizer for the surrounding farmlands. In this stage, the city's size was restricted by the primitive means of transporting food and necessary resources into the city and removing waste.[10]

The Urban Center

In the second stage, more efficient transportation made possible the development of much larger urban centers. Boats, barges, canals, and wharves, as well as roads, horses, carriages, and carts, enabled cities to rise up and thrive farther from agricultural areas. Ancient Rome, originally dependent on local produce, became a city fed by granaries in Africa and the Near East.

The population of a city is limited by how far a person can travel in one day to and from work and by how many people can be packed into an area (density). In the second stage, the internal size of a city was limited by pedestrian travel. A worker had to be able to walk to work, do a day's work, and walk home the same day. The density of people per square kilometer was limited by architectural techniques and primitive waste disposal. These cities never exceeded a population of 1 million, and only a few approached this size, most notably Rome and some cities in China.

The Industrial Metropolis

The Industrial Revolution allowed greater modification of the environment than had been possible before. Three technological advances that had significant effects on the city environment were improved medicine and sanitation, which led to the control of many diseases, and improved transportation.

Modern transportation makes a larger city possible. Workers can live farther from their place of work and commerce, and communication can extend over larger areas. Air travel has freed cities even more from the traditional limitation of situation. We now have thriving urban areas where previously transportation was poor: in the Far North (Fairbanks, Alaska) and on islands (Honolulu). These changes increase city dwellers' sense of separateness from their natural environment.

Subways and commuter trains have also led to the development of suburbs. In some cities, however, the negative effects of urban sprawl have prompted many people to return to the urban centers or to smaller, satellite cities surrounding the central city. The drawbacks of suburban commuting and the destruction of the landscape in suburbs have brought new appeal to the city center.

The Center of Civilization

We are at the beginning of a new stage in the development of cities. With modern telecommunications, people can work at home or at distant locations. Perhaps, as telecommunication frees us from the necessity for certain kinds of commercial travel and related activities, the city can become a cleaner, more pleasing center of civilization.

An optimistic future for cities requires a continued abundance of energy and material resources, which are certainly not guaranteed, and wise use of these resources. If energy resources are rapidly depleted, modern mass transit may fail, fewer people will be able to live in suburbs, and the cities will become more crowded. Reliance on coal and wood will increase air pollution. Continued destruction of the land within and near cities could compound transportation problems, making local production of food impossible. The future of our cities depends on our ability to plan and to use our resources wisely.

22.5 City Planning and the Environment

If people live in densely populated cities, ways must be found to make urban life healthy and pleasant and to keep the cities from polluting the very environment that their population depends on. City planners have found many ways to make cities pleasing environments: developing parks and connecting cities to rivers and nearby mountains in environmentally and aesthetically pleasing ways. City planning has a long and surprising history, with the paired goals of defense and beauty. Long experience in city planning, combined with modern knowledge from environmental sciences, can make cities of the future healthier and more satisfying to people and better integrated within the environment. Beautiful cities are not only healthy but also attract more people, relieving pressure on the countryside.

A city can never be free of environmental constraints, even though its human constructions give us a false sense of security. Lewis Mumford, a historian of cities, wrote, "Cities give us the illusion of self-sufficiency and independence and of the possibility of physical continuity without conscious renewal."[8,11] But this security is only an illusion.

A danger in city planning is the tendency to totally transform the features of a city center from natural to artificial—to completely replace grass and soil with pavement, gravel, houses, and commercial buildings, creating an impression that civilization has dominated the environment. Ironically, the artificial aspects of the city that make it seem so independent of the rest of the world actually make it more dependent on its rural surroundings for all resources. Although such a city appears to its inhabitants to grow stronger and more independent, it actually becomes more fragile.[8]

City Planning for Defense and Beauty

Many cities in history grew without any conscious plan. However, **city planning**—formal, conscious planning for new cities in modern Western civilization—can be traced back as far as the 15th century. Sometimes cities have been designed for specific social purposes, with little consideration of the environment. In other cases the environment and its effect on city residents have been major planning considerations.

Defense and beauty have been two dominant themes in formal city planning (see A Closer Look 22.2). We can think of these two types of cities as fortress cities and park cities. The ideas of the fortress city and the park city influenced the planning of cities in North America. The importance of aesthetic considerations is illustrated in the plan of Washington, DC, designed by Pierre Charles L'Enfant. L'Enfant mixed a traditional rectangular grid pattern of streets (which can be traced back to the Romans) with broad avenues set at angles. The goal was to create a beautiful city with many parks, including small ones at the intersections of avenues and streets. This design has made Washington, DC, one of the most pleasant cities in the United States.

The City Park

Parks have become more and more important in cities. A significant advance for U.S. cities was the 19th-century planning and construction of Central Park in New York City, the first large public park in the United States. The park's designer, Frederick Law Olmsted, was one of the most important modern experts on city planning. He took site and situation into account and attempted to blend improvements to a site with the aesthetic qualities of the city.[12]

Central Park is an example of "design with nature," a term coined much later, and its design influenced other U.S. city parks. For Olmsted, the goal of a city park was to provide psychological and physiological relief from city life through access to nature and beauty. Vegetation was one of the keys to creating beauty in the park, and Olmsted carefully considered the opportunities and limitations of topography, geology, hydrology, and vegetation.

In contrast to the approach of a preservationist, who might simply have strived to return the area to its natural, wild state, Olmsted created a naturalistic environment, keeping the rugged, rocky terrain but putting ponds where he thought they were desirable. To add variety, he constructed "rambles, " walkways that were densely planted and followed circuitous patterns. He created a "sheep meadow" by using explosives to flatten the terrain. In the southern part of the park, where there were flat meadows, he created recreational areas. To meet the needs of the city, he built transverse roads through the park and also created depressed roadways that allowed traffic to cross the park without detracting from the vistas seen by park visitors.

Olmsted has remained a major figure in American city planning, and the firm he founded continued to be important in city planning into the 20th century. His skill in creating designs that addressed both the physical and aesthetic needs of a city is further illustrated by his work in Boston. Boston's original site had certain advantages: a narrow peninsula with several hills that could be easily defended, a good harbor, and a good water supply. But as Boston grew, demand increased for more land for buildings, a larger area for docking ships, and a better water supply. The need to control ocean floods and to dispose of solid

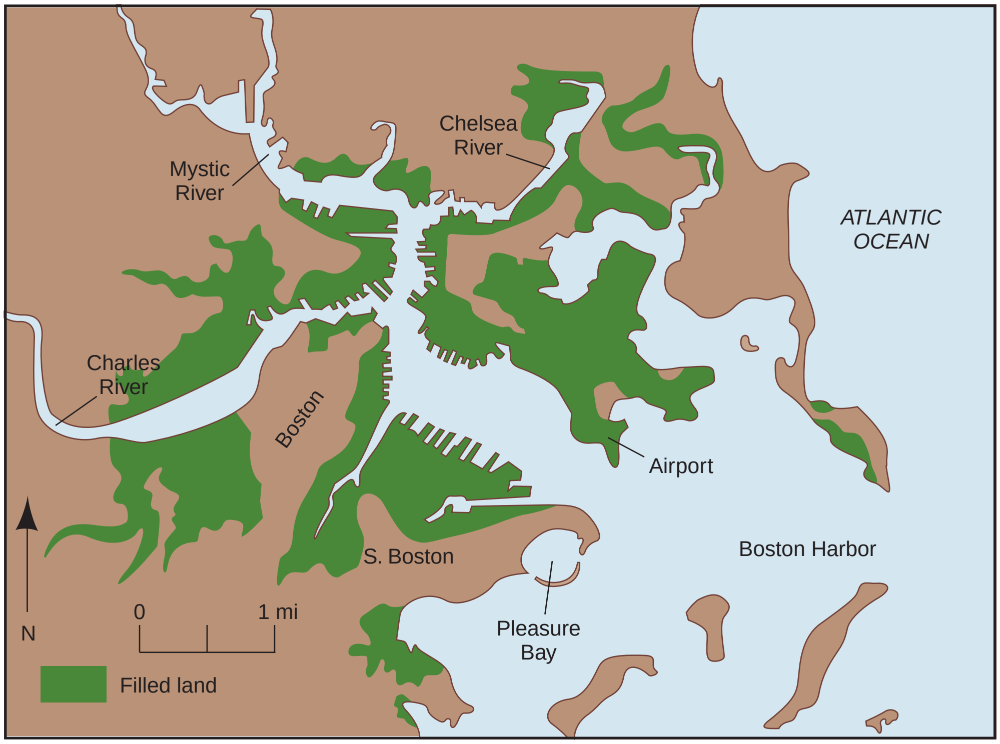


FIGURE 22.8 Nature integrated into a city plan. Boston has been modified over time to improve the environment and provide more building locations. This map of Boston shows land filled in to provide new building sites as of 1982. Although such landfill allows for expansion of the city, it can also create environmental problems, which then must be solved. (*Source*: A.W. Spirn, *The Granite Garden: Urban Nature and Human Design* [New York: Basic Books, 1984].)

and liquid wastes grew as well. Much of the original tidal flats area, which had been too wet to build on and too shallow to navigate, had been filled in (Figure 22.8). Hills had been leveled and the marshes filled with soil. The largest project had been the filling of Back Bay, which began in 1858 and continued for decades. Once filled, however, the area had suffered from flooding and water pollution.

Olmsted's solution to these problems was a water-control project called the "fens." His goal was to "abate existing nuisances" by keeping sewage out of the streams and ponds and building artificial banks for the streams to prevent flooding—and to do this in a natural-looking way. His solution included creating artificial watercourses by digging shallow depressions in the tidal flats, following meandering patterns like natural streams; setting aside other artificial depressions as holding ponds for tidal flooding; restoring a natural salt marsh planted with vegetation tolerant of brackish water; and planting the entire area to serve as a recreational park when not in flood. He put a tidal gate on the Charles River—Boston's major river—and had two major streams diverted directly through culverts into the Charles so that they flooded the fens only during flood periods. He reconstructed the Muddy River primarily to create new, accessible landscape. The result of Olmsted's vision was that control of water became an aesthetic addition to the city. The blending of several goals made the development of the fens a landmark in city planning. Although to the casual stroller it appears to be simply a park for recreation, the area serves an important environmental function in flood control.

Parks near rivers and the ocean are receiving more and more attention. For example, New York City is spending several hundred million dollars to build the Hudson River Park along the Hudson River, where previously abandoned docks and warehouses littered the shoreline and barred public access to the river.

An extension of the park idea was the "garden city," a term coined in 1902 by Ebenezer Howard. Howard believed that city and countryside should be planned together. A **garden city** was one that was surrounded by a **greenbelt**, a belt of parkways, parks, or farmland. The idea was to locate garden cities in a set connected by greenbelts, forming a system of countryside and urban landscapes. The idea caught on, and garden cities were planned and developed in Great Britain and the United States. Greenbelt, Maryland, just outside Washington, DC, is one of these cities, as is Lecheworth, England. Howard's garden city concept, like Olmsted's use of the natural landscape in designing city parks, continues to be a part of city planning today.

A CLOSER LOOK 22.2

A Brief History of City Planning

Defense and beauty have been two dominant themes in formal city planning. Ancient Roman cities were typically designed along simple geometric patterns that had both practical and aesthetic benefits. The symmetry of the design was considered beautiful but was also a useful layout for streets.

During the height of Islamic culture, in the first millennium, Islamic cities typically contained beautiful gardens, often within the grounds of royalty. Among the most famous urban gardens in the world are the gardens of the Alhambra, a palace in Granada, Spain (Figure 22.9). The gardens were created when this city was a Moorish capital, and they were maintained after Islamic control of Granada ended in 1492. Today, as a tourist attraction that receives 2 million visitors a year, the Alhambra gardens demonstrate the economic benefits of aesthetic considerations in city planning. They also illustrate that making a beautiful park a specific focus in a city benefits the city environment by providing relief from the city itself.

After the fall of the Roman Empire, the earliest planned towns and cities in Europe were walled fortress cities designed for defense. But even in these instances, city planners considered the aesthetics of the town. In the 15th century, one such planner, Leon Battista Alberti, argued that large and important towns should have broad and straight streets; smaller, less fortified towns should have winding streets to increase their beauty. He also advocated the inclusion of town squares and recreational areas, which continue to be important considerations in city planning.[13] One of the most successful of these walled cities is Carcassonne, in southern France, now the third most visited tourist site in that country. Today, walled cities have become major tourist attractions, again illustrating the economic benefits of good aesthetic planning in urban development.

The usefulness of walled cities essentially ended with the invention of gunpowder. The Renaissance sparked an interest in the ideal city, which in turn led to the development of the park city. A preference for gardens and parks, emphasizing recreation, developed in Western civilization in the 17th and 18th centuries. It characterized the plan of Versailles, France, with its famous formal parks of many sizes and tree-lined walks, and also the work of the Englishman Capability Brown, who designed parks in England and was one of the founders of the English school of landscape design, which emphasized naturalistic gardens.

FIGURE 22.9 Planned beauty. The Alhambra gardens of Granada, Spain, illustrate how vegetation can be used to create beauty within a city.

22.6 The City as an Environment

A city changes the landscape, and because it does, it also changes the relationship between biological and physical aspects of the environment. Many of these changes were discussed in earlier chapters as aspects of pollution, water management, or climate. You may find some mentioned again in the following sections, generally with a focus on how effective city planning can reduce the problems.

The Energy Budget of a City

Like any ecological and environmental system, a city has an "energy budget." The city exchanges energy with its environment in the following ways: (1) absorption and reflection of solar energy, (2) evaporation of water, (3) conduction of air, (4) winds (air convection), (5) transport of fuels into the city and burning of fuels by people in the city, and (6) convection of water (subsurface and surface stream flow). These in turn affect the climate in the city, and the city may affect the climate in the nearby surroundings, a possible landscape effect.

The Urban Atmosphere and Climate

Cities affect the local climate; as the city changes, so does its climate (see Chapter 20). Cities are generally less windy than nonurban areas because buildings and other structures obstruct the flow of air. But city buildings also channel the wind, sometimes creating local wind tunnels with high wind speeds. The flow of wind around one building is influenced by nearby buildings, and the total wind flow through a city is the result of the relationships among all the buildings. Thus, plans for a new building must take into account its location among other buildings as well as its shape. In some cases, when this has not been done, dangerous winds around tall buildings have blown out windows, as happened to the John Hancock Building in Boston on January 20, 1973, a famous example of the problem.

A city also typically receives less sunlight than the countryside because of the particulates in the atmosphere over cities—often over ten times more particulates than in surrounding areas.[15] Despite reduced sunlight, a city is a heat island, warmer than surrounding areas, for two reasons: (1) the burning of fossil fuels and other industrial and residential activities and (2) a lower rate of heat loss, partly because buildings and paving materials act as solar collectors (Figure 22.10).[14]

Solar Energy in Cities

Until modern times, it was common to use solar energy, through what is called today *passive solar energy*, to help heat city houses. Cities in ancient Greece, Rome, and China were designed so that houses and patios faced south and passive solar energy applications were accessible to each household.[19] The 20th century in America and Europe was a major exception to this approach because cheap and easily accessible fossil fuels led people to forget certain fundamental lessons. Today, the industrialized nations are beginning to appreciate the importance of solar energy once again. Solar photovoltaic devices that convert sunlight to electricity are becoming a common sight in many cities, and some cities have enacted solar energy ordinances that make it illegal to shade another property owner's building in such a way that it loses solar heating capability. (See Chapter 16 for a discussion of solar energy.)

Water in the Urban Environment

Modern cities affect the water cycle, in turn affecting soils and consequently plants and animals in the city. Because city streets and buildings prevent water infiltration, most rain runs off into storm sewers. The streets and sidewalks also add to the heat island effect by preventing water in the soil from evaporating to the atmosphere, a process that cools natural ecosystems. Chances of flooding increase both within the city and downstream outside the city. New, ecological methods of managing stormwater can alleviate these problems by controlling the speed and quality of water running off pavements and into streams. For example, a plan for the central library's parking lot in Alexandria, Virginia, includes wetland vegetation and soils that temporarily absorb runoff from the parking lot, remove some of the pollutants, and slow down the water flow (Figure 22.11).

Most cities have a single underground sewage system. During times of no rain or light rain, this system handles only sewage. But during periods of heavy rain, the runoff is mixed with the sewage and can exceed the capacity

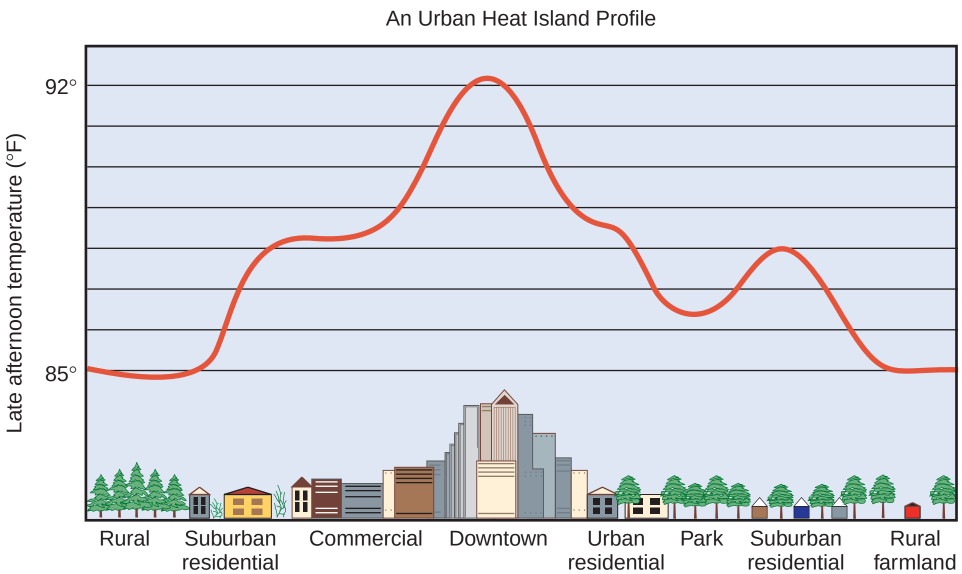


FIGURE 22.10 A typical urban heat island profile. The graph shows temperature changes correlated with the density of development and trees. (*Source*: Andrasko and Huang, in H. Akbari et al., *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing* [Washington, DC: U.S. EPA Office of Policy Analysis, 1992].)

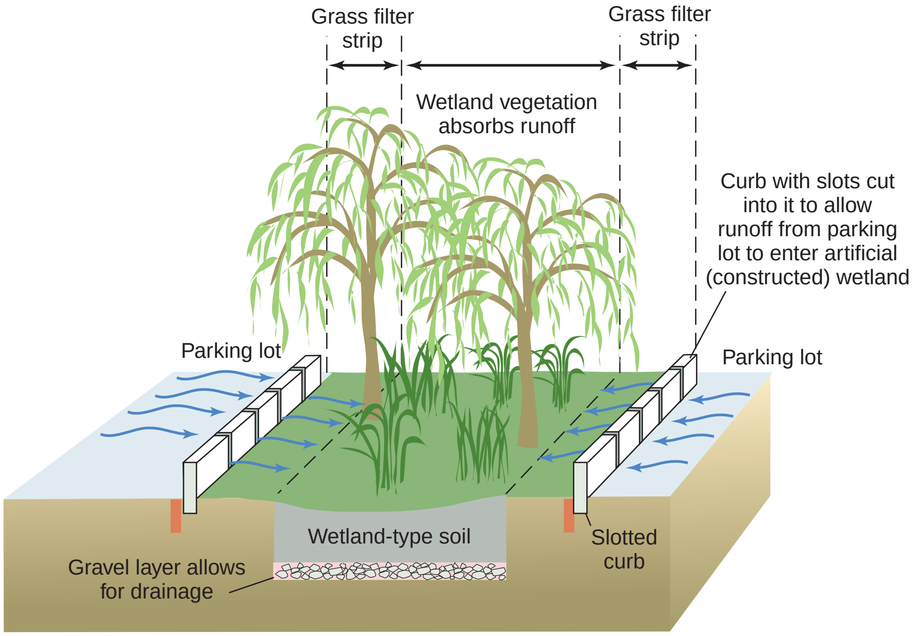


FIGURE 22.11 Planned for better drainage. A plan for the Alexandria, Virginia, central library parking lot includes wetland vegetation and soils that temporarily absorb runoff from the parking lot (see arrows). The landscape architecture firm of Rhodeside & Harwell planned the project. (*Source*: Modified after Rhodeside & Harwell Landscape Architects.)

of sewage-treatment plants, causing sewage to be released downstream without sufficient treatment. In most cities that already have such systems, the expense of building a completely new and separate runoff system is prohibitive, so other solutions must be found. One city that avoids this problem is Woodlands, Texas. It was designed by the famous landscape architect Ian McHarg, who originated the phrase "design with nature," the subject of A Closer Look 22.3.[15]

Because of reduced evaporation, midlatitude cities generally have lower relative humidity (2% lower in winter to 8% lower in summer) than the surrounding countryside. At the same time, cities can have higher rainfall than their surroundings because dust above a city provides particles for condensation of water vapor. Some urban areas have 5–10% more precipitation and considerably more cloud cover and fog than their surrounding areas. Fog is particularly troublesome in the winter and may impede ground and air traffic.

Soils in the City

A modern city has a great impact on soils. Since most of a city's soil is covered by cement, asphalt, or stone, the soil no longer has its natural cover of vegetation, and the natural exchange of gases between the soil and air is greatly reduced. No longer replenished by vegetation growth, these soils lose organic matter, and soil organisms die from lack of food and oxygen. In addition, the construction process and the weight of the buildings compact the soil, which restricts water flow. City soils, then, are more likely to be compacted, waterlogged, impervious to water flow, and lacking in organic matter.

Pollution in the City

In a city, everything is concentrated, including pollutants. City dwellers are exposed to more kinds of toxic chemicals in higher concentrations and to more human-produced noise, heat, and particulates than are their rural neighbors (see Chapter 15). This environment makes life riskier—in fact, lives are shortened by an average of one to two years in the most polluted cities in the United States. The city with the greatest number of early deaths is Los Angeles, with an estimated 5,973 early deaths per year, followed by New York with 4,024, Chicago with 3,479, Philadelphia with 2,590, and Detroit with 2,123.

Some urban pollution comes from motor vehicles, which emit nitrogen oxides, ozone, carbon monoxide, and other air pollutants from exhaust. Electric power plants also produce air pollutants. Home heating is a third source, contributing particulates, sulfur oxides, nitrogen oxides, and other toxic gases. Industries are a fourth source, contributing a wide variety of chemicals. The primary sources of particulate air pollution—which consists of smoke, soot, and tiny particles formed from emissions of sulfur dioxide and volatile organic compounds—are older, coal-burning power plants, industrial boilers, and gas- and diesel-powered vehicles.[16]

Although it is impossible to eliminate exposure to pollutants in a city, it is possible to reduce exposure through careful design, planning, and development. For example, when lead was widely used in gasoline, exposure to lead was greater near roads. Exposure could be reduced by placing houses and recreational areas away from roads and by developing a buffer zone using trees that are resistant to the pollutant and that absorb pollutants.

22.7 Bringing Nature to the City

As we saw in this chapter's opening case study about New York City's High Line, a practical problem is how to bring nature to the city—how to make plants and animals part of a city landscape (see A Closer Look 22.3). This has evolved into several specialized professions, including urban forestry (whose professionals are often called tree wardens), landscape architecture, city planning and management, and civil engineering specializing in urban development. Most cities have an urban forester on the payroll who determines the best sites for planting trees and the tree species best suited to those environments. These professionals take into account climate, soils, and the general influences of the urban setting, such as the shade imposed by tall buildings and the pollution from motor vehicles.

Cities and Their Rivers

Traditionally, rivers have been valued for their usefulness in transportation and as places to dump wastes and therefore not places of beauty or recreation. The old story was that a river renewed and cleaned itself every mile or every 3 miles (depending on who said it). That may have been relatively correct when there was one person or one family per linear river mile, but it is not for today's cities, with their high population densities and widespread use and dumping of modern chemicals.

Kansas City, Missouri, at the confluence of the Kansas and Missouri rivers, illustrates the traditional disconnect between a city and its river. The Missouri River's floodplain provides a convenient transportation corridor, so the south shore is dominated by railroads, while downtown the north shore forms the southern boundary of the city's airport. Except for a small riverfront park, the river has little place in this city as a source of recreation and relief for its citizens or in the conservation of nature.

The same used to be true of the Hudson River in New York, but that river has undergone a major cleanup since the beginning of the project *Clearwater,* led in part by folksinger Pete Seeger and also by activities of the city's Hudson River Foundation and Metropolitan Waterfront Alliance. Not only is the river cleaner, but an extensive Hudson River Park is being completed, transforming Manhattan's previously industrial and uninviting riverside into a beautifully landscaped and inviting park (Figure 22.12) extending for miles from the southern end of Manhattan to near the George Washington Bridge.

The throngs of sunbathers, picnickers, older people, young couples, and parents with children relaxing on the grass and enjoying the river views are proof of city dwellers' need for contact with nature. And a lesson we are learning is that for cities on rivers, one way to bring nature to the city is to connect the city to its river.

A CLOSER LOOK 22.3

Design with Nature

The new town of Woodlands, a suburb of Houston, Texas, is an example of professional planning. Woodlands was designed so that most houses and roads were on ridges; the lowlands were left as natural open space. The lowlands provide areas for temporary storage of floodwater and, because the land is unpaved, allow rain to penetrate the soil and recharge the aquifer for Houston. Preserving the natural lowlands has other environmental benefits as well. In this region of Texas, low-lying wetlands are habitats for native wildlife, such as deer. Large, attractive trees, such as magnolias, grow here, providing food and habitat for birds. The innovative city plan has economic as well as aesthetic and conservational benefits. It is estimated that a conventional drainage system would have cost $14 million more than the amount spent to develop and maintain the wetlands.[21]

A kind of soil important in modern cities is the soil that occurs on **made lands**—lands created from fill, sometimes as waste dumps of all kinds, sometimes to create more land for construction. The soils of made lands are different from those of the original landscape. They may be made of all kinds of trash, from newspapers to bathtubs, and may contain some toxic materials. The fill material is unconsolidated, meaning that it is loose material without rock structure. Thus, it is not well suited to be a foundation for buildings. Fill material is particularly vulnerable to earthquake tremors and can act somewhat like a liquid and amplify the effects of the earthquake on buildings. However, some made lands have been turned into well-used parks. For example, a marina park in Berkeley, California, is built on a solid-waste landfill. It extends into San Francisco Bay, providing public access to beautiful scenery, and is a windy location, popular for kite flying and family strolls. (See Chapter 23 for more information about solid-waste disposal.)

FIGURE 22.12 The newly built Hudson River Park on Manhattan's West Side illustrates the changing view of rivers and the improved use of riverfronts for recreation and urban landscape beauty.

FIGURE 22.13 Paris was one of the first modern cities to use trees along streets to provide beauty and shade, as shown in this picture of the famous Champs-Elysées.

Vegetation in Cities

Trees, shrubs, and flowers add to the beauty of a city. Plants fill different needs in different locations. Trees provide shade, which reduces the need for air-conditioning and makes travel much more pleasant in hot weather. In parks, vegetation provides places for quiet contemplation; trees and shrubs can block some of the city sounds, and their complex shapes and structures create a sense of solitude. Plants also provide habitats for wildlife, such as birds and squirrels, which many urban residents consider pleasant additions to a city.

The use of trees in cities has expanded since the Renaissance. In earlier times, trees and shrubs were set apart in gardens, where they were viewed as scenery but not experienced as part of ordinary activities. Street trees were first used in Europe in the 18th century; among the first cities to line streets with trees were London and Paris (Figure 22.13). In many cities, trees are now considered an essential element of the urban visual scene, and major cities have large tree-planting programs. In New York City, for example, 11,000 trees are planted each year, and in Vancouver, Canada, 4,000 are planted each year.[17] Trees are also increasingly used to soften the effects of climate near houses. In colder climates, rows of conifers planted to the north of a house can protect it from winter winds. Deciduous trees to the south can provide shade in the summer, reducing requirements for air-conditioning, yet allowing sunlight to warm the house in the winter (Figure 22.14).

Cities can even provide habitat for endangered plants. For example, Lakeland, Florida, uses endangered plants in local landscaping with considerable success. However, it is necessary to select species carefully because vegetation in cities must be able to withstand special kinds of stress, such as compacted soils, poor drainage, and air pollution. Because trees along city streets are often surrounded by cement, and because the soils tend to be compacted and drain poorly, the root systems are likely to suffer from extremes of drought on the one hand and soil saturation (immediately following or during a rainstorm) on the other. The solution to this particular problem is to specially prepare streets and sidewalks for tree growth. A tree-planting project was completed for the World Bank Building in Washington, DC, in 1996. Special care was taken to provide good growing conditions for trees, including aeration, irrigation, and adequate drainage so that the soils did not become waterlogged. The trees continue to grow and remain healthy.[23]

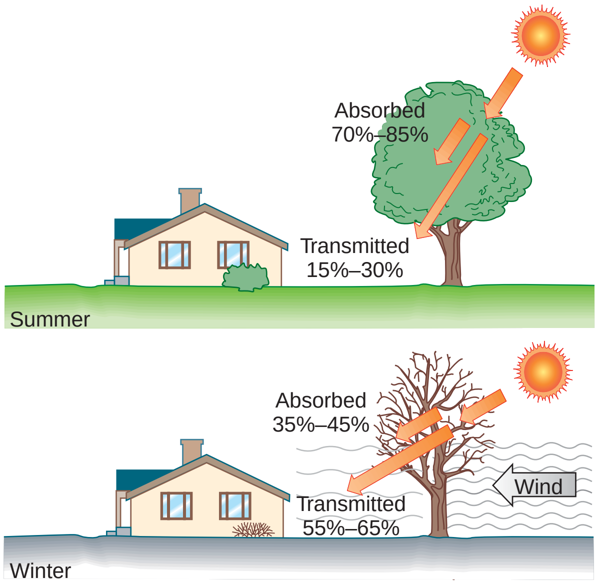


FIGURE 22.14 Trees cool homes. Trees can improve the microclimate near a house, protecting the house from winter winds and providing shade in the summer while allowing sunlight through in the winter. (*Source*: J. Huang and S. Winnett, in H. Akbari et al., *Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing* [Washington, DC: U.S. EPA Office of Policy Analysis, 1992].)

Many species of trees and plants are very sensitive to air pollution and will not thrive in cities. The eastern white pine of North America, for example, is extremely sensitive to ozone pollution and does not do well in cities with heavy motor-vehicle traffic or along highways. Dust, too, can interfere with the exchange of oxygen and carbon dioxide necessary for photosynthesis and respiration of the trees. City trees also suffer direct damage from pets, from the physical impact of bicycles, cars, and trucks, and from vandalism. Trees subject to such stresses are more susceptible to attacks by fungus diseases and insects. The lifetime of trees in a city is generally shorter than in their natural woodland habitats unless they are given considerable care.

Some species of trees are more useful and successful in cities than are others. An ideal urban tree would be resistant to all forms of urban stress, have a beautiful form and foliage, and produce no messy fruit, flowers, or leaf litter that required removal. In most cities, in part because of these requirements, only a few tree species are used for street planting. However, reliance on one or a few species results in ecologically fragile urban planting, as we learned when Dutch elm disease spread throughout the eastern United States, destroying urban elms and leaving large stretches of a city treeless. It is prudent to use a greater diversity of trees to avoid the effects of insect infestations and tree diseases.[18]

Cities, of course, have many recently disturbed areas, including abandoned lots and the medians in boulevards and highways. Disturbed areas provide habitat for early-successional plants, including many that we call "weeds," which are often introduced (exotic) plants, such as European mustard. Therefore, wild plants that do particularly well in cities are those characteristic of disturbed areas and of early stages in ecological succession (see Chapter 5). City roadsides in Europe and North America have wild mustards, asters, and other early-successional plants.

Urban "Wilds": The City as Habitat for Wildlife and Endangered Species

We don't associate wildlife with cities—indeed, with the exception of some birds and small, docile mammals such as squirrels, most wildlife in cities are considered pests. But there is much more wildlife in cities, a great deal of it unnoticed. In addition, there is growing recognition that urban areas can be modified to provide habitats for wildlife that people can enjoy. This can be an important method of biological conservation.[19, 20]

We can divide city wildlife into the following categories: (1) species that cannot persist in an urban environment and disappear; (2) those that tolerate an urban environment but do better elsewhere; (3) those that have adapted to urban environments, are abundant there, and are either neutral or beneficial to human beings; and (4) those that are so successful they become pests.

Cooper's hawks probably belong in the third category. They are doing pretty well in Tucson, Arizona, a city of 900,000 people. Although this hawk is a native of the surrounding Sonoran Desert, some of them are nesting in groves of trees within the city. Nest success in 2005 was 84%, between two-thirds and three-quarters of the juvenile hawks that left the nest were still alive six months later, and the population is increasing (Figure 23.15). Scientists studying the hawk in Tucson concluded that "urbanized landscape can provide high-quality habitat."[21]

Cities can even be home to rare or endangered species. Peregrine falcons once hunted pigeons above the streets of Manhattan. Unknown to most New Yorkers, the falcons nested on the ledges of skyscrapers and dived on their prey in an impressive display of predation. The falcons disappeared when DDT and other organic pollutants caused a thinning of their eggshells and a failure in reproduction, but they have been reintroduced into the city. The first reintroduction into New York City took place in 1982, and today 32 falcons are living there.[22] The reintroduction of peregrine falcons illustrates an important recent trend: the growing understanding that city environments can assist in the conservation of nature, including the conservation of endangered species.

In sum, cities are a habitat, albeit artificial. They can provide all the needs—physical structures and necessary resources such as food, minerals, and water—for many plants and animals. We can identify ecological food chains in cities, as shown in Figure 22.16 for insect-eating birds and for a fox. These can occur when areas cleared of buildings and abandoned begin to recover and are in an early stage of ecological succession. For some species, cities' artificial structures are sufficiently like their original habitat to be home.[23] Chimney swifts, for example, which once lived in hollow trees, are now common in chimneys and other vertical shafts, where they glue their nests to the walls with saliva. A city can easily have more chimneys per square kilometer than a forest has hollow trees.

FIGURE 22.15 Cooper's hawks, like this one, live, nest, and breed in the city of Tucson, Arizona.

Cities also have natural habitats in parks and preserves. In fact, modern parks provide some of the world's best wildlife habitats. In New York City's Central Park, approximately 260 species of birds have been observed—100 in a single day. Urban zoos, too, play an important role in conserving endangered species, and the importance of parks and zoos will increase as truly wild areas shrink.

Finally, cities that are seaports often have many species of marine wildlife at their doorsteps. New York City's waters include sharks, bluefish, mackerel, tuna, striped bass, and nearly 250 other species of fish.[24]

City environments can contribute to wildlife conservation in a number of ways. Urban kitchen gardens—backyard gardens that provide table vegetables and decorative plants—can be designed to provide habitats. For instance, these gardens can include flowers that provide nectar for threatened or endangered hummingbirds. Rivers and their riparian zones, ocean shorelines, and wooded parks can provide habitats for endangered species and ecosystems. For example, prairie vegetation, which once occupied more land area than any other vegetation type in the United States, is rare today, but one restored prairie exists within the city limits of Omaha, Nebraska. (Some urban nature preserves are not accessible to the public or offer only limited access, as is the case with the prairie preserve in Omaha.)

Urban drainage structures can also be designed as wildlife habitats. A typical urban runoff design depends on concrete-lined ditches that speed the flow of water from city streets to lakes, rivers, or the ocean. However, as with Boston's Back Bay design, discussed earlier, these features can be planned to maintain or create stream and marsh habitats, with meandering waterways and storage areas that do not interfere with city processes. Such areas can become habitats for fish and mammals (Figure 22.17). Modified to promote wildlife, cities can provide urban corridors that allow wildlife to migrate along their natural routes.[25] Urban corridors also help to prevent some of the effects of ecological islands (see Chapter 8) and are increasingly important to biological conservation.

Animal Pests

Pests are familiar to urban dwellers. The most common city pests are cockroaches, fleas, termites, rats, pigeons, and (since banning DDT) bedbugs, but there are many more, especially species of insects. In gardens and parks, pests include insects, birds, and mammals that feed on fruit and vegetables and destroy foliage of shade trees and plants. Pests compete with people for food and spread diseases. Indeed, before modern sanitation and medicine, such diseases played a major role in limiting human population density in cities. Bubonic plague is spread by fleas found on rodents; mice and rats in cities

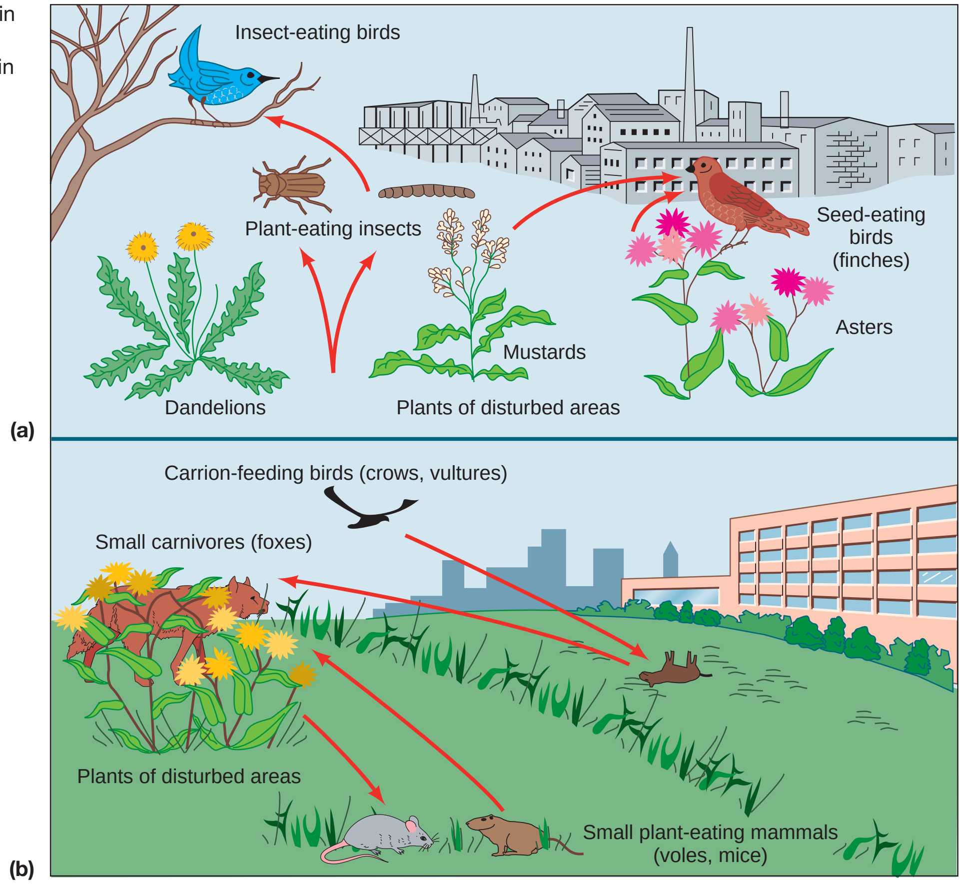


FIGURE 22.16 **(a)** An urban food chain based on plants of disturbed places and insect herbivores. **(b)** An urban food chain based on roadkill.

promoted the spread of the Black Death. Bubonic plague continues to be a health threat in cities—the World Health Organization reports several thousand cases a year.[26] Poor sanitation and high population densities of people and rodents set up a situation where the disease can strike.

An animal is a pest to people when it is in an undesired place at an undesirable time doing an unwanted thing. A termite in a woodland helps the natural regeneration of wood by hastening decay and speeding the return of chemical elements to the soil, where they are available to living plants. But termites in a house are pests because they threaten the house's physical structure.

Animals that do well enough in cities to become pests have certain characteristics in common. They are generalists in their food choice, so they can eat what we eat (including the leftovers we throw in the trash), and they have a high reproductive rate and a short average lifetime.

Controlling Pests

We can best control pests by recognizing how they fit their natural ecosystem and identifying the things that control them in nature. People often assume that the only way to control animal pests is with poisons, but there are limitations to this approach. Early poisons used in pest control were generally also toxic to people and pets (see Chapter 11). Another problem is that reliance on one toxic compound can cause a species to develop a resistance to it, which can lead to rebound—a renewed increase in that pest's population. A pesticide used once and spread widely will greatly reduce the population of the pest. However, when the pesticide loses its effectiveness, the pest population can increase rapidly as long as habitat is suitable and food plentiful. This is what happened when an attempt was made to control Norway rats in Baltimore.

One of the keys to controlling pests is to eliminate their habitats. For example, the best way to control rats is to reduce the amount of open garbage and eliminate areas to hide and nest. Common access areas used by rats are the spaces within and between walls and the openings between buildings where pipes and cables enter. Houses can be constructed to restrict access by rats. In older buildings, we can seal areas of access.

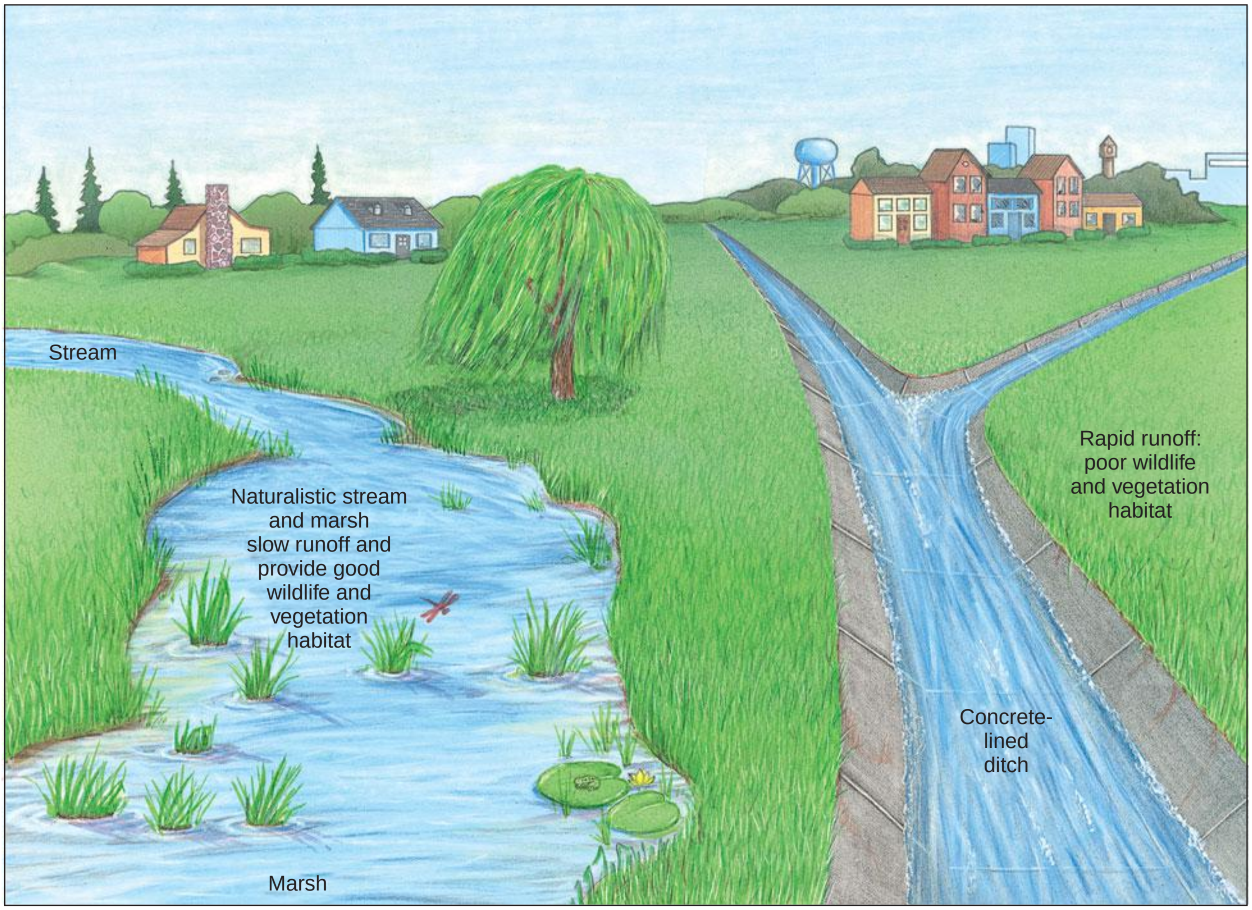


FIGURE 22.17 How water drainage systems in a city can be modified to provide wildlife habitat. In the community on the right, concrete-lined ditches speed runoff and have little value to fish and wildlife. In the community on the left, the natural stream and marsh were preserved; water is retained between rains, and an excellent habitat is provided. (*Source*: D.L. Leedly and L.W. Adams, A *Guide to Urban Wildlife Management* [Columbia, MD: National Institute for Urban Wildlife, 1984], pp. 20–21.)

CRITICAL THINKING ISSUE

How Can Urban Sprawl Be Controlled?

As the world becomes increasingly urbanized, individual cities are growing in area as well as population. Residential areas and shopping centers move into undeveloped land near cities, impinging on natural areas and creating a chaotic, unplanned human environment. "Urban sprawl" has become a serious concern in communities all across the United States. According to the U.S. EPA, in a recent six-month period approximately 5,000 people left Baltimore City to live in suburbs, with the result that nearly 10,000 acres of forests and farmlands were converted to housing. At this rate, the state of Maryland could use as much land for development in the next 25 years as it has used in the entire history of the state.[27] In the past ten years, 22 states have enacted new laws to try to control urban sprawl.

The city of Boulder, Colorado, has been in the forefront of this effort since 1959, when it created the "blue line"—a line at an elevation of 1,761 m (the city itself is at 1,606 m) above which it would not extend city water or sewer services. Boulder's citizens felt, however, that the blue line was insufficient to control development and maintain the city's scenic beauty in the face of rapid population growth. (Boulder's population had grown in the decade before 1959 from 29,000 to 66,000 and reached 96,000 by 1998.) To prevent uncontrolled development in the area between the city and the blue line, in 1967 Boulder began to use a portion of the city sales tax to purchase land, creating a 10,800-hectare greenbelt around the city proper.

In 1976 Boulder went one step further and limited increases in new residences to 2% a year. Two years later, recognizing that planned development requires a regional approach, the city and surrounding Boulder County adopted a coordinated development plan. By the early 1990s, it had become apparent that further growth control was needed for nonresidential building. The plan that the city finally adopted reduced the allowable density of many commercial and industrial properties, in effect limiting jobs rather than limiting building space.

Boulder's methods to limit the size of its population have worked. The most recent census (2002) showed that the population had increased by a mere 2,000 people and totaled just a little more than 94,000.

The benefits of Boulder's controlled-growth initiatives have been a defined urban–rural boundary; rational, planned development; protection of sensitive environmental areas and scenic vistas; and large areas of open space within and around the city for recreation. And in spite of its growth-control measures, Boulder's economy has remained strong. However, restraints on residential growth forced many people who found jobs in Boulder to seek affordable housing in adjoining communities, where populations ballooned. The population of Superior, Colorado, for example, grew from 225 in 1990 to 9,000 in 2000. Further, as commuting workers—40,000 a day—tried to get to and from their jobs in Boulder, traffic congestion and air pollution increased. In addition, because developers had built housing but not stores in the outlying areas, shoppers flocked into Boulder's downtown mall. When plans for a competing mall in the suburbs were finally announced, however, Boulder officials worried about the loss of revenue if the new mall drew shoppers away from the city. At the same time, sprawl from Denver (only 48 km from Boulder), as well as its infamous "brown cloud" of polluted air, began to spill out along the highway connecting the two communities.

Critical Thinking Questions

1. Is a city an open or a closed system (see Chapter 3)? Use examples from the case of Boulder to support your answer.
2. As Boulder takes steps to limit growth, it becomes an even more desirable place to live, which subjects it to even greater growth pressures. What ways can you suggest to avoid such a positive-feedback loop?
3. Some people in Boulder think the next step is to increase residential density within the city. Do you think people living there will accept this plan? What are the advantages and disadvantages of increasing density?
4. To some, the story of Boulder is the saga of a heroic battle against commercial interests that would destroy environmental resources and a unique quality of life. To others, it is the story of an elite group building an island of prosperity and the good life for themselves. Which do you think it is?

SUMMARY

- As an urban society, we must recognize the city's relation to the environment. A city influences and is influenced by its environment and is an environment itself.
- Like any other life-supporting system, a city must maintain a flow of energy, provide necessary material resources, and have ways of removing wastes. These functions are accomplished through transportation and communication with outlying areas.
- Because cities depend on outside resources, they developed only when human ingenuity resulted in modern agriculture and thus excess food production. The history of cities divides into four stages: (1) the rise of

towns; (2) the era of classic urban centers; (3) the period of industrial metropolises; and (4) the age of mass telecommunication, computers, and new forms of travel.

- Locations of cities are strongly influenced by environment. It is clear that cities are not located at random but in places of particular importance and environmental advantage. A city's site and situation are both important.
- A city creates an environment that is different from surrounding areas. Cities change local climate; they are commonly cloudier, warmer, and rainier than surrounding areas.
- In general, life in a city is riskier because of higher concentrations of pollutants and pollutant-related diseases.
- Cities favor certain animals and plants. Natural habitats in city parks and preserves will become more important as wilderness shrinks.
- Trees are an important part of urban environments, but cities place stresses on trees. Especially important are the condition of urban soils and the supply of water for trees.
- Cities can help to conserve biological diversity, providing habitat for some rare and endangered species.
- As the human population continues to increase, we can envision two futures: one in which people are dispersed widely throughout the countryside and cities are abandoned except by the poor; and another in which cities attract most of the human population, freeing much landscape for conservation of nature, production of natural resources, and public-service functions of ecosystems.

REEXAMINING THEMES AND ISSUES

Human Population

As the world's human population increases, we are becoming an increasingly urbanized species. Present trends indicate that in the future, most citizens of most nations will live in their country's single largest city. Thus, concern about urban environments will be increasingly important.

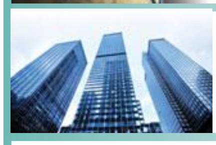
Cities contain the seeds of their own destruction: The very artificiality of a city gives its inhabitants the sense that they are independent of their surrounding environment. But the opposite is the case: The more artificial a city, the more it depends on its surrounding environment for resources and the more susceptible it becomes to major disasters unless this susceptibility is recognized and planned for. The keys to sustainable cities are an ecosystem approach to urban planning and a concern with the aesthetics of urban environments.

Sustainability

Cities depend on the sustainability of all renewable resources and must therefore recognize that they greatly affect their surrounding environments. Urban pollution of rivers that flow into an ocean can affect the sustainability of fish and fisheries. Urban sprawl can have destructive effects on endangered habitats and ecosystems, including wetlands. At the same time, cities designed to support vegetation and some wildlife can contribute to the sustainability of nature.

Global Perspective

The great urban centers of the world produce global effects. As an example, because people are concentrated in cities and because many cities are located at the mouths of rivers, most major river estuaries of the world are severely polluted.



Urban World

The primary message of this chapter is that Earth is becoming urbanized and that environmental science must deal more and more with urban issues.

People and Nature

It has been a modern tendency to focus environmental conservation efforts on wilderness, large parks, and preserves outside of cities. Meanwhile, city environments have been allowed to decay. As the world becomes increasingly urbanized, however, a change in values is necessary. If we are serious about conserving biological diversity, we must assign greater value to urban environments. The more pleasant city environments are, and the more recreation people can find in them, the less pressure there will be on the countryside.

Science and Values

Modern environmental sciences tell us much that we can do to improve the environments of cities and the effects of cities on their environments. What we choose to do with this knowledge depends on our values. Scientific information can suggest new options, and we can select among these for the future of our cities, depending on our values.

KEY TERMS

city planning **506**
fall line **501**
garden city **507**
greenbelt **507**
made lands **511**
site **500**
situation **500**

STUDY QUESTIONS

1. Should we try to save New Orleans or just give up and move the port at the mouth of the Mississippi River elsewhere? Explain your answer in terms of environment and economics.
2. Which of the following cities are most likely to become ghost towns in the next 100 years? In answering this question, use your knowledge of changes in resources, transportation, and communications.
   (a) Honolulu, Hawaii
   (b) Fairbanks, Alaska
   (c) Juneau, Alaska
   (d) Savannah, Georgia
   (e) Phoenix, Arizona
3. Some futurists picture a world that is one giant biospheric city. Is this possible? If so, under what conditions?
4. The ancient Greeks said that a city should have only as many people as can hear the sound of a single voice. Would you apply this rule today? If not, how would you plan the size of a city?
5. You are the manager of Central Park in New York City and receive the following two offers. Which would you approve? Explain your reasons.
   (a) A gift of $1 billion to plant trees from all the eastern states.
   (b) A gift of $1 billion to set aside half the park to be forever untouched, thus producing an urban wilderness.
6. Your state asks you to locate and plan a new town. The purpose of the town is to house people who will work at a wind farm—a large area of many windmills, all linked to produce electricity. You must first locate the site for the wind farm and then plan the town. How would you proceed? What factors would you take into account?
7. Visit your town center. What changes, if any, would make better use of the environmental location? How could the area be made more livable?
8. In what ways does air travel alter the location of cities? The value of land within a city?
9. You are put in charge of ridding your city's parks of slugs, which eat up the vegetable gardens rented to residents. How would you approach controlling this pest?
10. It is popular to suggest that in the Information Age people can work at home and live in the suburbs and the countryside, so cities are no longer necessary. List five arguments for and five arguments against this point of view.

FURTHER READING

Beveridge, C.E., and P. Rocheleau, *Frederick Law Olmsted: Designing the American Landscape* (New York: Rizzoli International, 1995). The most important analysis of the work of the father of landscape architecture.

Howard, E., *Garden Cities of Tomorrow* (Cambridge, MA: MIT Press, 1965, reprint). A classic work of the 19th century that has influenced modern city design, as in Garden City, New Jersey, and Greenbelt, Maryland. It presents a methodology for designing cities with the inclusion of parks, parkways, and private gardens.

McHarg, I.L., *Design with Nature* (New York: Wiley, 1995). A classic book about cities and environment.

Ndubisi, F., *Ecological Planning: A Historical and Comparative Synthesis* (Baltimore: Johns Hopkins University Press, 2002). An important discussion of an ecological approach to cities.

CHAPTER 23

Materials Management

College student on campus texting on a smartphone. These phones are e-waste when disposed of, but the plastic and metals in them can be recycled for a profit.

LEARNING OBJECTIVES

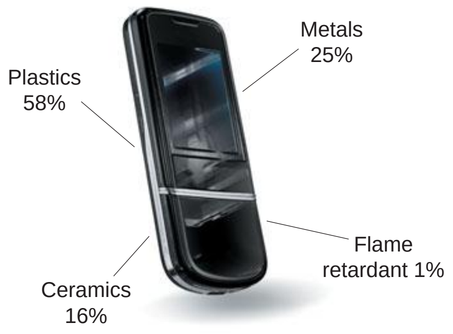
The waste-management concept of "dilute and disperse" (for example, dumping waste into a river) is a holdover from our frontier days, when we mistakenly believed that land and water were limitless resources. We next attempted to "concentrate and contain" waste in disposal sites—which also proved to pollute land, air, and water. We are now focusing on *managing materials* to reduce environmental degradation associated with resource use and eventually eliminate waste entirely. Finally, we are getting it right! After reading this chapter, you should understand . . .

- That the standard of living in modern society is related in part to the availability of natural resources;
- The importance of resources to society;
- The differences between mineral resources and reserves;
- The factors that control the environmental impact of mineral exploitation;
- How wastes generated from the use of mineral resources affect the environment;
- The social impacts of mineral exploitation;
- How sustainability may be linked to the way we use nonrenewable minerals.
- The emerging concept of *materials management* and how to achieve it;
- The advantages and disadvantages of each of the major methods that constitute integrated waste management;
- The various methods of managing hazardous chemical waste;
- The problems related to ocean dumping and why they will likely persist for some time.

CASE STUDY

Treasures of the Cell Phone

The number of people who use cell phones in the United States has risen from about 5 million in 1990 to nearly 200 million today. In 2009 more than 1 billion cell phones were sold worldwide, about half of them in Asia and Japan. Along with calls, text messaging, and video, cell phones have connected us as never before (see opening photograph). Cell phones are commonly replaced every two to three years as new features and services become available—witness the iPhone's popularity in 2008 when the new phones came out. Each cell phone is small, but the millions of phones retired each year in the United States collectively contain a treasure chest of valuable metals worth over $300 million, not counting the cost of recycling (Table 23.1). Worldwide, their value probably exceeds a billion dollars, but although the money potentially available is attractive, a very small percentage of discarded cell phones are recycled. Most end up stored in our closets or disposed of at municipal solid-waste facilities.



The life cycle of a cell phone is shown in Figure 23.1 and is typical of most electronic waste (e-waste).[1] The primary reason more e-waste is not recycled is that we lack a simple, effective, small-scale, inexpensive way to do it. We also need to better educate people about the environmental value of recycling and to offer more attractive financial incentives to do it. Some states (California,

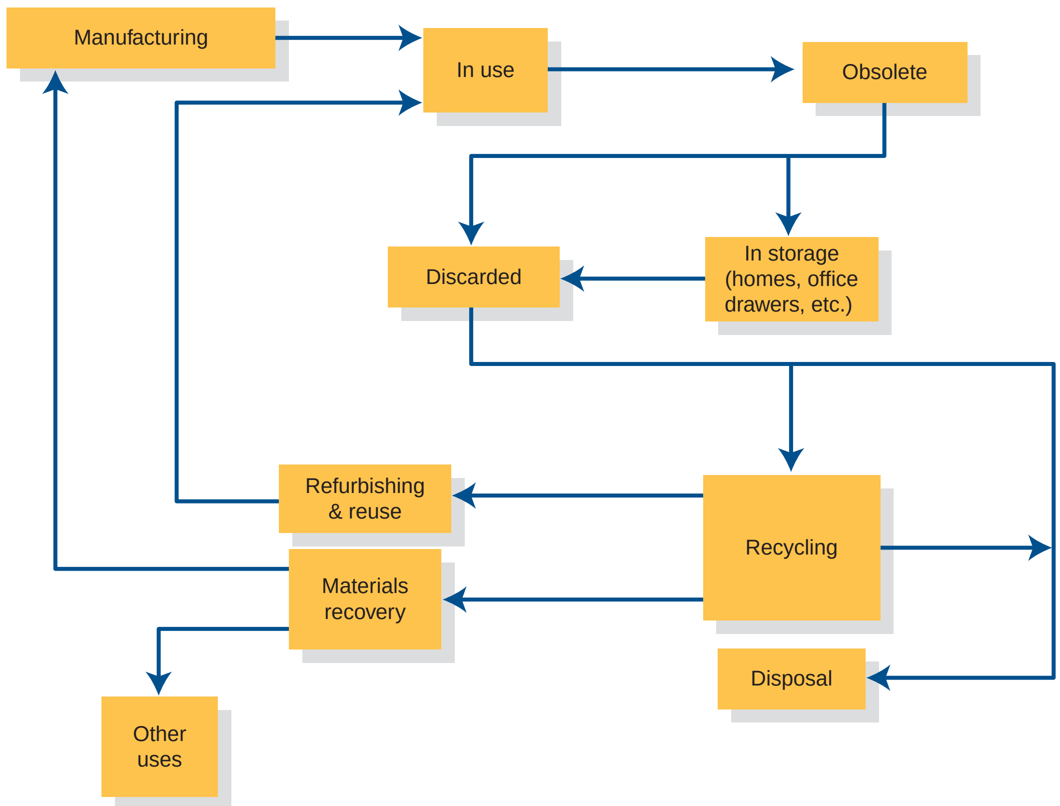


FIGURE 23.1 Composition and life cycle of a cell phone. (*Source*: Modified from D.E. Sullivan, 2006, "Recycled Cell Phones—A Treasure Trove of Valuable Metals," U.S. Geological Survey Fact Sheet 2006–3097.)

Table 23.1 METAL CONTENT AND VALUE OF U.S. CELL PHONES, NOT COUNTING COST TO RECYCLE

	METAL CONTENT AND VALUE ESTIMATED FOR A TYPICAL CELL PHONE		METAL CONTENT AND VALUE FOR 500 MILLION OBSOLETE CELL PHONES IN STORAGE IN 2005	
METAL	WT (g)	VALUE	WT (t)	VALUE
Copper	16	$0.03	7,900	$17 million
Silver	0.35	$0.06	178	$31 million
Gold	0.034	$0.40	17	$199 million
Palladium	0.015	$0.13	7.4	$63 million
Platinum	0.00034	$0.01	0.18	$3.9 million
Total		$0.63	8,102	$314 million

Source: Modified from Sullivan, D.E., 2006. Recycled cell phones—A treasure trove of valuable metals. U.S. Geological Survey Fast Sheet 2006–3097.

for example) have laws that require building the recycling costs into the prices of products.

Our failure to manage cell phones and other e-waste reminds us that we have failed in the past 50 years to move from a throwaway, waste-oriented society to a society that sustains natural resources through improved materials management. In some cases we are moving in that direction by producing less waste and recycling more discarded products. With this in mind, in this chapter we introduce concepts of waste management applied to urban waste, hazardous chemical waste, and waste in the marine environment.

23.1 The Importance of Resources to Society

Modern society depends on the availability of both **renewable resources** (air, surface water, some groundwater, plants, animals, and some energy sources) and **nonrenewable** resources (soil, some groundwater, oil, coal, and most minerals).[2-4] What partially differentiates renewable from nonrenewable resources is their availability in a human time framework. Air and water, along with biological resources such as fish and crops, are regularly replenished as long as the processes that renew them continue to operate at an adequate rate. Nonrenewable resources, such as oil and minerals, even those that are being replenished by Earth processes today, are not being replenished in a time frame useful to people. Thus, strategies to use resources sustainably are linked to specific resources. We can sustain water resources by careful water management (see Chapter 18), but sustaining minerals or oil requires strategies linked more to conservation, recycling, reuse, and substitution than to management of next year's supply delivered by Earth processes.

Many products made from both renewable and nonrenewable resources are found and consumed in a typical American home (see Figure 23.2 for nonrenewable minerals used in a home office). Consider this morning's breakfast (food is a renewable resource). You probably drank from a glass made primarily of sand; ate from dishes made of clay; flavored your food with salt mined from Earth; ate fruit grown with the aid of fertilizers, such as potassium carbonate (potash) and phosphorus; and used utensils made of stainless steel, which comes from processing iron ore and other minerals. While eating your tasty renewable resources, you may have viewed the news on a television or computer screen, listened to music on your iPod, or made appointments using your cell phone. All these electronic items are made from metals and petroleum.

Resources are vital to people, and the standard of living increases with their availability in useful forms. Indeed, the availability of resources is one measure of a society's wealth. Those who have been most successful in locating and extracting or importing and using resources have grown and prospered. Without resources to grow food, construct buildings and roads, and manufacture everything from computers to televisions to automobiles, modern technological civilization as we know it would not be possible. For example, to maintain our standard of living in the United States, each person requires about 10 tons of nonfuel minerals per year.[5] We use other resources, such as food and water, in much greater amounts.

1. Computer—Includes gold, silica, nickel, aluminum, zinc, iron, petroleum products and about thirty other minerals.
2. Pencil—Includes graphite and clays.
3. Telephone—Includes copper, gold and petroleum products.
4. Books—Includes limestone and clays.
5. Pens—Includes limestone, mica, petroleum products, clays, silica and talc.
6. Film—Includes petroleum products and silver.
7. Camera—Includes silica, zinc, copper, aluminum and petroleum products
8. Chair—Includes aluminum and petroleum products.
9. Television—Includes aluminum, copper, iron, nickel, silica, rare earth, and strontium.
10. Stereo—Includes gold, iron, nickel, beryllium and petroleum products.
11. Compact Disc—Includes aluminum and petroleum products.
12. Metal Chest—Includes iron and nickel. The brass trim is made of copper and zinc.
13. Carpet—Includes limestone, petroleum products and selenium.
14. Drywall—Includes gypsum clay, vermiculite, calcium carbonate and micas.
15. Geologic Map—Includes clays, petroleum products, mineral pigments.
16. Concrete Foundation—Includes limestone, clays, sand and gravel
17. Paint-mineral Pigments—Includes pigments (such as iron, zinc and titanium).
18. Cosmetics—Includes mineral chemicals.

FIGURE 23.2 Mineral products used in a home office. (*Source*: Modified from S.J. Kropschot and K.M. Johnson, 2006. U.S. 65. Mineral Resources Program. USGS Circular 1289. Menlo Park, CA)

23.2 Materials Management: What It Is

Materials management has the visionary environmental goal of sustainably obtaining and using renewable and nonrenewable resources. This goal can be pursued in the following ways:[6]

- Eliminate subsidies for extracting virgin materials such as minerals, oil, and timber.
- Establish "green building" incentives that encourage the use of recycled-content materials and products in new construction.
- Assess financial penalties for production that uses poor materials-management practices.
- Provide financial incentives for industrial practices and products that benefit the environment by enhancing sustainability (for example, by reducing waste production and using recycled materials).
- Provide more incentives for people, industry, and agriculture to develop materials-management programs that eliminate or reduce waste by using it as raw material for other products.

Materials management in the United States today is beginning to influence where industries are located. For example, because approximately 50% of the steel produced in the nation now comes from scrap, new steel mills are no longer located near resources such as coal and iron ore. New steel mills are now found in a variety of places, from California to North Carolina and Nebraska; their resource is the local supply of scrap steel. Because they are starting with scrap metal, the new industrial facilities use far less energy and cause much less pollution than older steel mills that must start with virgin iron ore.[7]

Similarly, the recycling of paper is changing where new paper mills are constructed. In the past, mills were built near forested areas where the timber for paper production was being logged. Today, they are being built near cities that have large supplies of recycled paper. New Jersey, for example, has 13 paper mills using recycled paper and 8 steel "mini-mills" producing steel from scrap metal. What is remarkable is that New Jersey has little forested land and no iron mines. Resources for the paper and steel mills come from materials already in use, exemplifying the power of materials management.[7]

We have focused on renewable resources in previous parts of this book (Chapter 11, agriculture; Chapter 12, forests; Chapter 13, wildlife; Chapter 18, water; and Chapter 21, air). We discussed nonrenewable resources with respect to fossil fuels in Chapter 15. The remainder of this chapter will discuss other nonrenewable mineral resources and how to sustain them as long as possible by intelligent waste management.

23.3 Mineral Resources

Minerals can be considered a very valuable, nonrenewable heritage from the geologic past. Although new deposits are still forming from Earth processes, these processes are producing new deposits too slowly to be of use to us today or anytime soon. Also, because mineral deposits are generally in small, hidden areas, they must be discovered, and unfortunately most of the easy-to-find deposits have already been discovered and exploited. Thus, if modern civilization were to vanish, our descendants would have a harder time finding rich mineral deposits than we did. It is interesting to speculate that they might mine landfills for metals thrown away by our civilization. Unlike biological resources, minerals cannot be easily managed to produce a sustained yield; the supply is finite. Recycling and conservation will help, but, eventually, the supply will be exhausted.

How Mineral Deposits Are Formed

Metals in mineral form are generally extracted from naturally occurring, unusually high concentrations of Earth materials. When metals are concentrated in such high amounts by geologic processes, **ore deposits** are formed. The discovery of natural ore deposits allowed early peoples to exploit copper, tin, gold, silver, and other metals while slowly developing skills in working with metals.

The origin and distribution of mineral resources is intimately related to the history of the biosphere and to the entire geologic cycle (see Chapter 6). Nearly all aspects and processes of the geologic cycle are involved to some extent in producing local concentrations of useful materials. Earth's outer layer, or crust, is silica-rich, made up mostly of rock-forming minerals containing silica, oxygen, and a few other elements. The elements are not evenly distributed in the crust: Nine elements account for about 99% of the crust by weight (oxygen, 45.2%; silicon, 27.2%; aluminum, 8.0%; iron, 5.8%; calcium, 5.1%; magnesium, 2.8%; sodium, 2.3%; potassium, 1.7%; and titanium, 0.9%). In general, the remaining elements are found in trace concentrations.

The ocean, covering nearly 71% of Earth, is another reservoir for many chemicals other than water. Most elements in the ocean have been weathered from crustal rocks on the land and transported to the oceans by rivers. Others are transported to the ocean by wind or glaciers. Ocean water contains about 3.5% dissolved solids, mostly chlorine (55.1% of the dissolved solids by weight). Each cubic kilometer of ocean water contains about 2.0 metric tons of zinc, 2.0 metric tons of copper, 0.8 metric ton of tin, 0.3 metric ton of silver, and 0.01 metric ton of gold. These concentrations are low compared with those in the crust, where corresponding values (in metric tons/km^3) are zinc, 170,000; copper, 86,000; tin, 5,700; silver, 160; and gold, 5. After rich crustal ore deposits are depleted, we will be more likely to extract metals from lower-grade deposits or even from common rock than from ocean water, unless mineral-extraction technology becomes more efficient.

Why do the minerals we mine occur in deposits—with anomalously high local concentrations? Planetary scientists now believe that all the planets in our solar system were formed by the gravitational attraction of the forming sun, which brought together the matter dispersed around it. As the mass of the proto-Earth increased, the material condensed and was heated by the process. The heat was sufficient to produce a molten liquid core, consisting primarily of iron and other heavy metals, which sank toward the center of the planet. When molten rock material known as *magma* cools, heavier minerals that crystallize (solidify) early may slowly sink toward the bottom of the magma, whereas lighter minerals that crystallize later are left at the top. Deposits of an ore of chromium, called chromite, are thought to be formed in this way. When magma containing small amounts of carbon is deeply buried and subjected to very high pressure during slow cooling (crystallization), diamonds (which are pure carbon) may be produced (Figure 23.3).[8, 9]

Earth's crust formed from generally lighter elements and is a mixture of many different kinds. The elements in the crust are not uniformly distributed because geologic processes (such as volcanic activity, plate tectonics, and sedimentary processes), as well as some biological processes, selectively dissolve, transport, and deposit elements and minerals.

FIGURE 23.3 Diamond mine near Kimberley, South Africa. This is the largest hand-dug excavation in the world.

Sedimentary processes related to the transport of sediments by wind, water, and glaciers often concentrate materials in amounts sufficient for extraction. As sediments are transported, running water and wind help segregate them by size, shape, and density. This sorting is useful to people. The best sand or sand and gravel deposits for construction, for example, are those in which the finer materials have been removed by water or wind. Sand dunes, beach deposits, and deposits in stream channels are good examples. The sand and gravel industry amounts to several billion dollars annually and, in terms of the total volume of materials mined, is one of the largest nonfuel mineral industries in the United States.[5]

Rivers and streams that empty into oceans and lakes carry tremendous quantities of dissolved material from the weathering of rocks. Over geologic time, a shallow marine basin may be isolated by tectonic activity that uplifts its boundaries, or climate variations, such as the ice ages, may produce large inland lakes with no outlets. As these basins and lakes eventually dry up, the dissolved materials drop out of solution and form a wide variety of compounds, minerals, and rocks that have important commercial value.[10]

Biological processes form some mineral deposits, such as phosphates and iron ore deposits. The major iron ore deposits exist in sedimentary rocks that were formed more than 2 billion years ago.[10] Although the processes are not fully understood, it appears that major deposits of iron stopped forming when the atmospheric concentration of oxygen reached its present level.[11]

Organisms, too, form many kinds of minerals, such as the calcium minerals in shells and bones. Some of these minerals cannot be formed inorganically in the biosphere. Thirty-one biologically produced minerals have been identified.[12]

Weathering, the chemical and mechanical decomposition of rock, concentrates some minerals in the soil, such as native gold and oxides of aluminum and iron. (The more soluble elements, such as silica, calcium, and sodium, are selectively removed by soil and biological processes.) If sufficiently concentrated, residual aluminum oxide forms an ore of aluminum known as bauxite. Important nickel and cobalt deposits are also found in soils developed from iron- and magnesium-rich igneous rocks.

23.4 Figuring Out How Much Is Left

Estimating how much is left of our valuable and nonrenewable mineral resources will help us estimate how long they are likely to last at our present rate of use and motivate us to do everything we can to sustain them as long as possible for future generations. We can begin by looking at the classification of minerals as *resources* and *reserves*.

Mineral Resources and Reserves

Mineral **resources** are broadly defined as known concentrations of elements, chemical compounds, minerals, or rocks. Mineral **reserves** are concentrations that at the time of evaluation can be legally and economically extracted as a commodity that can be sold at a profit (Figure 23.4).

The main point here is that *resources are not reserves*. An analogy from a student's personal finances may help clarify this point. A student's reserves are liquid assets, such as money in the bank, whereas the student's resources include the total income the student can expect to earn during his or her lifetime. This distinction is often critical to the student in school because resources that may become available in the future cannot be used to pay this month's bills.[6] For planning purposes, it is important to continually reassess all components of a total resource, considering new technology, the probability of geologic discovery, and shifts in economic and political conditions.[13]

Availability and Use of Our Mineral Resources

Earth's mineral resources can be divided into broad categories according to their use: elements for metal production and technology, building materials, minerals for the chemical industry, and minerals for agriculture. Metallic minerals can be further classified by their abundance. Abundant metals include iron, aluminum, chromium, manganese, titanium, and magnesium. Scarce metals include copper, lead, zinc, tin, gold, silver, platinum, uranium, mercury, and molybdenum.

Some minerals, such as salt (sodium chloride), are necessary for life. Primitive peoples traveled long distances

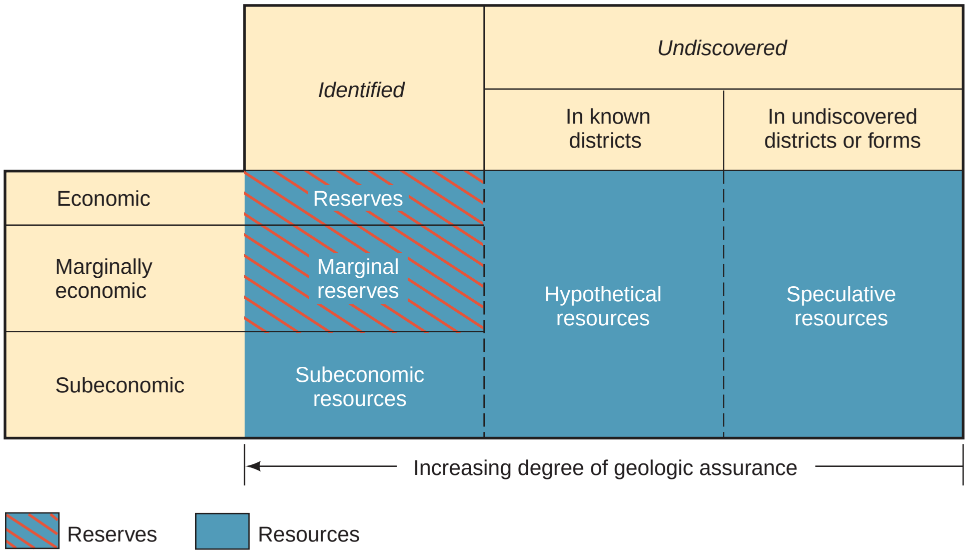


FIGURE 23.4 Classification of mineral resources used by the U.S. Geological Survey and the U.S. Bureau of Mines. (*Source: Principles of a Resource Preserve Classification for Minerals*, U.S. Geological Survey Circular 831, 1980.)

to obtain salt when it was not locally available. Other minerals are desired or considered necessary to maintain a particular level of technology.

When we think about minerals, we usually think of metals; but with the exception of iron, the predominant minerals are not metallic. Consider the annual world consumption of a few selected elements. Sodium and iron are used at a rate of approximately 100–1,000 million metric tons per year; and nitrogen, sulfur, potassium, and calcium at a rate of approximately 10–100 million metric tons per year, primarily as soil conditioners or fertilizers. Elements such as zinc, copper, aluminum, and lead have annual world consumption rates of about 3–10 million metric tons, and gold and silver are consumed at annual rates of 10,000 metric tons or less. Of the metallic minerals, iron makes up 95% of all the metals consumed; and nickel, chromium, cobalt, and manganese are used mainly in alloys of iron (as in stainless steel).

The basic issue associated with mineral resources is not actual exhaustion or extinction but the cost of maintaining an adequate stock by mining and recycling. At some point, the costs of mining exceed the worth of material. When the availability of a particular mineral becomes limited, there are four possible solutions:

1. Find more sources.
2. Recycle and reuse what has already been obtained.
3. Reduce consumption.
4. Find a substitute.

Which choice or combination of choices is made depends on social, economic, and environmental factors.

U.S. Supply of Mineral Resources

Domestic supplies of many mineral resources in the United States are insufficient for current use and must be supplemented by imports from other nations. For example, the United States imports many of the minerals needed for its complex military and industrial system, called strategic minerals (such as bauxite, manganese, graphite, cobalt, strontium, and asbestos). Of particular concern is the possibility that the supply of a much-desired or much-needed mineral will be interrupted by political, economic, or military instability in the supplying nation.

That the United States—along with many other countries—depends on a steady supply of imports to meet its domestic demand for them does not necessarily mean that sufficient kinds and amounts can't be mined domestically. Rather, it suggests economic, political, or environmental reasons that make it easier, more practical, or more desirable to import the material. This has resulted in political alliances that otherwise would be unlikely. Industrial countries often need minerals from countries whose policies they don't necessarily agree with; as a result they make political concessions, on human rights and other issues, that they would not otherwise make.[3]

Moreover, the fact remains that mineral resources are limited, and this raises important questions. How long will a particular resource last? How much short-term or long-term environmental deterioration are we willing to accept to ensure that resources are developed in a particular area? How can we make the best use of available resources?

23.5 Impacts of Mineral Development

The impact of mineral exploitation depends on ore quality, mining procedures, local hydrologic conditions, climate, rock types, size of operation, topography, and many more interrelated factors. In addition, our use of mineral resources has a significant social impact.

Environmental Impacts

Exploration for mineral deposits generally has a minimal impact on the environment if care is taken in sensitive areas, such as arid lands, marshes, and areas underlain by permafrost. Mineral mining and processing, however, generally have a considerable impact on land, water, air, and living things. Furthermore, as it becomes necessary to use ores of lower and lower grades, the environmental effects tend to worsen. One example is the asbestos fibers in the drinking water of Duluth, Minnesota, from the disposal of waste from mining low-grade iron ore.

A major practical issue is whether open-pit or underground mines should be developed in an area. As you saw in our earlier discussion of coal mining in Chapter 15, there are important differences between the two kinds of mining.[2] The trend in recent years has been away from subsurface mining and toward large, open-pit mines, such as the Bingham Canyon copper mine in Utah (Figure 23.5). The Bingham Canyon mine is one of the world's largest man-made excavations, covering nearly 8 km^2 (3 mi^2) to a maximum depth of nearly 800 m (2,600 ft).

Surface mines and quarries today cover less than 0.5% of the total area of the United States, but even though their impacts are local, numerous local occurrences will eventually constitute a larger problem. Environmental degradation tends to extend beyond the immediate vicinity of a mine. Large mining operations remove material in some areas and dump waste in others, changing topography. At the very least, severe aesthetic degradation is the result. In addition, dust may affect the air quality, even though care is taken to reduce it by sprinkling water on roads and on other sites that generate dust.

A potential problem with mineral resource development is the possible release of harmful trace elements into the environment. Water resources are particularly vulnerable even if drainage is controlled and sediment pollution is reduced (see Chapter 15 for more about this, including a discussion of acid mine drainage). The white streaks in Figure 23.6 are mineral deposits apparently leached from tailings from a zinc mine in Colorado. Similar-looking deposits may cover rocks in rivers for many kilometers downstream from some mining areas.

FIGURE 23.5 Aerial photograph of Bingham Canyon Copper Pit, Utah. It is one of the largest artificial excavations in the world.

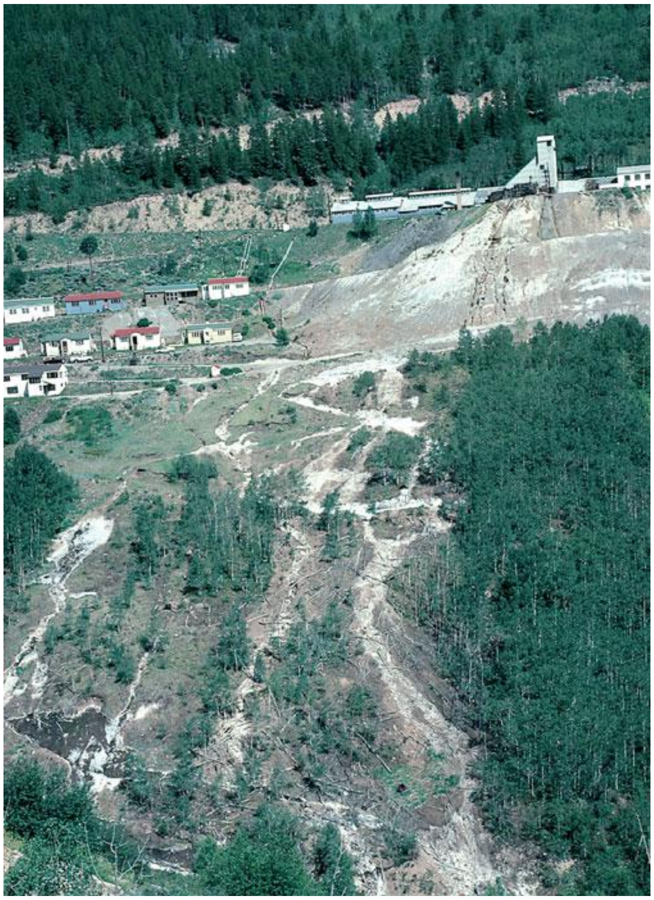


FIGURE 23.6 Tailings from a lead, zinc, and silver mine in Colorado. White streaks on the slope are mineral deposits apparently leached from the tailings.

Mining-related physical changes in the land, soil, water, and air indirectly affect the biological environment. Plants and animals killed by mining activity or by contact with toxic soil or water are some of the direct impacts. Indirect impacts include changes in nutrient cycling, total biomass, species diversity, and ecosystem stability. Periodic or accidental discharge of low-grade pollutants through failure of barriers, ponds, or water diversions, or through the breaching of barriers during floods, earthquakes, or volcanic eruptions, also may damage local ecological systems to some extent.

Social Impacts

The social impacts of large-scale mining result from the rapid influx of workers into areas unprepared for growth. This places stress on local services, such as water supplies, sewage and solid-waste disposal systems, and also on schools, housing, and nearby recreation and wilderness areas. Land use shifts from open range, forest, and agriculture to urban patterns. Construction and urbanization affect local streams through sediment pollution, reduced water quality, and increased runoff. Air quality suffers as a result of more vehicles, construction dust, and power generation.

Perversely, closing down mines also has adverse social impacts. Nearby towns that have come to depend on the income of employed miners can come to resemble the well-known "ghost towns" of the old American West. The price of coal and other minerals also directly affects the livelihood of many small towns. This is especially evident in the Appalachian Mountain region of the United States, where coal mines have closed partly because of lower prices for coal and partly because of rising mining costs. One of the reasons mining costs are rising is the increased level of environmental regulation of the mining industry. Of course, regulations have also helped make mining safer and have facilitated land reclamation. Some miners, however, believe the regulations are not flexible enough, and there is some truth to their arguments. For example, some mined areas might be reclaimed for use as farmland now that the original hills have been leveled. Regulations, however, may require the restoration of the land to its original hilly state, even though hills make inferior farmland.

Minimizing the Environmental Impact of Mineral Development

Minimizing the environmental impacts of mineral development requires consideration of the entire cycle of mineral resources shown in Figure 23.7. This diagram reveals that waste is produced by many components of the cycle. In fact, the major environmental impacts of mineral use are related to waste products. Waste produces pollution that may be toxic to people, may harm natural ecosystems and the biosphere, and may be aesthetically displeasing. Waste may attack and degrade air, water, soil, and living things. Waste also depletes nonrenewable mineral resources and, when simply disposed of, provides no offsetting benefits for human society.

Environmental regulations at the federal, state, and local levels address pollution of air and water by all aspects of the mineral cycle, and may also address reclamation of land used for mining minerals. Today, in the United States, approximately 50% of the land used by the mining industry has been reclaimed.

Minimizing the environmental effects of mining takes several interrelated paths:[3]

- *Reclaiming* areas disturbed by mining (see A Closer Look 23.1).
- *Stabilizing soils* that contain metals to minimize their release into the environment. Often this requires placing contaminated soils in a waste facility.
- *Controlling air emissions* of metals and other materials from mining areas.
- *Treating contaminated water before it can leave a mining site or treating contaminated water that has left a mining site.*
- *Treating waste onsite and offsite.* Minimizing onsite and offsite problems by controlling sediment, water, and air pollution through good engineering and conservation practices is an important goal. Of particular interest is the development of biotechnological processes such as biooxidation, bioleaching, and biosorption, the bonding of waste to microbes, as well as genetic engineering of microbes. These practices have enormous potential for both extracting metals and minimizing environmental degradation. At several sites, for example, constructed wetlands use acid-tolerant plants to remove metals from mine wastewaters and neutralize acids by biological activity.[14] The Homestake Gold Mine in South Dakota uses biooxidation to convert contaminated water from the mining operation into substances that are environmentally safe; the process uses bacteria that have a natural ability to oxidize cyanide to harmless nitrates.[15]
- *Practicing the three R's of waste management.* That is, **R**educe the amount of waste produced, **R**euse waste as much as possible, and maximize **R**ecycling opportunities. Wastes from some parts of the mineral cycle, for example, may themselves be considered ores because they contain materials that might be recycled to provide energy or other products.[16–18]

We will look at the three R's in greater detail in Section 23.7, Integrated Waste Management.

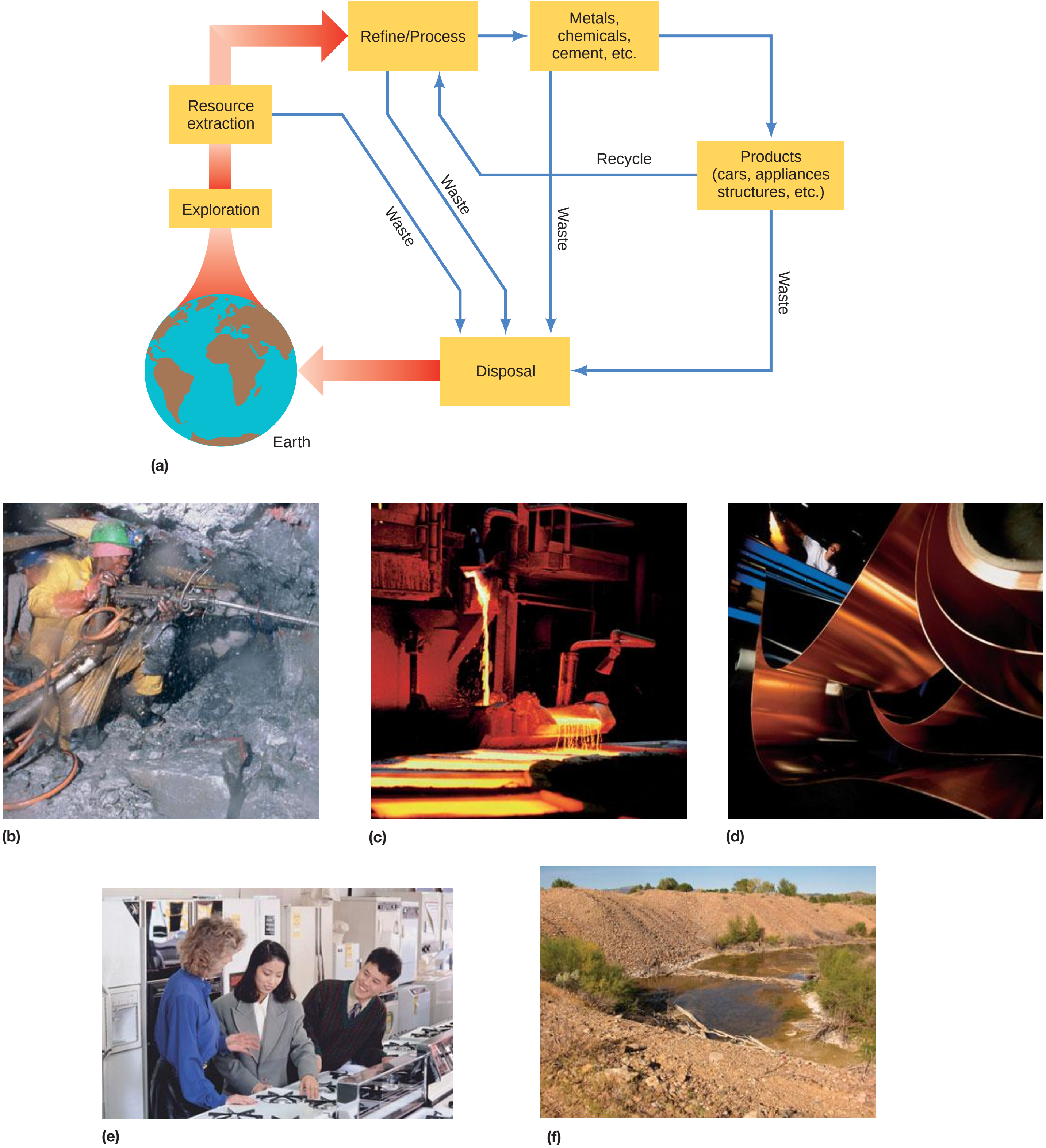


FIGURE 23.7 **(a)** Simplified flowchart of the resource cycle: **(b)** mining gold in South Africa; **(c)** copper smelter, Montana; **(d)** sheets of copper for industrial use; **(e)** appliances made in part from metals; and **(f)** disposal of mining waste from a Montana gold mine into a tailings pond.

A CLOSER LOOK 23.1

Golden, Colorado: Open-Pit Mine Becomes a Golf Course

The city of Golden, Colorado, has an award-winning golf course on land that, for about 100 years, was an open-pit mine (quarry) excavated in limestone rock (Figure 23.8). The mine produced clay for making bricks from clay layers between limestone beds. Over the life of the mine, the clay was used as a building material at many sites, including prominent buildings in the Denver area, such as the Colorado Governor's Mansion. The mine site included unsightly pits with vertical limestone walls as well as a landfill for waste disposal. However, it had spectacular views of the Rocky Mountain foothills. Today the limestone cliffs with their exposed plant and dinosaur fossils have been transformed into golf greens, fairways, and a driving range. The name Fossil Trace Golf Club reflects its geologic heritage. The course includes trails to fossil locations and also has channels, constructed wetlands, and three lakes that store floodwater runoff, helping to protect Golden from flash floods. The reclamation project started with a grassroots movement by the people of Golden to have a public golf course. The reclamation is now a moneymaker for the city and demonstrates that mining sites can not only be reclaimed, but also be transformed into valuable property.

FIGURE 23.8 This award-winning golf course in Golden, Colorado, was for a century an open-pit mine (quarry) for clay to produce bricks.

23.6 Materials Management and Our Waste

History of Waste Disposal

During the first century of the Industrial Revolution, the volume of waste produced in the United States was relatively small and could be managed using the concept of "dilute and disperse." Factories were located near rivers because the water provided a number of benefits, including easy transport of materials by boat, enough water for processing and cooling, and easy disposal of waste into the river. With few factories and a sparse population, dilute and disperse was sufficient to remove the waste from the immediate environment.[19]

As industrial and urban areas expanded, the concept of dilute and disperse became inadequate, and a new concept, "concentrate and contain," came into use. It has become apparent, however, that containment was, and is, not always achieved. Containers, whether simple trenches excavated in the ground or metal drums and tanks, may leak or break and allow waste to escape. Health hazards resulting from past waste-disposal practices have led to the present situation, in which many people have little confidence in government or industry to preserve and protect public health.[20]

In the United States and many other parts of the world, people are facing a serious solid-waste disposal problem. Basically, we are producing a great deal of waste and don't have enough acceptable space for disposing of it. It has been estimated that within the next few years approximately half the cities in the United States may run out of landfill space. Philadelphia, for example, is essentially out of landfill space now and is bargaining with other states on a monthly or yearly basis to dispose of its trash. The Los Angeles area has landfill space for only about ten more years.

To say we are actually running out of space for landfills isn't altogether accurate—land used for landfills is minute compared to the land area of the United States. Rather, existing sites are being filled, and it is difficult to site new landfills. After all, no one wants to live near a waste-disposal site, be it a sanitary landfill for municipal waste, an incinerator that burns urban waste, or a hazardous-waste disposal operation for chemical materials.

This attitude is widely known as NIMBY ("not in my backyard").

The environmentally correct concept with respect to waste management is to consider wastes as resources out of place. Although we may not soon be able to reuse and recycle all waste, it seems apparent that the increasing cost of raw materials, energy, transportation, and land will make it financially feasible to reuse and recycle more resources and products. Moving toward this objective is moving toward an environmental view that there is no such thing as waste. Under this concept, waste would not exist because it would not be produced—or, if produced, would be a resource to be used again. This is referred to as the "zero waste" movement.

Zero waste is the essence of what is known as **industrial ecology**, the study of relationships among industrial systems and their links to natural systems. Under the principles of industrial ecology, our industrial society would function much as a natural ecosystem functions. Waste from one part of the system would be a resource for another part.[21]

Until recently, zero waste production was considered unreasonable in the waste-management arena. However, it is catching on. The city of Canberra, Australia, may be the first community to propose a zero waste plan. Thousands of kilometers away, in the Netherlands, a national waste-reduction goal of 70 to 90% has been set. How this goal is to be met is not entirely clear, but a large part of the planning involves taxing waste in all its various forms, from smokestack emissions to solids delivered to landfills. Already, in the Netherlands, pollution taxes have nearly eliminated discharges of heavy metals into waterways. At the household level, the government is considering programs—known as "pay as you throw"—that would charge people by the volume of waste they produce. Taxing waste, including household waste, motivates people to produce less of it.[22]

Of particular importance to waste management is the growing awareness that many of our waste-management programs involve moving waste from one site to another, not really managing it. For example, waste from urban areas may be placed in landfills; but eventually these landfills may cause new problems by producing methane gas or noxious liquids that leak from the site and contaminate the surrounding areas. Managed properly, however, methane produced from landfills is a resource that can be burned as a fuel (an example of industrial ecology).

In sum, previous notions of waste disposal are no longer acceptable, and we are rethinking how we deal with materials, with the objective of eliminating the concept of waste entirely. In this way, we can reduce the consumption of minerals and other virgin materials, which depletes our environment, and live within our environment more sustainably.[21]

23.7 Integrated Waste Management

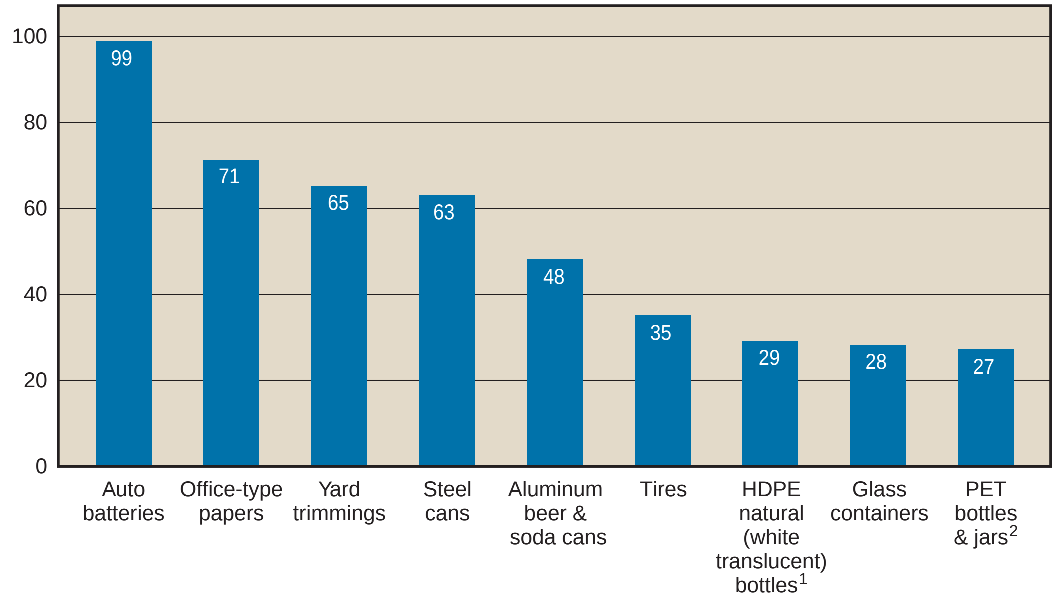
The dominant concept today in managing waste is known as **integrated waste management (IWM)**, which is best defined as a set of management alternatives that includes *reuse, source reduction, recycling, composting, landfill,* and *incineration*.[20]

Reduce, Reuse, Recycle

The ultimate objective of the three R's of IWM is to reduce the amount of urban and other waste that must be disposed of in landfills, incinerators, and other waste-management facilities. Study of the *waste stream* (the waste produced) in areas that use IWM technology suggests that the amount (by weight) of urban refuse disposed of in landfills or incinerated can be reduced by at least 50% and perhaps as much as 70%. A 50% reduction by weight could be achieved by (1) source reduction, such as packaging better designed to reduce waste (10% reduction); (2) large-scale composting programs (10% reduction); and (3) recycling programs (30% reduction).[20]

As this list indicates, recycling is a major player in reducing the urban waste stream. Metals such as iron, aluminum, copper, and lead have been recycled for many years and are still being recycled today. The metal from almost all of the millions of automobiles discarded annually in the United States is recycled.[16, 17] The total value of recycled metals is about $50 billion. Iron and steel account for approximately 90% by weight and 40% by total value of recycled metals. Iron and steel are recycled in such large volumes for two reasons. First, the market for iron and steel is huge, and as a result there is a large scrap-collection and scrap-processing industry. Second, an enormous economic and environmental burden would result from failure to recycle because over 50 million tons of scrap iron and steel would have to be disposed of annually.[17, 18]

Today in the United States we recycle over 30% of our total municipal solid waste, up 10% from 25 years ago. This amounts to 99% of automobile batteries, 63% of steel cans, 71% office type papers, 48% of aluminum cans, 35% of tires, 28% of glass containers, and about 30% of various plastic containers (Figure 23.9).[23] This is encouraging news. Can recycling actually reduce the waste stream by 50%? Recent work suggests that the 50% goal is reasonable. In fact, it has been reached in some parts of the United States, and the potential upper limit for recycling is considerably higher. It is estimated that as much as 80 to 90% of the U.S. waste stream might be recovered through what is known as "intensive recycling."[24] A pilot study involving 100 families in East Hampton, New York,



[1] HDPE is high-density polyethylene produced from ethylene to make blow-molded bottles.

[2] PET is a type of plastic labled with a recycling number code (in a triangle) on the bottom of the bottle.

FIGURE 23.9 Recycling rates of selected materials from municipal solid waste in 2008 for the United States. (*Source*: Municipal solid-waste generation, recycling, and disposal in the United States: facts and figures 2008. Basic Information 2009. www.epa.gov.)

achieved a level of 84%. More realistic for many communities is partial recycling, which targets specific materials, such as glass, aluminum cans, plastic, organic material, and newsprint. Partial recycling can provide a significant reduction, and in many places it is approaching or even exceeding 50%.[25, 26]

Recycling is simplified with **single-stream recycling,** in which paper, plastic, glass, and metals are not separated before collection; the waste is commingled in one container and separated later at recycling centers. This is more convenient for homeowners, reduces the cost of collection, and increases the rate of recycling. Thus, single-stream recycling is growing rapidly.

Public Support for Recycling

An encouraging sign of public support for the environment is the increased willingness of industry and business to support recycling on a variety of scales. For example, fast-food restaurants are using less packaging and providing onsite bins for recycling paper and plastic. Groceries and supermarkets are encouraging the recycling of plastic and paper bags by providing bins for their collection, and some offer inexpensive reusable canvas shopping bags instead of disposables. Companies are redesigning products so that they can be more easily disassembled after use and the various parts recycled. As this idea catches on, small appliances, such as electric frying pans and toasters, may be recycled rather than ending up in landfills. The automobile industry is also responding by designing automobiles with coded parts so that they can be more easily disassembled (by professional recyclers) and recycled, rather than left to become rusting eyesores in junkyards.

On the consumer front, people are now more likely to purchase products that can be recycled or that come in containers that are more easily recycled or composted. Many consumers have purchased small home appliances that crush bottles and aluminum cans, reducing their volume and facilitating recycling. The entire arena is rapidly changing, and innovations and opportunities will undoubtedly continue.

As with many other environmental solutions, implementing the IWM concept successfully can be a complex undertaking. In some communities where recycling has been successful, it has resulted in glutted markets for recycled products, which has sometimes required temporarily stockpiling or suspending the recycling of some items. It is apparent that if recycling is to be successful, markets and processing facilities will also have to be developed to ensure that recycling is a sound financial venture as well as an important part of IWM.

Recycling of Human Waste

The use of human waste, or "night soil," on croplands is an ancient practice. In Asia, recycling of human waste has a long history. Chinese agriculture was sustained for thousands of years through collection of human waste, which was spread over agricultural fields. The practice grew, and by the early 20th century the land application of sewage was a primary disposal method in many metropolitan areas in countries including Mexico, Australia, and the United States.[27] Early uses of human waste for agriculture occasionally spread infectious diseases through bacteria, viruses, and parasites in waste applied to crops. Today, with the globalization of agriculture, we still see occasional warnings and outbreaks of disease from contaminated vegetables (see Chapter 19).

A major problem with recycling human waste is that, along with human waste, thousands of chemicals and metals flow through our modern waste stream. Even garden waste that is composted may contain harmful chemicals, such as pesticides.[27]

23.8 Municipal Solid-Waste Management

Municipal solid-waste management continues to be a problem in the United States and other parts of the world. In many areas, particularly in developing countries, waste-management practices are inadequate. These practices, which include poorly controlled open dumps and illegal roadside dumping, can spoil scenic resources, pollute soil and water, and pose health hazards.

Illegal dumping is a social problem as much as a physical one because many people are simply disposing of waste as inexpensively and as quickly as possible, perhaps not seeing their garbage as an environmental problem. If nothing else, this is a tremendous waste of resources, since much of what is dumped could be recycled or reused. In areas where illegal dumping has been reduced, the keys have been awareness, education, and alternatives. Education programs teach people about the environmental problems of unsafe, unsanitary dumping of waste, and funds are provided for cleanup and for inexpensive collection and recycling of trash at sites of origin.

We look next at the composition of solid waste in the United States and then go on to describe specific disposal methods: onsite disposal, composting, incineration, open dumps, and sanitary landfills.

Composition of Solid Waste

The average content of unrecycled solid waste likely to end up at a disposal site in the United States is shown in Figure 23.10. It is no surprise that paper is by far the most abundant component. However, considerable variation can be expected, based on factors such as land use, economic base, industrial activity, climate, and time of year.

People have many misconceptions about our waste stream.[28] With all the negative publicity about fast-food packaging, polystyrene foam, and disposable diapers, many people assume that these make up a large percentage of the waste stream and are responsible for the rapid filling of landfills. However, excavations into modern landfills using archaeological tools have cleared up some misconceptions. We now know that fast-food packaging accounts for only about 0.25% of the average landfill; disposable diapers, approximately 0.8%; and polystyrene products about 0.9%.[29] Paper is a major constituent in landfills, perhaps as much as 50% by volume and 40% by weight. The largest single item is newsprint, which accounts for as much as 18% by volume.[29] Newsprint is one of the major items targeted for recycling because big environmental dividends can be expected. However (and this is a value judgment), the need to deal with the major waste products doesn't mean that we need not cut down on our use of disposable diapers, polystyrene, and other paper products. In addition to creating a need for disposal, these products are made from resources that might be better managed.

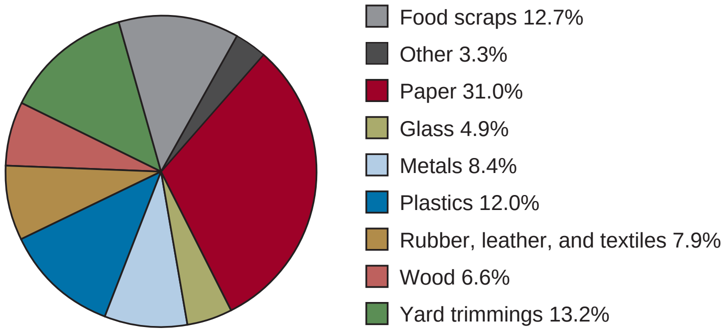


FIGURE 23.10 U.S. municipal solid-waste generation before recycling in 2008 was about 250 million tons, or about 4.6 lbs (2 kg) per person. (*Source*: Municipal solid waste generation, recycling, and disposal in the United States: facts and figures 2008_Basic Information 2009.www.epa.gov.)

Onsite Disposal

A common onsite disposal method in urban areas is the garbage-disposal device installed in the wastewater pipe under the kitchen sink to grind garbage and flush it into the sewer system. This effectively reduces the amount of handling and quickly removes food waste. What's left of it is transferred to sewage-treatment plants, where solids remaining as sewage sludge still must be disposed of.[30, 31]

Composting

Composting is a biochemical process in which organic materials, such as lawn clippings and kitchen scraps, decompose to a rich, soil-like material. The process involves rapid partial decomposition of moist solid organic waste by aerobic organisms. Although simple backyard compost piles may come to mind, large-scale composting as a waste-management option is generally carried out in the controlled environment of mechanical digesters. This technique is popular in Europe and Asia, where intense farming creates a demand for compost. However, a major drawback of composting is the necessity of separating organic material from other waste. Therefore, it is probably economically advantageous only where organic material is collected separately from other waste. Another negative is that composting plant debris previously treated with herbicides may produce a compost toxic to some plants. Nevertheless, composting is an important component of IWM, and its contribution continues to grow.[30, 31]

Incineration

Incineration burns combustible waste at temperatures high enough (900°–1,000°C, or 1,650°–1,830°F) to consume all combustible material, leaving only ash and noncombustibles to dispose of in a landfill. Under ideal conditions, incineration may reduce the volume of waste by 75–95%.[31] In practice, however, the actual decrease in volume is closer to 50% because of maintenance problems as well as waste-supply problems. Besides reducing a large volume of combustible waste to a much smaller volume of ash, incineration has another advantage: It can be used to supplement other fuels and generate electrical power.

Incineration of urban waste is not necessarily a clean process; it may produce air pollution and toxic ash. In the United States, for example, incineration is apparently a significant source of environmental dioxin, a carcinogenic toxin (see Chapter 10).[32] Smokestacks from incinerators also may emit oxides of nitrogen and sulfur, which lead to acid rain; heavy metals, such as lead, cadmium, and mercury; and carbon dioxide, which is related to global warming.

In modern incineration facilities, smokestacks fitted with special devices trap pollutants, but the process of pollutant abatement is expensive. The plants themselves are expensive, and government subsidization may be needed to aid in their establishment. Evaluation of the urban waste stream suggests that an investment of $8 billion could build enough incinerators in the United States to burn approximately 25% of the solid waste that is generated. However, a similar investment in source reduction, recycling, and composting could divert as much as 75% of the nation's urban waste stream away from landfills.[24]

The economic viability of incinerators depends on revenue from the sale of the energy produced by burning the waste. As recycling and composting increase, they will compete with incineration for their portion of the waste stream, and sufficient waste (fuel) to generate a profit from incineration may not be available. The main conclusion that can be drawn based on IWM principles is that a combination of reusing, recycling, and composting could reduce the volume of waste requiring disposal at a landfill by at least as much as incineration.[24]

Open Dumps (Poorly Controlled Landfills)

In the past, solid waste was often disposed of in open dumps (now called landfills), where refuse was piled up and left uncovered. Thousands of open dumps have been closed in recent years, and new open dumps are banned in the United States and many other countries. Nevertheless, many are still being used worldwide (Figure 23.11).[31]

Sanitary Landfills

A **sanitary landfill** (also called a municipal solid-waste landfill) is designed to concentrate and contain refuse without creating a nuisance or hazard to public health or safety. The idea is to confine the waste to the smallest practical area, reduce it to the smallest practical volume, and cover it with a layer of compacted soil at the end of each day of operation, or more frequently if necessary. Covering the waste is what makes the landfill sanitary. The compacted layer restricts (but does not eliminate) continued access to the waste by insects, rodents, and other animals, such as seagulls. It also isolates the refuse, minimizing the amount of surface water seeping into it and the amount of gas escaping from it.[33]

Leachate

The most significant hazard from a sanitary landfill is pollution of groundwater or surface water. If waste buried in a landfill comes into contact with water percolating down from the surface or with groundwater moving laterally through the refuse, **leachate**—noxious, mineralized liquid capable of transporting bacterial pollutants—is

FIGURE 23.11 Urban garbage dump in Rio de Janeiro, Brazil. At this site, people are going through the waste and recycling materials that can be reused or resold. This activity is all too common in dumps for large cities in the developing world. In some cases several thousand scavengers, including children, sift through tons of burning garbage to collect cans and bottles.

produced.[34] For example, two landfills dating from the 1930s and 1940s on Long Island, New York, have produced subsurface leachate trails (plumes) several hundred meters wide that have migrated kilometers from the disposal site. The nature and strength of the leachate produced at a disposal site depend on the composition of the waste, the amount of water that infiltrates or moves through the waste, and the length of time that infiltrated water is in contact with the refuse.[31]

Site Selection

The siting of a sanitary landfill is very important and must take into consideration a number of factors, including topography, location of the groundwater table, amount of precipitation, type of soil and rock, and location of the disposal zone in the surface water and groundwater flow system. A favorable combination of climatic, hydrologic, and geologic conditions helps to ensure reasonable safety in containing the waste and its leachate.[35] The best sites are in arid regions, where disposal conditions are relatively safe because little leachate is produced. In a humid environment, some leachate is always produced; therefore, an acceptable level of leachate production must be established to determine the most favorable sites in such environments. What is acceptable varies with local water use, regulations, and the ability of the natural hydrologic system to disperse, dilute, and otherwise degrade the leachate to harmless levels.

Elements of the most desirable site in a humid climate with moderate to abundant precipitation are shown in Figure 23.12. The waste is buried above the water table in relatively impermeable clay and silt that water cannot easily move through. Any leachate therefore remains in the vicinity of the site and degrades by natural filtering action and chemical reactions between clay and leachate.[36, 37]

Siting waste-disposal facilities also involves important social considerations. Often, planners choose sites where they expect minimal local resistance or where they perceive land to have little value. Waste-disposal facilities are frequently located in areas where residents tend to have low socioeconomic status or belong to a particular racial or ethnic group. The study of social issues in siting waste facilities, chemical plants, and other such facilities is an emerging field known as **environmental justice**.[38, 39]

Monitoring Pollution in Sanitary Landfills

Once a site is chosen for a sanitary landfill and before filling starts, monitoring the movement of groundwater should begin. Monitoring involves periodically taking samples of water and gas from specially designed monitoring wells. Monitoring the movement of leachate and gases should continue as long as there is any possibility of pollution and is particularly important after

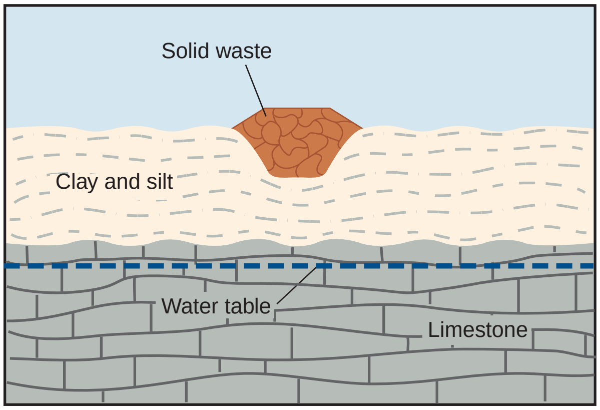


FIGURE 23.12 The most desirable landfill site in a humid environment. Waste is buried above the water table in a relatively impermeable environment. (*Source*: W.J. Schneider, *Hydraulic Implications of Solid-Waste Disposal*, U.S. Geological Survey Circular 601F, 1970.)

the site is completely filled and permanently covered. Continued monitoring is necessary because a certain amount of settling always occurs after a landfill is completed; and if small depressions form, surface water may collect, infiltrate, and produce leachate. Monitoring and proper maintenance of an abandoned landfill reduce its pollution potential.[33]

How Pollutants Can Enter the Environment from Sanitary Landfills

Pollutants from a solid-waste disposal site can enter the environment through as many as eight paths (Figure 23.13):[40]

1. Methane, ammonia, hydrogen sulfide, and nitrogen gases can be produced from compounds in the waste and the soil and can enter the atmosphere.
2. Heavy metals, such as lead, chromium, and iron, can be retained in the soil.
3. Soluble materials, such as chloride, nitrate, and sulfate, can readily pass through the waste and soil to the groundwater system.
4. Overland runoff can pick up leachate and transport it into streams and rivers.
5. Some plants (including crops) growing in the disposal area can selectively take up heavy metals and other toxic materials. These materials are then passed up the food chain as people and animals eat the plants.
6. If plant residue from crops left in fields contains toxic substances, these substances return to the soil.
7. Streams and rivers may become contaminated by waste from groundwater seeping into the channel (3) or by surface runoff (4).
8. Wind can transport toxic materials to other areas.

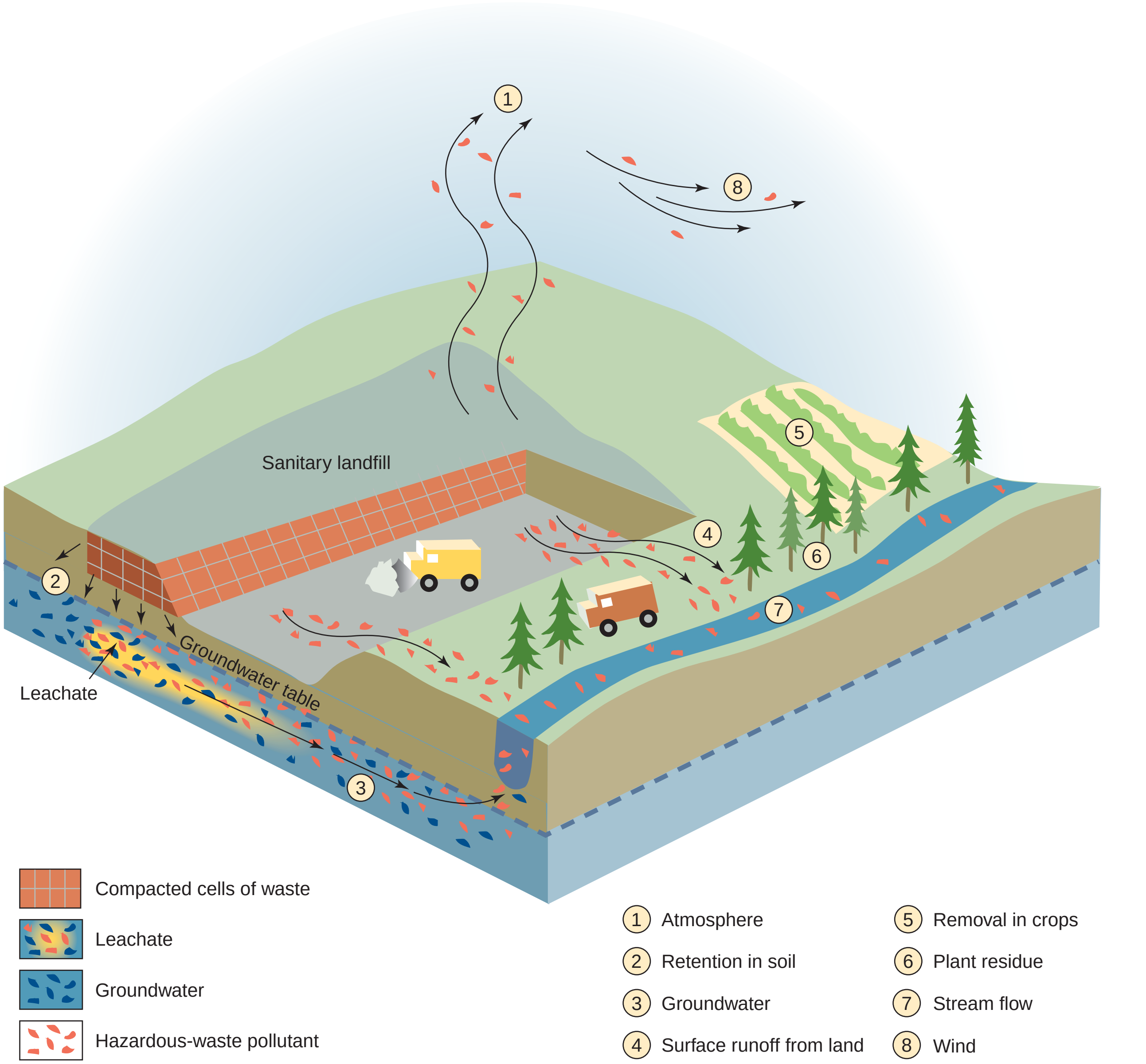


FIGURE 23.13 Idealized diagram showing eight paths that pollutants from a sanitary landfill site may follow to enter the environment.

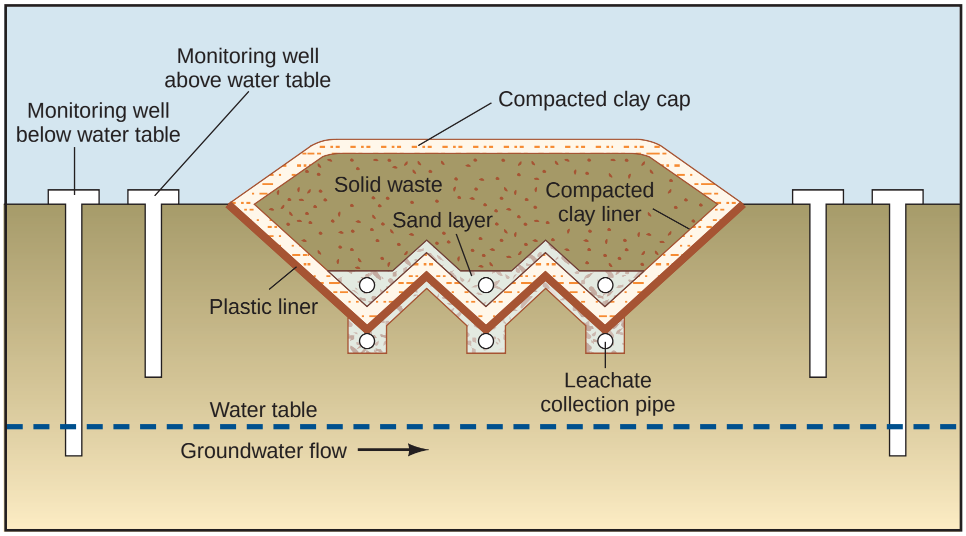
Modern sanitary landfills are engineered to include multiple barriers: clay and plastic liners to limit the movement of leachate; surface and subsurface drainage to collect leachate; systems to collect methane gas from decomposing waste; and groundwater monitoring to detect leaks of leachate below and adjacent to the landfill. A thorough monitoring program considers all eight possible paths by which pollutants enter the environment. In practice, however, monitoring seldom includes all pathways. It is particularly important to monitor the zone above the water table to identify potential pollution before it reaches and contaminates groundwater, where correction would be very expensive. Figure 23.14 shows (a) an idealized diagram of a landfill that uses the multiple-barrier approach and (b) a photograph of a landfill site under construction.

Federal Legislation for Sanitary Landfills

New landfills that opened in the United States after 1993 must comply with stricter requirements under the Resource Conservation and Recovery Act of 1980. The legislation, as its title states, is intended to strengthen and standardize the design, operation, and monitoring of sanitary landfills. Landfills that cannot comply with regulations face closure. However, states may choose between two options: (1) comply with federal standards or (2) seek EPA approval of solid-waste management plans.

The federal standards include the following:

- Landfills may not be sited on floodplains, wetlands, earthquake zones, unstable land, or near airports (birds drawn to landfill sites are a hazard to aircraft).



(a)

(b)

FIGURE 23.14 **(a)** Idealized diagram of a solid-waste facility (sanitary landfill) illustrating multiple-barrier design, monitoring system, and leachate collection system. **(b)** Rock Creek landfill under construction in Calaveras County, California. This municipal solid-waste landfill is underlain by a compacted clay liner, exposed in the center left portion of the photograph. The darker slopes, covered with gravel piles, overlie the compacted clay layer. These form a vapor barrier designed to keep moisture in the clay so it won't crack. Trenches at the bottom of the landfill are lined with plastic and are part of the leachate collection system for the landfill. The landfill is also equipped with a system to monitor the water below the leachate collection system.

- Landfills must have liners.
- Landfills must have a leachate collection system.
- Landfill operators must monitor groundwater for many specified toxic chemicals.
- Landfill operators must meet financial assurance criteria to ensure that monitoring continues for 30 years after the landfill is closed.

EPA approval of a state's landfill program allows greater flexibility:

- Groundwater monitoring may be suspended if the landfill operator can demonstrate that hazardous constituents are not migrating from the landfill.
- Alternative types of daily cover over the waste may be used.
- Alternative groundwater-protection standards are allowed.
- Alternative schedules for documentation of groundwater monitoring are allowed.
- Under certain circumstances, landfills in wetlands and fault zones are allowed.
- Alternative financial assurance mechanisms are allowed.

Given the added flexibility, it appears advantageous for states to develop EPA-approved waste-management plans.

Reducing the Waste that Ends Up in a Landfill

Most of the municipal solid waste we generate is from our homes, and over 50% of it could be diverted from the landfill by the 3 R's of waste management: reduce, reuse, and recycle. Diversion may eventually be increased to as much as 85% through improved waste management. In other words, the life of the landfill can be extended by keeping more waste out of the landfill through conservation and recycling, or by turning waste, even waste that is presently buried, into a source of clean energy. The latter involves first removing materials that can be recycled, then linking noncombustion thermal or biochemical processes with the

Table 23.2 ACTIONS YOU CAN TAKE TO REDUCE THE WASTE YOU GENERATE

Keep track of the waste you personally generate: Know how much waste you produce. This will make you conscious of how to reduce it.

Recycle as much as is possible and practical: Take your cans, glass, and paper to a recycling center or use curbside pickup. Take your hazardous materials such as batteries, cell phones, computers, paint, used oil, and solvents to a hazardous waste collection site.

Reduce packaging: Whenever possible buy your food items in bulk or concentrated form.

Use durable products: Choose automobiles, light bulbs, furniture, sports equipment, and tools that will last a longer time.

Reuse products: Some things may be used several times. For example, you can reuse boxes and shipping "bubble wrap" to ship packages.

Purchase products made from recycled material: Many bottles, cans, boxes, containers, cartons, carpets, clothing, floor tiles, and other products are made from recycled material. Select these whenever you can.

Purchase products designed for ease in recycling: Products as large as automobiles along with many other items are being designed with recycling in mind. Apply pressure to manufacturers to produce items that can be easily recycled.

Source: Modified from U.S. Environmental Protection Agency. Accessed April 21, 2006 at www.epa.gov.

remaining solid waste to produce electricity and alternative fuels (for example, biodiesel). The less waste in the landfill, the less potential for pollution of ground and surface water, along with the important fringe benefit of green energy.

The average waste per person in the United States increased from about 1 kg (2.2 lb) per day in 1960 to 2 kg (4.5 lb) per day in 2008. This is an annual growth rate of about 1.5% per year and is not sustainable because the doubling time for waste production is only a few decades. The 236 million tons we produced in 2003 would be close to 500 million tons by 2050, and we are already having big waste-management problems today. Table 23.2 lists some of the many ways you could reduce the waste you generate. What other ways can you think of?

23.9 Hazardous Waste

So far in this chapter we have discussed integrated waste management and materials management for the everyday waste stream from homes and businesses. We now consider the important topic of hazardous waste.

Creation of new chemical compounds has proliferated in recent years. In the United States, approximately 1,000 new chemicals are marketed each year, and about 70,000 chemicals are currently on the market. Although many have been beneficial to people, approximately 35,000 chemicals used in the United States are classified as definitely or potentially hazardous to people or ecosystems if they are released into the environment as waste—and unfortunately, a lot of it is.

The United States currently produces about 700 million metric tons of hazardous chemical waste per year, referred to more commonly as **hazardous waste**. About 70% of it is generated east of the Mississippi River, and about half of the total by weight is generated by chemical-products industries. The electronics industry (see A Closer Look 23.2 for discussion of e-waste) and petroleum and coal products industries each contribute about 10%.[41-43] Hazardous waste may also enter the environment when buildings are destroyed by events such as fires and hurricanes, releasing paints, solvents, pesticides, and other chemicals that were stored in them, or when debris from damaged buildings is later burned or buried. As a result, collection of such chemicals after natural disasters is an important goal in managing hazardous materials.

In the mid-20th century, as much as half the total volume of hazardous waste produced in the United States was indiscriminately dumped.[42] Some was illegally dumped on public or private lands, a practice called midnight dumping. Buried drums of illegally dumped hazardous waste have been discovered at hundreds of sites by contractors constructing buildings and roads. Cleanup has been costly and has delayed projects.[41]

The case of Love Canal is a well-known hazardous-waste horror story. In 1976, in a residential area near Niagara Falls, New York, trees and gardens began to die. Rubber on tennis shoes and bicycle tires disintegrated. Puddles of toxic substances began to ooze through the soil. A swimming pool popped from its foundation and floated in a bath of chemicals.

The story of Love Canal started in 1892 when William Love excavated a canal 8 km (5 mi) long as part of the development of an industrial park. The development didn't need the canal when inexpensive electricity arrived, so the uncompleted canal remained unused for decades

A CLOSER LOOK 23.2

"e-waste": A Growing Environmental Problem

Hundreds of millions of computers and other electronic devices—such as cell phones, iPods, televisions, and computers games—are discarded every year. The average life of a computer is about three years, and it is not manufactured with recycling in mind. That is changing in the United States. as the cost to recycle TV and computer screens is charged to their manufacturers.

When we take our electronic waste, called **e-waste**, to a location where computers are turned in, we assume that it will be handled properly, but this is too often not what happens. In the United States, which helped start the technology revolution and produces most of the e-waste, its eventual disposal may cause serious environmental problems. The plastic housing for computers, for example, may produce toxins when burned. Computer parts also have small amounts of heavy metals—including gold, tin, copper, cadmium, and mercury—that are harmful and may cause cancer if inhaled, ingested, or absorbed through the skin. At present, many millions of computers are disposed of by what is billed as recycling, but the EPA has no official process to ensure that this e-waste won't cause future problems. In fact, most of these computers are being exported under the label of "recycling" to countries such as Nigeria and China.

China's largest e-waste facility is in Guiyu, near Hong Kong. People in the Guiyu area process more than 1 million tons of e-waste each year with little thought to the potential toxicity of the material the workers are handling (Figure 23.15). In the United States, computers cannot be recycled profitably without charging the people who dump them a fee. Even with that, many U.S. firms ship their e-waste out of the country, where greater profits are possible. The revenue to the Guiyu area is about $1 million per year, so the central government is reluctant to regulate the activity. Workers at locations where computers are disassembled may be unaware that some of the materials they are handling are toxic and that they thus have a hazardous occupation. Altogether, in the Guiyu area, more than 5,000 family-run facilities specialize in scavenging e-waste for raw materials. While doing this, they are exposing themselves to a variety of toxins and potential health problems.

FIGURE 23.15 e-waste being processed in China—a hazardous occupation.

To date, the United States has not made a proactive attempt to regulate the computer industry so that less waste is produced. In fact, the United States is the only major nation that did not ratify an international agreement that restricts and bans exports of hazardous e-waste.[43]

Our current ways of handling e-waste are not sustainable, and the value we place on a quality environment should include the safe handling and recycling of such waste. Hopefully, that is the path we will take in the future. There are positive signs. Some companies are now processing e-waste to reclaim metals such as gold and silver. Others are designing computers that use less toxic materials and are easier to recycle. The European Union is taking a leadership role in requiring more responsible management of e-waste.

and became a dump for wastes. From 1920 to 1952, some 20,000 tons of more than 80 chemicals were dumped into the canal. In 1953 the Hooker Chemical Company—which produced the insecticide DDT as well as an herbicide and chlorinated solvents, and had dumped chemicals into the canal—was pressured to donate the land to the city of Niagara Falls for $1.00. The city knew that chemical wastes were buried there, but no one expected any problems. Eventually, several hundred homes and an elementary school were built on and near the site, and for years everything seemed fine. Then, in 1976–1977, heavy rains and snows triggered a number of events, making Love Canal a household word.[41]

A study of the site identified many substances suspected of being carcinogens, including benzene, dioxin, dichlorethylene, and chloroform. Although officials admitted that little was known about the impact of these chemicals, there was grave concern for people living in the area. Eventually, concern centered on alleged high rates of miscarriages, blood and liver abnormalities, birth defects, and chromosome damage. The government had to destroy about 200 homes and a school, and about 800 families were relocated and reimbursed. After about $400 million was spent on cleaning up the site, the EPA eventually declared the area clean, and about 280 remaining homes were sold.[44] Today, the community around the canal is known as Black Creek Village, and many people live there.

Uncontrolled or poorly controlled dumping of chemical waste has polluted soil and groundwater in several ways:

- In some places, chemical waste is still stored in barrels, either stacked on the ground or buried. The barrels may eventually corrode and leak, polluting surface water, soil, and groundwater.
- When liquid chemical waste is dumped into an unlined lagoon, contaminated water may percolate through soil and rock to the groundwater table.
- Liquid chemical waste may be illegally dumped in deserted fields or even along roads.

Some sites pose particular dangers. The floodplain of a river, for example, is not an acceptable site for storing hazardous waste. Yet, that is exactly what occurred at a site on the floodplain of the River Severn near a village in one of the most scenic areas of England. Several fires at the site in 1999 were followed by a large fire of unknown origin on October 30, 2000. Approximately 200 tons of chemicals, including industrial solvents (xylene and toluene), cleaning solvents (methylene chloride), and various insecticides and pesticides, produced a fireball that rose into the night sky (Figure 23.16). Wind gusts of hurricane strength spread toxic smoke and ash to nearby farmlands and villages, which had to be evacuated. People exposed to the smoke complained of a variety of symptoms, including headaches, stomachaches and vomiting, sore throats, coughs, and difficulty breathing.

A few days later, on November 3, the site flooded (Figure 23.17). The floodwaters interfered with cleanup after the fire and increased the risk of downstream contamination by waterborne hazardous wastes. In one small village, contaminated floodwaters apparently inundated farm fields, gardens, and even homes.[45] Of course, the solution to this problem is to clean up the site and move waste storage to a safer location.

23.10 Hazardous-Waste Legislation

Recognition in the 1970s that hazardous waste was a danger to people and the environment and that the waste was not being properly managed led to important federal legislation in the United States.

Resource Conservation and Recovery Act

Management of hazardous waste in the United States began in 1976 with passage of the Resource Conservation and Recovery Act (RCRA). At the heart of the act is identification of hazardous wastes and their life cycles. The idea was to issue guidelines and assign responsibilities to those who manufacture, transport, and dispose of hazardous waste. This

FIGURE 23.16 On October 30, 2000, fire ravaged a site on the floodplain of the River Severn in England where hazardous waste was being stored. Approximately 200 tons of chemicals burned.

FIGURE 23.17 Flooding on November 3, 2000, followed the large fire at a hazardous-waste storage site on the floodplain of the River Severn in England (see Figure 23.16 at left).

is known as "cradle-to-grave" management. Regulations require stringent record keeping and reporting to verify that the wastes are not a public nuisance or a health problem.

RCRA applies to solid, semisolid, liquid, and gaseous hazardous wastes. It considers a waste hazardous if its concentration, volume, or infectious nature may contribute to serious disease or death or if it poses a significant hazard to people and the environment as a result of improper management (storage, transport, or disposal).[41] The act classifies hazardous wastes in several categories: materials highly toxic to people and other living things; wastes that may ignite when exposed to air; extremely corrosive wastes; and reactive unstable wastes that are explosive or generate toxic gases or fumes when mixed with water.

Comprehensive Environmental Response, Compensation, and Liability Act

In 1980, Congress passed the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). It defined policies and procedures for release of hazardous substances into the environment (for example, landfill regulations). It also mandated development of a list of sites where hazardous substances were likely to produce or already had produced the most serious environmental problems and established a revolving fund (*Superfund*) to clean up the worst abandoned hazardous-waste sites. In 1984 and 1986, CERCLA was strengthened by amendments that made the following changes:

- Improved and tightened standards for disposal and cleanup of hazardous waste (for example, requiring double liners, monitoring landfills).
- Banned land disposal of certain hazardous chemicals, including dioxins, polychlorinated biphenyls (PCBs), and most solvents.
- Initiated a timetable for phasing out disposal of all untreated liquid hazardous waste in landfills or surface impoundments.
- Increased the Superfund. The fund was allocated about \$8.5 billion in 1986; Congress approved another \$5.1 billion for fiscal year 1998, which almost doubled the Superfund budget.[46]

The Superfund has had management problems, and cleanup efforts are far behind schedule. Unfortunately, the funds available are not sufficient to pay for decontaminating all targeted sites. Furthermore, present technology may not be sufficient to treat all abandoned waste-disposal sites; it may be necessary to simply try to confine waste at those sites until better disposal methods are developed. It seems apparent that abandoned disposal sites are likely to remain problems for some time to come.

Federal legislation has also changed the ways in which real estate business is conducted. For example, there are provisions by which property owners may be held liable for costly cleanup of hazardous waste on their property, even if they did not directly cause the problem. As a result, banks and other lending institutions might be held liable for release of hazardous materials by their tenants.

The Superfund Amendment and Reauthorization Act (SARA) of 1986 permits a possible defense against such liability if the property owner completed an **environmental audit** before purchasing the property. Such an audit involves studying past land use at the site, usually determined by analyzing old maps, aerial photographs, and reports. It may also involve drilling and sampling groundwater and soil to determine whether hazardous materials are present. Environmental audits are now completed routinely before purchasing property for development.[46]

In 1990 the U.S. Congress reauthorized hazardous-waste-control legislation. Priorities include:

- Establishing who is responsible (liable) for existing hazardous waste problems.
- When necessary, assisting in or providing funding for cleanup at sites identified as having a hazardous-waste problem.
- Providing measures whereby people who suffer damages from the release of hazardous materials are compensated.
- Improving the required standards for disposal and cleanup of hazardous waste.

23.11 Hazardous-Waste Management: Land Disposal

Management of hazardous chemical waste involves several options, including recycling; onsite processing to recover by-products that have commercial value; microbial breakdown; chemical stabilization; high-temperature decomposition; incineration; and disposal by **secure landfill** (Figure 23.18) or deep-well injection. A number of technological advances have been made in toxic-waste management; as land disposal becomes more expensive, the recent trend toward onsite treatment is likely to continue. However, onsite treatment will not eliminate all hazardous chemical waste; disposal of some waste will remain necessary.

Table 23.3 compares hazardous "waste" reduction technologies for treatment and disposal. Notice that all available technologies cause some environmental disruption. There is no simple solution for all waste-management issues.

Table 23.3 COMPARISON OF HAZARD REDUCTION TECHNOLOGIES

	DISPOSAL		TREATMENT			
PARAMETER COMPARED	**LANDFILLS AND IMPOUNDMENTS**	**INJECTION WELLS**	**INCINERATION AND OTHER THERMAL DESTRUCTION**	**HIGH-TEMPERATURE DECOMPOSITION[a]**	**CHEMICAL STABILIZATION**	**MICROBIAL BREAKDOWN**
Effectiveness: how well it contains or destroys hazardous characteristics	Low for volatiles, high for unsoluble solids	High, for waste compatible with the disposal environment	High	High for many chemicals	High for many metals	High for many metals and some organic waste such as oil
Reliability issues	Siting, construction, and operation Uncertainties: long-term integrity and cover	Site history and geology, well depth, construction, and operation	Monitoring uncertainties with respect to high degree of DRE: surrogate measures, PICs, incinerability[b]	Mobile units; on-site treament avoids hauling risks Operational simplicity	Some inorganics still soluble Uncertain leachate production	Monitoring uncertainties during construction and operation
Environment media most affected	Surface water and groundwater	Surface water and groundwater	Air	Air	Groundwater	Soil, groundwater
Least compatible wastes[c]	Highly toxic, persistent chemicals	Reactive; corrosive; highly toxic, mobile, and persistent	Highly toxic organics, high heavy-metal concentration	Some inorganics	Organics	Highly toxic persistent chemicals
Relative costs	Low to moderate	Low	Moderate to high	Moderate to high	Moderate	Moderate
Resource recovery potential	None	None	Energy and some acids	Energy and some metals	Possible building materials	Some metals

[a]Molten salt, high-temperature fluid well, and plasma arc treatments.

[b]DRE=destruction and removal efficiency; PIC = product of incomplete combustion.

[c]Wastes for which this method may be less effective for reducing exposure, relative to other technologies. Wastes listed do not necessarily denote common usage.

Source: Modified after Council on Environmental Quality, 1983.

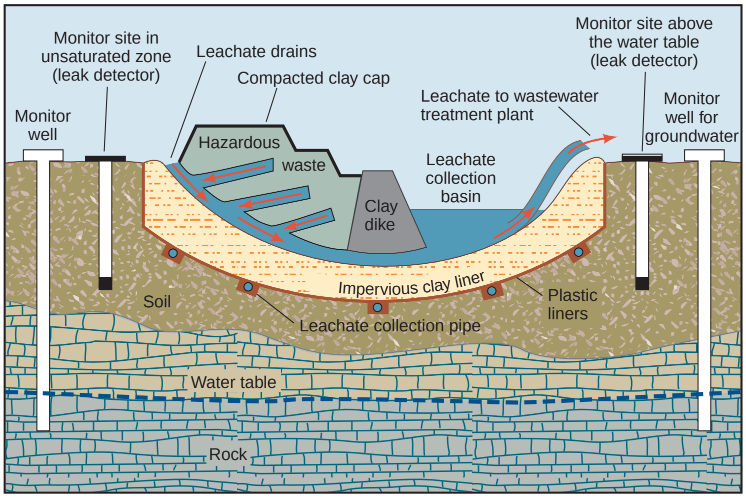


FIGURE 23.18 A secure landfill for hazardous chemical waste. The impervious liners, systems of drains, and leak detectors are integral parts of the system to ensure that leachate does not escape from the disposal site. Monitoring in the unsaturated zone is important and involves periodic collection of soil water.

Direct land disposal of hazardous waste is often not the best initial alternative. The consensus is that even with extensive safeguards and state-of-the-art designs, land disposal alternatives cannot guarantee that the waste will be contained and will not cause environmental disruption in the future. This concern holds true for all land disposal facilities, including landfills, surface impoundments, land application, and injection wells. Pollution of air, land, surface water, and groundwater may result if a land disposal site fails to contain hazardous waste. Pollution of groundwater is perhaps the most significant risk because groundwater provides a convenient route for pollutants to reach people and other living things.

Some of the paths that pollutants may take from land disposal sites to contaminate the environment include leakage and runoff to surface water or groundwater from improperly designed or maintained landfills; seepage, runoff, or air emissions from unlined lagoons; percolation and seepage from failure of surface land application of waste to soils; leaks in pipes or other equipment associated with deep-well injection; and leaks from buried drums, tanks, or other containers.[47-50]

23.12 Alternatives to Land Disposal of Hazardous Waste

Our handling of hazardous chemical waste should be multifaceted. In addition to the disposal methods just discussed, chemical-waste management should include such processes as source reduction, recycling and resource recovery, treatment, and incineration. Recently, it has been argued that these alternatives to land disposal are not being used to their full potential—that is, the volume of waste could be reduced, and the remaining waste could be recycled or treated in some form prior to land disposal of the treatment residues.[51] The advantages of source reduction, recycling, treatment, and incineration include the following:

- Useful chemicals can be reclaimed and reused.
- Treatment may make wastes less toxic and therefore less likely to cause problems in landfills.
- The volume of waste that must eventually be disposed of is reduced.
- Because a reduced volume of waste is finally disposed of, there is less stress on the dwindling capacity of waste-disposal sites.

Although some of the following techniques have been discussed as part of integrated waste management, they have special implications and complications in regard to hazardous wastes.

Source Reduction

The object of source reduction in hazardous-waste management is to reduce the amount of hazardous waste generated by manufacturing or other processes. For example, changes in the chemical processes involved, equipment and raw materials used, or maintenance measures may successfully reduce the amount or toxicity of hazardous waste produced.[51]

Recycling and Resource Recovery

Hazardous chemical waste may contain materials that can be recovered for future use. For example, acids and solvents collect contaminants when they are used in manufacturing processes. These acids and solvents can be processed to remove the contaminants and then be reused in the same or different manufacturing processes.[51]

Treatment

Hazardous chemical waste can be treated by a variety of processes to change its physical or chemical composition and reduce its toxicity or other hazardous characteristics. For example, acids can be neutralized, heavy metals can be separated from liquid waste, and hazardous chemical compounds can be broken up through oxidation.[51]

Incineration

High-temperature incineration can destroy hazardous chemical waste. However, incineration is considered a waste treatment, not a disposal method, because the process produces an ash residue that must itself be disposed of in a landfill. Hazardous waste has also been incinerated offshore on ships, creating potential air pollution and ash-disposal problems in the marine environment—an environment we consider next.

23.13 Ocean Dumping

Oceans cover more than 70% of Earth. They play a part in maintaining our global environment and are of major importance in the cycling of carbon dioxide, which helps regulate the global climate. Oceans are also important in cycling many chemical elements important to life, such as nitrogen and phosphorus, and are a valuable resource because they provide us with such necessities as food and minerals.

It seems reasonable that such an important resource would receive preferential treatment, and yet oceans have long been dumping grounds for many types of waste, including industrial waste, construction debris, urban sewage, and plastics (see A Closer Look 23.3). Ocean dumping contributes to the larger problem of ocean pollution, which has seriously damaged the marine environment and caused a health hazard. Figure 23.19 shows locations in the oceans of the world that are accumulating pollution continuously, or have intermittent pollution problems, or have potential for pollution from ships in the major shipping lanes. Notice that the areas with continual or intermittent pollution are near the shore.

Unfortunately, these are also areas of high productivity and valuable fisheries. Shellfish today often contain organisms that cause diseases such as polio and hepatitis. In the United States, at least 20% of the nation's commercial shellfish beds have been closed (mostly temporarily) because of pollution. Beaches and bays have been closed (again, mostly temporarily) to recreational uses. Lifeless zones in the marine environment have been created. Heavy kills of fish and other organisms have occurred, and profound changes in marine ecosystems have taken place (see Chapter 22).[52, 53]

Marine pollution has a variety of specific effects on oceanic life, including the following:

- Death or retarded growth, vitality, and reproductivity of marine organisms.
- Reduction of dissolved oxygen necessary for marine life, due to increased biochemical oxygen demand.
- Eutrophication caused by nutrient-rich waste in shallow estuaries, bays, and parts of the continental shelf, resulting in oxygen depletion and subsequent killing of algae, which may wash up and pollute coastal areas. (See Chapter 19 for a discussion of eutrophication in the Gulf of Mexico.)
- Habitat change caused by waste-disposal practices that subtly or drastically change entire marine ecosystems.[52]

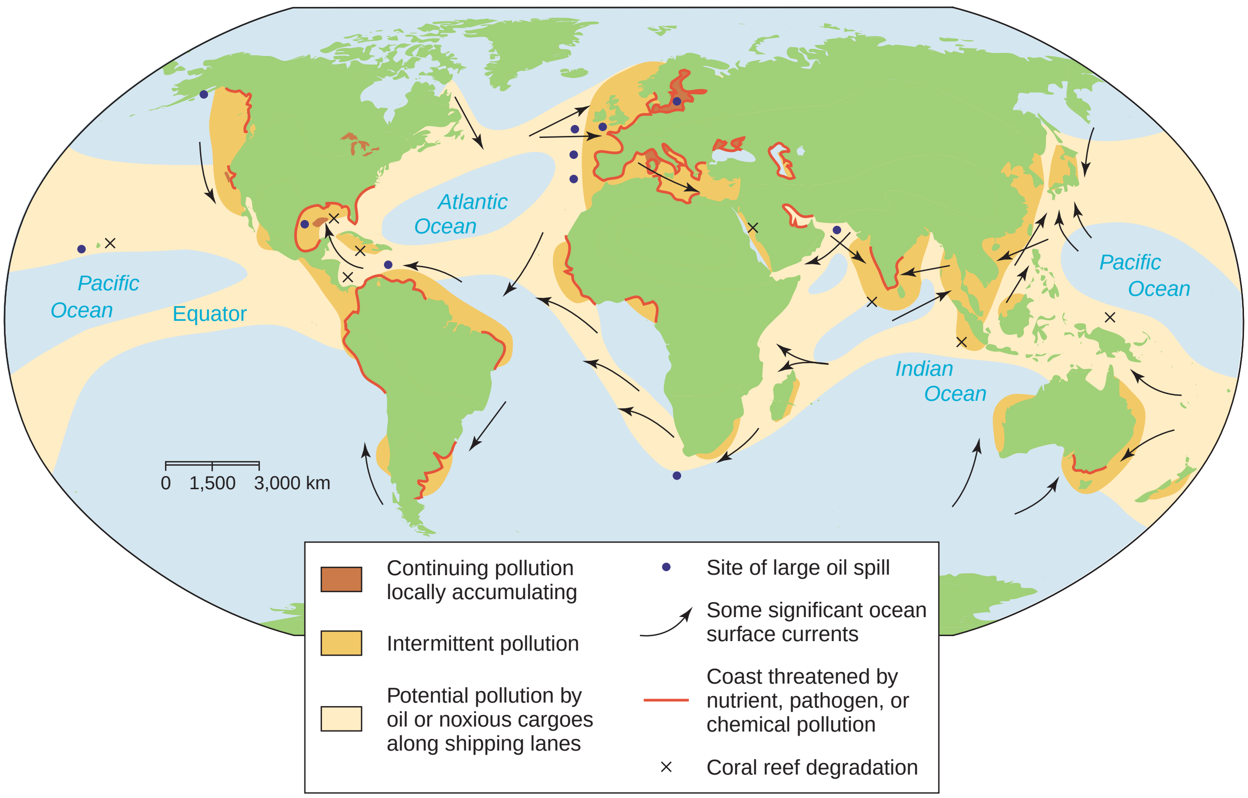


FIGURE 23.19 Ocean pollution of the world. Notice that the areas of continuing and locally accumulating pollution, as well as the areas with intermittent pollution, are in nearshore environments. (*Source*: Modified from the Council on Environmental Quality, *Environmental Trends*, 1981, with additional data from A.P. McGinn, "Safeguarding the Health of the Oceans," WorldWatch Paper 145 [Washington, DC: WorldWatch Institute, 1999], pp. 22–23.)

A CLOSER LOOK 23.3

Plastics in the Ocean

Vast quantities of plastic are used for a variety of products, ranging from beverage containers to cigarette lighters. For decades, people have been dumping plastics into the oceans. Some are dumped by passengers from passing ships; others are dropped as litter along beaches and swept into the water by the tides. Once in the ocean, plastics that float move with the currents and tend to accumulate where currents converge, concentrating the debris. Convergent currents of the Pacific (Figure 23.20) have a whirlpool-like action that concentrates debris near the center of these zones. One such zone is north of the equator, near the northwestern Hawaiian Islands. These islands are so remote that most people would expect them to be unspoiled, even pristine. In fact, however, there are literally hundreds of tons of plastics and other types of human debris on these islands. Recently, the National Oceanographic and Atmospheric Administration collected more than 80 tons of marine debris on Pearl and Hermes Atolls. Plastic debris is also widespread throughout the western North Atlantic Ocean. In the large North Atlantic subtropical gyre about 1200 km (750 mi) in diameter, centered about 1000 km (625 mi) east of Florida.[54] Most plastic is small fragments of a few mm up to about 1/2 size of a penny, and apparently is being digested by microbes.

The island ecosystems include sea turtles, monk seals, and a variety of birds, including albatross. Marine scientist Jean-Michel Cousteau and his colleagues have been studying the problem of plastics on the northwestern Hawaiian Islands, including Midway Island and Kure Atoll. They reported that the beaches of some of the islands and atolls look like a "recycling bin" of plastics. They found numerous cigarette lighters, some with fuel still in them, as well as caps from plastic bottles and all kinds of plastic toys and other debris. Birds on the islands pick up the plastic, attracted to it but not knowing what it is, and eat it. Figure 23.21 shows a dead albatross with debris in its stomach that caused its death. Plastic rings from a variety of products are also ingested by sea turtles and have been found around the snouts of seals, causing them to starve to death. In some areas, the carcasses of albatrosses litter the shorelines.

The solution to the problem is to be more careful about recycling plastic products to ensure they do not enter the marine environment. Collecting plastic items that accumulate on beaches is a step in the right direction, but it is a reactive response. Better to be proactive and reduce the source of the pollution.

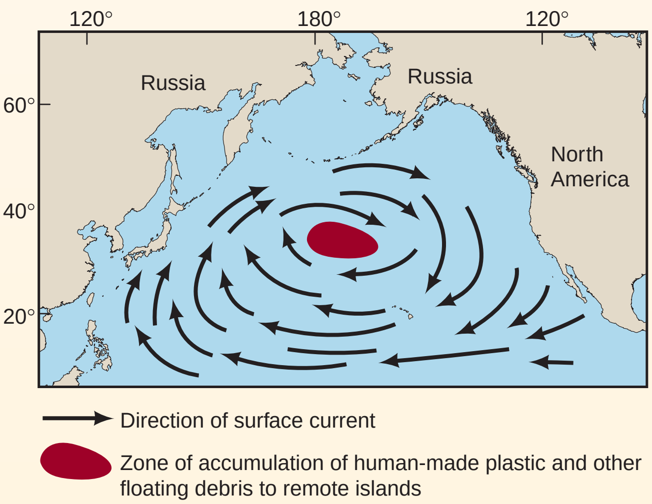


FIGURE 23.20 General circulation of the North Pacific Ocean. Arrows show the direction of the currents. Notice the tightening clockwise spiral pattern that carries floating debris to remote islands.

FIGURE 23.21 Albatross killed on a remote Pacific island by ingesting a large volume of plastic and other debris delivered by ocean currents. The photograph is not staged—the bird actually ingested all the plastic shown!

Marine waters of Europe are in particular trouble, in part because urban and agricultural pollutants have raised concentrations of nutrients in seawater. Blooms (heavy, sudden growth) of toxic algae are becoming more common. For example, in 1988 a bloom was responsible for killing nearly all marine life to a depth of about 15 m (50 ft), in the waterway connecting the North Sea to the Baltic Sea. It is believed that urban waste and agricultural runoff contributed to the toxic bloom.

Although oceans are vast, they are basically giant sinks for materials from continents, and parts of the marine environment are extremely fragile.[53] One area of concern is the *microlayer*, the upper 3 mm of ocean water. The base of the marine food chain consists of planktonic life abundant in the microlayer, and the young of certain fish and shellfish also reside there in the early stages of their life. Unfortunately, these upper few millimeters of the ocean also tend to concentrate pollutants, such as toxic chemicals and heavy metals. One study reported that concentrations of heavy metals—including zinc, lead, and copper—in the microlayer are from 10 to 1,000 times higher than in the deeper waters. It is feared that disproportionate pollution of the microlayer will have especially serious effects on marine organisms.[53] There is also concern that ocean pollution is a threat to some marine ecosystems, such as coral reefs, estuaries. salt marshes, and mangrove swamps.

Marine pollution can also have major impacts on people and society. Contaminated marine organisms, as we mentioned, may transmit toxic elements or diseases to people who eat them. In addition, beaches and harbors polluted by solid waste, oil, and other materials may not only damage marine life but also lose their visual appeal and other amenities. Economic loss is considerable as well. Loss of shellfish from pollution in the United States, for example, amounts to many millions of dollars per year. A great deal of money also is spent cleaning up solid waste, liquid waste, and other pollutants in coastal areas.[51]

23.14 Pollution Prevention

Approaches to waste management are changing. During the first several decades of environmental concern and management (the 1970s and 1980s), the United States approached the problem through government regulations and waste-control measures: chemical, physical, or biological treatment and collection (for eventual disposal), or transformation or destruction of pollutants after they had been generated. This was considered the most cost-effective approach to waste management.

With the 1990s came a growing emphasis on **pollution prevention—**ways to stop generating so much waste, rather than ways to dispose of it or manage it. This approach, which is part of materials management, includes the following:[55]

- Purchasing the proper amount of raw materials so that no excess remains to be disposed of.
- Exercising better control of materials used in manufacturing processes so that less waste is produced.
- Substituting nontoxic chemicals for hazardous or toxic materials currently used.
- Improving engineering and design of manufacturing processes so less waste is produced.

These approaches are often called P-2 approaches, for "pollution prevention." Probably the best way to illustrate the P-2 process is through a case history.[55]

A Wisconsin firm that produced cheese was faced with the disposal of about 2,000 gallons a day of a salty solution generated during the cheese-making process. Initially, the firm spread the salty solution on nearby agricultural lands—common practice for firms that could not discharge wastewater into publicly owned treatment plants. This method of waste disposal, when done incorrectly, caused the level of salts in the soil to rise so much that it damaged crops. As a result, the Department of Natural Resources in Wisconsin placed limitations on this practice.

The cheese firm decided to modify its cheese-making processes to recover salt from the solution and reuse it in production. This involved developing a recovery process that used an evaporator. The recovery process reduced the salty waste by about 75% and at the same time reduced the amount of the salt the company had to purchase by 50%. The operating and maintenance costs for recovery were approximately 3 cents per pound of salt recovered, and the extra cost of the new equipment was recovered in only two months. The firm saved thousands of dollars a year by recycling its salt.

The case history of the cheese firm suggests that rather minor changes can often result in large reductions of waste produced. And this case history is not an isolated example. Thousands of similar cases exist today as we move from the era of recognizing environmental problems, and regulating them at a national level, to providing economic incentives and new technology to better manage materials.[55]

23.15 Sustainable Resource Management

Sustaining renewable resources, such as water, wildlife, crops, and forests, though complex and sometimes difficult to achieve, is fairly easy to understand. Management of the environment must include development of goals and procedures to ensure that what makes a particular resource renewable persists over the long term (numerous generations). We have devoted several chapters in this book to sustainability with respect to renewable resources (water, air, energy, crops, forests, fish, and wildlife). However, simultaneously considering sustainable development and mineral exploitation and use is problematic. This is because, even with the most careful use, nonrenewable mineral resources will eventually be used up, and sustainability is a long-term concept that requires finding ways to assure future generations a fair share of Earth's resources. Recently, it has been argued that, given human ingenuity and sufficient lead time, we can find solutions for sustainable development that incorporate nonrenewable mineral resources.

Human ingenuity is important because often it is not the mineral we need so much as what we use the mineral for. For example, we mine copper and use it to transmit electricity in wires or electronic pulses in telephone wires. It is not the copper itself we desire but the properties of copper that allow these transmissions. We can use fiberglass cables in telephone wires, eliminating the need for copper. Digital cameras have eliminated the need for film development that uses silver. The message is that it is possible to compensate for a nonrenewable mineral by finding new ways to do things. We are also learning that we can use raw mineral materials more efficiently. For example, in the late 1800s when the Eiffel Tower was constructed, 8,000 metric tons of steel were used. Today the tower could be built with only a quarter of that amount.[56]

Finding substitutes or ways to more efficiently use nonrenewable resources generally requires several decades of research and development. A measure of how much time we have for finding solutions to the depletion of nonrenewable reserves is the ***R*-to-*C* ratio**, where *R* is the known reserves (for example, hundreds of thousands of tons of a metal) and *C* is the rate of consumption (for example, thousands of tons per year used by people). The *R*-to-*C* ratio is often misinterpreted as the time a reserve will last at the present rate of consumption. During the past 50 years, the *R*-to-*C* ratios for metals, such as zinc and copper, have fluctuated around 30 years. During that time, consumption of the metals roughly tripled, but we discovered new deposits. Although the *R*-to-*C* ratio is a *present* analysis of a dynamic system in which both the amount of reserves and consumption may change over time, it does provide a view of how scarce a particular mineral resource may be. Metals with relatively small ratios can be viewed as being in short supply, and it is those resources for which we should find substitutes through technological innovation.[56]

In sum, we may approach sustainable development and use of nonrenewable mineral resources by developing more efficient ways of mining resources and finding ways to more efficiently use available resources, recycling more and applying human ingenuity to find substitutes for a nonrenewable mineral.

CRITICAL THINKING ISSUE

Can We Make Recycling a More Financially Viable Industry?

There is enthusiastic public support for recycling in the United States today. Many people understand that managing our waste has many advantages to society as a whole and the environment in particular. People like the notion of recycling because they correctly assume they are helping to conserve resources, such as forests, that make up much of the nonurban environment of the planet. Large cities from New York to Los Angeles have initiated recycling programs, but many people are concerned that recycling is not yet "cost-effective."

To be sure, there are success stories, such as a large urban paper mill on New York's Staten Island that recycles more than 1,000 tons of paper per day. It is claimed that this paper mill saves more than 10,000 trees a day and uses only about 10% of the electricity required to make paper from virgin wood processing. On the West Coast, San Francisco has an innovative and ambitious recycling program that diverts nearly 50% of the urban waste from landfills to recycling programs. The city is even talking about the concept of zero waste, hoping to achieve total recycling of waste by 2020. In part, this is achieved by instigating a "pay-as-you-throw-away" approach; businesses and individuals are charged for disposal of garbage but not for materials that are recycled. Materials from the waste of the San Francisco urban area are shipped as far away as China and the Philippines to be recycled into usable products; organic waste is sent to agricultural areas; and metals, such as aluminum, are sent around California and to other states where they are recycled.

To understand some of the issues concerning recycling and its cost, consider the following points:

- The average cost of disposal at a landfill is about $40/ton in the United States, and even at a higher price of about $80/ton it may be cheaper than recycling.
- Landfill fees in Europe range from $200 to $300/ton.
- Europe has been more successful in recycling, in part because countries such as Germany hold manufacturers responsible for disposing of the industrial goods they produce, as well as the packaging.
- In the United States, packaging accounts for approximately one-third of all waste generated by manufacturing.
- The cost to cities such as New York, which must export their waste out of state, is steadily rising and is expected to exceed the cost of recycling within about ten years.
- Placing a 10-cent refundable deposit on all beverage containers except milk would greatly increase the number recycled. For example, states with a deposit system have an average recycling rate of about 70–95% of bottles and cans, whereas states that do not have a refundable-deposit system average less than 30%.
- When people have to pay for trash disposal at a landfill, but are not charged for materials that are recycled—such as paper, plastic, glass, and metals—the success of recycling is greatly enhanced.
- Beverage companies do not particularly favor requiring a refundable deposit for containers. They claim that the additional costs would be several billion dollars, but do agree that recovery rates would be higher, providing a steadier supply of recycled metal, such as aluminum, as well as plastic.
- Education is a big issue with recycling. Many people still don't know which items are recyclable and which are not.
- Global markets for recyclable materials, such as paper and metals, have potential for expansion, particularly for large urban areas on the seacoast, where shipping materials is economically viable. Recycling in the United States today is a $14 billion industry; and if it is done right, it generates new jobs and revenue for participating communities.
- The economic downturn since 2004 has resulted in much lower prices for recycled materials, such as paper, and even aluminum. The drop in demand for recycled materials in 2009 was global.

Critical Thinking Questions

1. What can be done about the global problem of e-waste? Could more be recycled safely?
2. What can be done to help recycling industries become more cost-effective?
3. What are some of the indirect benefits to society and the environment from recycling?
4. Defend or criticize the contention that if we really want to improve the environment by reducing our waste, we have to focus on more than the fact that recycling waste may cost more than dumping it at a landfill.
5. What are the recycling efforts in your community and university, and how could they be improved?
6. Do you think the global economic downturn since 2004 will cause a permanent problem for the recycling industry? Why? Why not?

SUMMARY

- Mineral resources are usually extracted from naturally occurring, anomalously high concentrations of Earth materials. Such natural deposits allowed early peoples to exploit minerals while slowly developing technological skills.
- Mineral resources are not mineral reserves. Unless discovered and developed, resources cannot be used to ease present shortages.
- The availability of mineral resources is one measure of the wealth of a society. Modern technological civilization would not be possible without the exploitation of mineral resources. However, it is important to recognize that mineral deposits are not infinite and that we cannot maintain exponential population growth on a finite resource base.
- The United States and many other affluent nations rely on imports for their supplies of many minerals. As other nations industrialize and develop, such imports may be more difficult to obtain, and affluent countries may have to find substitutes for some minerals or use a smaller portion of the world's annual production.

- The mining and processing of minerals greatly affect the land, water, air, and biological resources and have social impacts as well, including increased demand for housing and services in mining areas.
- Sustainable development and use of nonrenewable resources are not necessarily incompatible. Reducing consumption, reusing, recycling, and finding substitutes are environmentally preferable ways to delay or alleviate possible crises caused by the convergence of a rapidly rising population and a limited resource base.
- The history of waste-disposal practices since the Industrial Revolution has progressed from dilution and dispersion to the concept of integrated waste management (IWM), which emphasizes the three R's: reducing waste, reusing materials, and recycling.
- One goal of the emerging concept of industrial ecology is a system in which the concept of waste doesn't exist because waste from one part of the system would be a resource for another part.
- The most common way to dispose of solid waste is the sanitary landfill. However, around many large cities, space for landfills is hard to find, partly because few people wish to live near a waste-disposal site.
- Hazardous chemical waste is one of the most serious environmental problems in the United States. Hundreds or even thousands of abandoned, uncontrolled disposal sites could be time bombs that will eventually cause serious public health problems. We know that we will continue to produce some hazardous chemical waste. Therefore, it is imperative that we develop and use safe ways to dispose of it.
- Ocean dumping is a significant source of marine pollution. The most seriously affected areas are near shore, where valuable fisheries often exist.
- Pollution prevention (P-2)—identifying and using ways to prevent the generation of waste—is an important emerging area of materials management.

REEXAMINING THEMES AND ISSUES

Human Population

Materials-management strategies are inextricably linked to the human population. As the population increases, so does the waste generated. In developing countries where population increase is the most dramatic, increases in industrial output, when linked to poor environmental control, produce or aggravate waste-management problems.

Sustainability

Assuring a quality environment for future generations is closely linked to materials management. Of particular importance here are the concepts of integrated waste management, materials management, and industrial ecology. Carried to their natural conclusion, the ideas behind these concepts would lead to a system in which the issue would no longer be waste management but instead resource management. Pollution prevention (P-2) is a step in this direction.

Global Perspective

Materials management is becoming a global problem. Improper management of materials contributes to air and water pollution and can cause environmental disruption on a regional or global scale. For example, waste generated by large inland cities and disposed of in river systems may eventually enter the oceans and be dispersed by the global circulation patterns of ocean currents. Similarly, soils polluted by hazardous materials may erode, and the particles may enter the atmosphere or water system, to be dispersed widely.

Urban World

Because so much of our waste is generated in the urban environment, cities are a focus of special attention for materials management. Where population densities are high, it is easier to implement the principles behind "reduce, reuse, and recycle." There are greater financial incentives for materials management where waste is more concentrated.

People and Nature

Production of waste is a basic process of life. In nature, waste from one organism is a resource for another. Waste is recycled in ecosystems as energy flows and chemicals cycle. As a result, the concept of waste in nature is much different than that in the human waste stream. In the human system, waste may be stored in facilities such as landfills, where it may remain for long periods, far from natural cycling. Our activities to recycle waste or burn it for energy move us closer to transforming waste into resources. Converting waste into resources brings us closer to nature by causing urban systems to operate in parallel with natural ecosystems.

Science and Values

People today value a quality, pollution-free environment. The way materials have been managed continues to affect health and other environmental problems. An understanding of these problems has resulted in a considerable amount of work and research aimed at reducing or eliminating the impact of resource use. How a society manages its waste is a sign of the maturity of the society and its ethical framework. Accordingly, we have become more conscious of environmental justice issues related to materials management.

KEY TERMS

composting **532**
environmental audit **540**
environmental justice **534**
e-waste **538**
hazardous waste **537**
incineration **533**
industrial ecology **530**
integrated waste management (IWM) **530**
leachate **533**
materials management **522**
nonrenewable resources **521**
ore deposits **523**
pollution prevention **545**
R-to-*C* ratio **546**
renewable resources **521**
reserves **524**
resources **524**
sanitary landfill **533**
secure landfill **540**
single-stream recycling **531**

STUDY QUESTIONS

1. What is the difference between a resource and a reserve?
2. Under what circumstances might sewage sludge be considered a mineral resource?
3. If surface mines and quarries cover less than 0.5% of the land surface of the United States, why is there so much environmental concern about them?
4. A deep-sea diver claims that the oceans can provide all our mineral resources with no negative environmental effects. Do you agree or disagree?
5. What factors determine the availability of a mineral resource?
6. Using a mineral resource involves four general phases: (a) exploration, (b) recovery, (c) consumption, and (d) disposal of waste. Which phase do you think has the greatest environmental effect?
7. Have you ever contributed to the hazardous-waste problem through disposal methods used in your home, school laboratory, or other location? How big a problem do you think such events are? For example, how bad is it to dump paint thinner down a drain?
8. Why is it so difficult to ensure safe land disposal of hazardous waste?
9. Would you approve the siting of a waste-disposal facility in your part of town? If not, why, and where do you think such facilities should be?
10. Why might there be a trend toward onsite disposal rather than land disposal of hazardous waste? Consider the physical, biological, social, legal, and economic aspects of the question.
11. Considering how much waste has been dumped in the nearshore marine environment, how safe is it to swim in bays and estuaries near large cities?

12. Do you think we should collect household waste and burn it in special incinerators to make electrical energy? What problems and what advantages do you see for this method, compared with other waste-management options?
13. Should companies that dumped hazardous waste years ago, when the problem was not understood or recognized, be held liable today for health problems to which their dumping may have contributed?
14. Suppose you found that the home you had been living in for 15 years was atop a buried waste-disposal site. What would you do? What kinds of studies should be done to evaluate potential problems?

FURTHER READING

Allenby, B.R., ***Industrial Ecology: Policy Framework and Implementation*** (Upper Saddle River, NJ: Prentice Hall, 1999). A primer on industrial ecology.

Ashley, S., It's not easy being green. ***Scientific American***, April 2002, pp. 32–34. A look at the economics of developing biodegradable products and a little of the chemistry involved.

Brookins, D.G., ***Mineral and Energy Resources*** (Columbus, Ohio: Charles E. Merrill, 1990). A good summary of mineral resources.

Kesler, S.F., ***Mineral Resources, Economics and the Environment*** (Upper Saddle River, NJ: Prentice Hall, 1994). A good book about mineral resources.

Kreith, F. ed., ***Handbook of Solid Waste Management*** (New York: McGraw-Hill, 1994). Thorough coverage of municipal waste management, including waste characteristics, federal and state legislation, source reduction, recycling, and landfilling.

Watts, R.J., ***Hazardous Wastes*** (New York: John Wiley, 1998). A to Z of hazardous wastes.

CHAPTER 24

Our Environmental Future

The *Deepwater Horizon* oil drilling platform on fire April 22, 2010. Eleven workers were killed.

LEARNING OBJECTIVES

The learning objectives of this final chapter are to put it all together and then ask yourself the following questions:

- How can we take what we have learned and apply it to improving the environment?
- How can we think about a future in which we use our environment wisely—an "ecotopia"?
- Can we do this in a way that is good for people, human societies, and for nature?
- Will our environmental future "self-organize," or will it require more laws and formal planning?
- How have environmental laws affected people and environment, and what guidance does that experience provide for us in planning the future?

CASE STUDY

The Oil Spill in the Gulf of Mexico in 2010

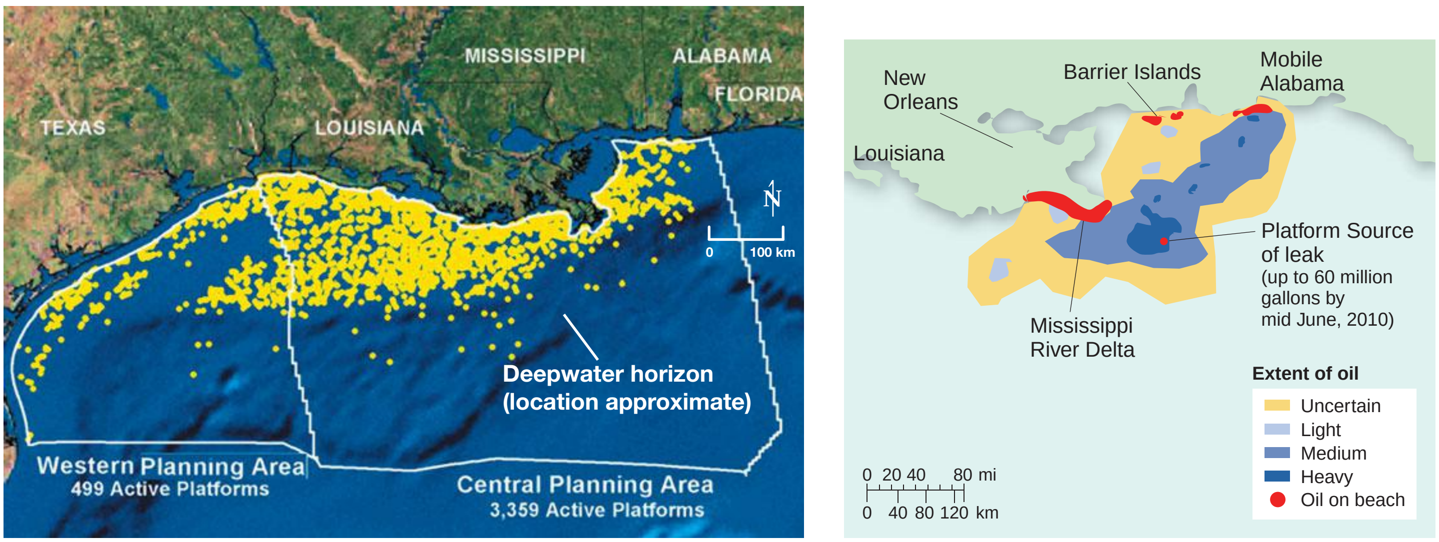
America's biggest oil spill began on April 20, 2010, about 66 km (41 miles) south of the Louisiana Coast in the Gulf of Mexico. Everything about the spill was big, very big (Figure 24.1a). It happened on the *Deepwater Horizon,* a floating, semisubmerged drilling platform whose surface was larger than a football field—121m (396 ft) long and 78 m (256 feet) wide. Built in 2001 at a cost of $600 million and owned by Transocean, the platform had previously dug the deepest offshore gas and oil well ever, down 10,685 m (35,055 feet). In February 2010, Transocean began a new job under lease by British Petroleum (BP), drilling in waters 1,500 m (5,000 ft) deep. BP's plan was to use this platform to drill an exploratory well into the bedrock below to a depth of 5,600 m (18,360 feet)—almost 3½ miles into the rock! Pipes descended from the platform through the seawater to the bedrock below, and then drilling began. The wellhead, which sits atop the seafloor, contains devices to control the drilling, to insert drilling fluids (called "muds") into the hole drilled below, and to control the upward flow of oil and gas once those deposits are reached.

On April 20, things went wrong. Methane (natural gas) from the oil and gas deposits that were being drilled into from the platform broke through the wellhead at the surface far below. It rose rapidly, reaching the platform in a short time, starting a fire there at 9:56 P.M. local time, and then causing a major explosion. Eleven of the 126 crew members were killed, and many others were injured; some saved themselves by diving off the collapsing rig into the ocean. The fire was big—so big and bright that people in boats that came to help said it was hard to look at and melted the paint off the boats.

The *Deepwater Horizon* burned for 36 hours and then, on April 22, it sank, and the oil spill began in earnest. At first, the U.S. Coast Guard reported that 8,000 barrels a day were leaking, but it was difficult to determine just how much oil was pouring out thousands of feet below. By July the best estimate was about 60,000 barrels per day. The oil spread widely; by mid-June 2010, medium to heavy amounts of oil had reached more than 160 km (100 miles) east of the platform's position (Figure 24.1*b*).[1]

The total amount of oil spilled by mid-July when the leak was stopped was about 5 million barrels (210 million gallons). At this rate of release, the BP spill equaled the *Exxon Valdez* oil spill (until then the largest spill in U.S. history) every 4½ days.

To put these large numbers in perspective, the average school gymnasium would hold about 1.3 million gallons of oil. Thus, the oil spilled in just the first two months of the BP spill would fill over 100 school gymnasiums.

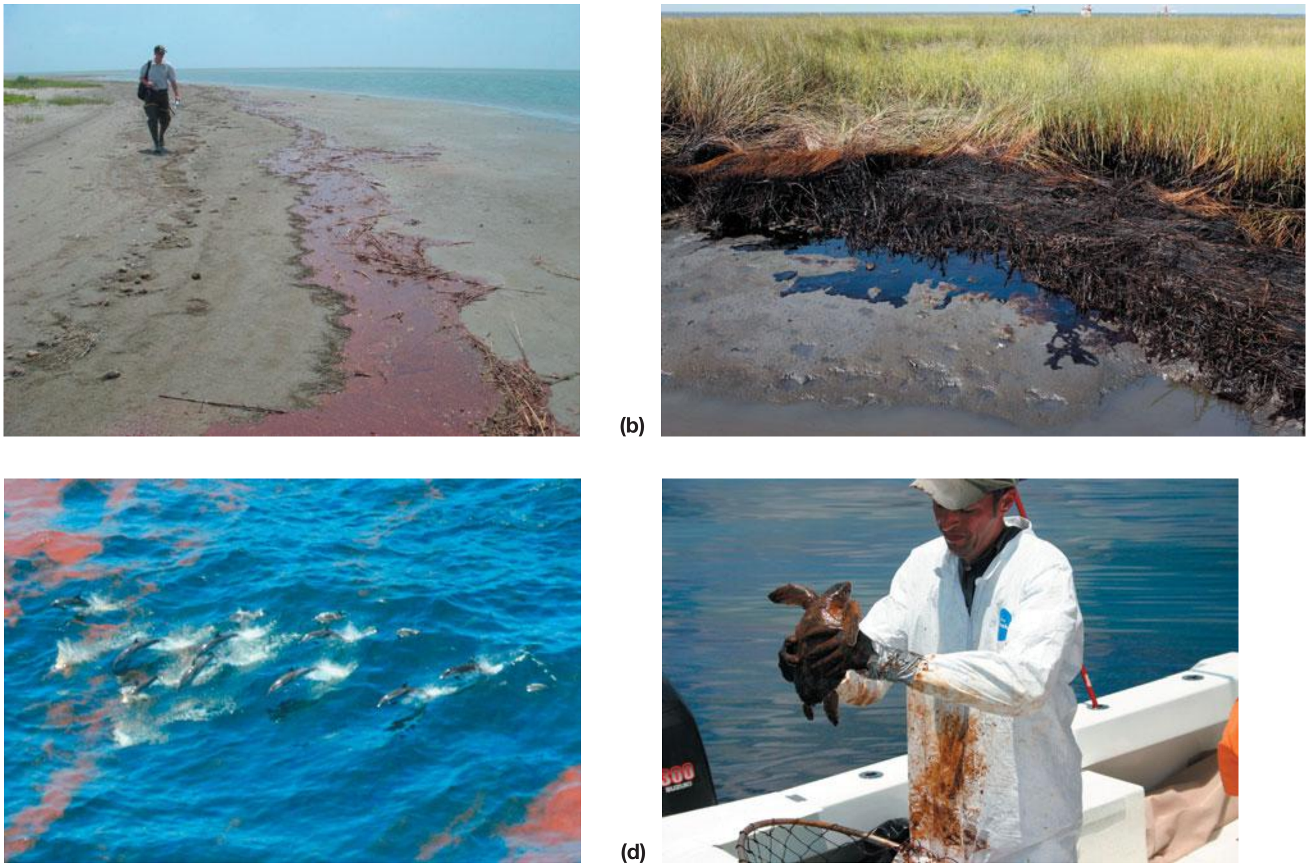


(a) (b)

FIGURE 24.1 **(a)** Active oil platforms (about 4,000) on the northern slope of the Gulf of Mexico. The location of the *Deepwater Horizon* is shown; **(b)** the extent of the Gulf spill as of mid-June 2010. (*Source*: Modified after NOAA.)

How does this compare to other blowouts and oil spills? The largest known blowout on land, which happened in Iran in 1956, involved about 120,000 barrels per day and lasted 3 months before being capped, releasing a total of almost 11 million barrels. A number of other "gushers" in the history of oil drilling released about 100,000 barrels per day. (We discuss other spills on land and offshore in Chapter 15.)

Any way you look at it, the BP spill is a lot of oil released into the Gulf's fragile marine and coastal environments. Spilled oil that remains near the water surface moves with currents and winds, some of it ending up on shorelines, partly covering plants and animals, infiltrating the sediment, and doing other kinds of ecological damage (Figure 24.2). Although most effects of oil spills are relatively short-lived (days to a few years), previous marine spills have killed thousands of seabirds, temporarily spoiled beaches, and caused loss of tourist and fishing revenues. Complicating matters, four species of sea turtles (loggerheads, Kemp's ridley, leatherback, and green) lay their eggs along Gulf State coasts that either have already been reached by the oil or are likely to in the near future. By June 25, 2010, 555 turtles had been found within the spill, 417 of them were dead.[2]



(a) (b) (c) (d)

(e)

FIGURE 24.2 Oil on land: **(a)** Chandeleur Beach, Louisiana, 2010; **(b)** oil invades a Louisiana coastal wetland marsh in 2010; **(c)** dolphins swimming through some of the BP oil spill; **(d)** Kemp's ridley sea turtle at a rehabilitation center; **(e)** oil-covered seabird in Louisiana.

A large volume of natural gas (methane) has been released with the oil, some dissolved in the oil and some from gas pockets. Eventually, much of the methane in the water is degraded by bacteria, whose increased respiration decreases oxygen levels in the water. Scientists studying the oxygen content of the deep water near the oil rig have found oxygen depletion of 2% to 30% at depths of about 1,000 feet.

The spill is an economic disaster for BP and for the U.S. states along the Gulf coast. If the oil that was spilled in the first 60 days had been obtained and sold, it would have provided BP with about $288 million. But by that time BP had already admitted that the spill had cost the company $1 billion, and BP had agreed to provide the U.S. government with $20 billion to repay those who suffered damage from the spill. Fishermen, for example, have been put out of work because a large area of the Gulf's waters—from Morgan City west of New Orleans, Louisiana, to well east of Panama City, Florida, and south parallel to the Florida Keys, approximately 300 miles east–west and 300 miles north–south—were closed to fishing (Figure 24.3). Some closed areas were opened by August 2010. People in tourist areas lost money, too, because vacationers are choosing other locations where they won't have to contend with oil on beaches. All the supporting businesses for fishing and tourism also suffered.

Will the Gulf recover from the 2010 oil spill? Certainly it will. Scientific studies of previous oil spills show that there is always an immediate (scientists call it an "acute") effect, killing fish, birds, and marine mammals and damaging vegetation and nearshore algae. Over the long run, the oil decomposes and much of it becomes food for bacteria, or nutrients for algae and plants. However, studies of previous oil spills also show that some oil remains even decades after spills, and therefore the effects on people, economics, and the environment that people value and enjoy are, from a human perspective, damaged for a long time.

FIGURE 24.3 A large part of the commercial fisheries in the Gulf of Mexico were closed to fishing by late June 2010 because of the BP oil spill.

By late August 2010 it was hard to find much floating oil in the Gulf and some saltmarsh plants were showing signs of recovery. Recovery may be quicker in the Gulf than in Alaska because the warm water favors biologic decomposition of the oil, the oil is light and the Gulf is a very large, deep, body of water subject to active surface processes from storm generated wind and waves.

How did the BP spill happen? As with many major environmental disasters, a series of poor decisions were involved, including a failure to take advantage of the safest and best technology. Before the blowout, problems with the well caused workers and others to express concern about being able to prevent an incident in which oil or natural gas would escape. The *Deepwater Horizon* had problems prior to the blowout and received 18 government citations for pollution. The BP wellhead had been fitted with a blowout preventer, but not with remote control or acoustically activated triggers for use in an emergency. The blowout preventer malfunctioned shortly after the heavy drilling mud had been withdrawn from the wellhead (the function of the drilling mud is to help keep oil from moving up the well to the surface). This is considered one of the major mistakes because without the mud and with the blowout-preventer malfunction, there was only water pressure to keep the oil and gas from escaping, and that was a recipe for disaster.

In addition, the response to the oil spill was inadequate. Rather than proactive, it was reactive: Each time something went wrong, there was spur-of-the- moment action. Also lacking was a clear line of authority and responsibility. The drilling was being done offshore by a private corporation, but it had large-scale effects, many of which were on government lands and waters and thus came under government control. Some available technologies that could have been applied were not; others were applied in too limited and tentative a way (Figure 24.4). News reports were rife with speculation by poorly informed people about all sorts of things that might be done, from gathering the oil with hay to blowing up the well with an atomic bomb.

About 6,000 boats were deployed with about 25,000 workers to try to minimize the spread of the spill by collecting it in the sea and on land. Some oil was burned, and chemical dispersants were applied from aircraft as well as at the bottom of the sea where the leak was occurring. These dispersants are chemicals and have environmental impacts themselves. It is known that these chemicals can damage marine ecosystems, but in this situation some scientists considered dispersants the lesser of two evils. Dispersants are being used, but their long-term impact, particularly on the deep-sea bed and in the seawater, is largely un-

(a)

(b)

FIGURE 24.4 Cleaning up an oil spill. **(a)** Boats use booms and skimmers to collect oil during 2010 spill; **(b)** cleaning a Louisiana beach, 2010.

known. This brings up an important point: The science of the deep-ocean basin has not progressed enough to be able to adequately predict the processes there and how they will interact with the oil and dispersants. [3]

The *Deepwater Horizon* was just one of nearly 4,000 other platforms in the Gulf off the coast of the United States. From the perspective of environmental science, what lessons can we take home from the BP oil spill?

First of all, it did not have to happen. Best practices—those that take advantage of the best and safest modern technology, developed from modern science—were not followed.

Second, modern industrialized nations use huge amounts of petroleum, and even with widespread movements away from petroleum, the need will not cease quickly. Therefore, it is essential that oil exploration and development make use of the best available technology and science, including the sciences that inform us about the environmental and ecological effects of an oil spill.

And third, after decades of concern about offshore oil spills, the technologies to deal with their cleanup remain insufficient. What is needed is an oversight program that includes advance planning, early warning, and rapid and sufficient response. Given the huge amount of money spent on energy within the United States and the importance of energy to our nation's standard of living, creativity, and productivity, we can no longer deal with such things as oil spills in a haphazard way.

24.1 Imagine an Ecotopia

Imagine a future in which we use our environment wisely—an "ecotopia." A learning objective of this chapter is to work out, to the best that present information allows, what you think is possible and desirable for this future world, focusing primarily on the United States, and also describe how this might be accomplished. Having read this book, you may well imagine a future in which, for example, we move away from fossil fuels and shift to renewable energy, no longer needing to damage the environment by mining and burning fossil fuels, nor forced to import them from uncertain and unfriendly sources. But which alternative energy sources would you favor?

This may seem an empty academic exercise, but unless we have an idea of what we want, we won't know in which direction to seek our future. Ideas are powerful, as history has proved. Wars have been fought over ideas. Ideas led Europeans to the New World and forged the American democracy. So what seems simply an academic exercise could be a powerful force for the future. It is not difficult today to imagine an "ecotopia"—a world in which the environment, human societies, and individuals are treated well in the present and helped to persist long into the future. But it would be extremely difficult to help it come about. What would that ecotopia be like? Here are a dozen qualities you would probably want to include:

- Since human population growth is the underlying environmental problem, an ecotopia would have to include a human population that had stabilized or even perhaps declined.
- All living resources would be sustainable, as would harvests of those resources.
- There would be enough wilderness and other kinds of natural or naturalistic areas for everyone to have opportunities for recreation and the enjoyment of nature.
- Pollution would be minimized.
- The risk of extinction of many species would be minimized.
- There would be enough functioning ecosystems to handle the public-service functions of ecosystems.

- Representatives of all natural ecosystems would be sustained in their dynamic ecological states.
- Poverty would be alleviated, benefiting both people and environment, because when you are poor it is hard to devote your resources to anything beyond immediate necessities.
- Energy would be abundant but, as much as possible, not cause pollution or otherwise damage land, water, and ecosystems.
- Water would be available to meet the needs of people and natural ecosystems,
- Natural resources, both finite and renewable, would also be available, and recycled where possible.
- Societies would have ample resources to be creative and innovative.

Admittedly, achieving all of this—and/or whatever else you've thought of—will be far from easy.

24.2 The Process of Planning a Future

Both human societies and natural ecosystems are complex systems. One of the questions asked by modern science is the degree to which such systems are *self-organizing*. A seed of a plant, for example, is a self-organizing system: It can develop into a mature plant without any outside planning or rational effort. But plants grown in agriculture are not simply left to their self-organizing abilities. Farmers plan for them and carry out those plans, and in these ways a plant is no longer completely self-organizing.

In our discussion of ecosystems in Chapter 5, we said that an ecosystem is the basic unit that can sustain life, and, in that sense, is necessary for life to persist. To some extent ecosystems show self-organizing characteristics, as in ecological succession, but that process of succession isn't as fixed, neat, and perfect a pattern as the growth of a seed into a mature plant.

One of the major themes of this book is the connection between people and nature. We understand today that human societies are linked to natural ecosystems. To what degree can these linked, complex systems self-organize? In various chapters, we have reviewed some examples that appear as self-organization. For example, as we saw in Chapter 22 (urban environments), cities developed at important transportation centers and where local resources could support a high density of people. In medieval Europe, bridges and other transportation aids developed in response to local needs. People arriving at a river would pay the farmer whose land lay along the river to row them across. Sometimes this would become more profitable than farming, or at least an important addition to the farmer's income. Eventually, he might build a toll bridge. People would congregate naturally at such a crossing and begin to trade. A town would develop.[4] The combination of environment and society led in a self-organizing way to cities.[4]

In contrast, the oil-drilling platform *Deepwater Horizon* was not self-organizing at all. It was imagined, designed, and built by a large manufacturing corporation with a planned purpose: to serve as a floating platform for drilling into difficult oil and gas reserves. It functioned within the laws of the United States and international treaties that affected activities in the Gulf of Mexico. These are external plans and agreements to regulate and control how the complex structure of the *Deepwater Horizon* could be and would be used. The failure of this platform was also not the result of self-organization, but of external (human) decisions.

In a democracy, planning with the environment in mind leads to a tug-of-war between individual freedom and the welfare of society as a whole. On one hand, citizens of a democracy want freedom to do what they want, wherever they want, especially on land that, in Western civilizations, is "owned" by the citizens or where citizens have legal rights to water or other resources. On the other hand, land and resource development and use affect society at large, and in either direct or indirect ways everyone benefits or suffers from a specific development. Society's concerns lead to laws, regulations, bureaucracies, forms to fill out, and limitations on land use.

Our society has formal planning processes for land use. These processes have two qualities: a set of rules (laws, regulations, etc.) requiring forms to be filled out and certain procedures to be followed; and an imaginative attempt to use land and resources in ways that are beautiful, economically beneficial, and sustainable. All human civilizations plan the development and use of land and resources in one way or another—through custom or by fiat of a king or emperor, if not by democratic processes. For thousands of years, experts have created formal plans for cities (see Chapter 22) and for important buildings and other architectural structures, such as bridges.

How can we balance freedom of individual action with effects on society? How can we achieve a sustainable use of Earth's natural resources, making sure that they will still be available for future generations to use and enjoy? In short, the questions are: Who speaks for nature? Who legally represents the environment? The landowner? Society at large? At this time, we have no definitive answers. Planning is a social experiment in which we all participate. Planning occurs at every level of activity, from a garden to a house, a neighborhood, a city park and its surroundings, a village, town, or city, a county, state, or nation. However, the history of our laws provides insight into our modern dilemma.

Issues of environmental planning and review are closely related to how land is used. Land use in the United States is dominated by agriculture and forestry; only a small portion of land (about 3%) is urban. However, rural lands are being converted to nonagricultural uses at about 9,000 km^2 (about 3,500 mi^2) per year. About half the conversion is for wilderness areas, parks, recreational areas, and wildlife refuges; the other half is for urban development, transportation networks, and other facilities. On a national scale, there is relatively little conversion of rural lands to urban uses. But in rapidly growing urban areas, increasing urbanization may be viewed as destroying agricultural land and exacerbating urban environmental problems, and urbanization in remote areas with high scenic and recreational value may be viewed as potentially damaging to important ecosystems.

24.3 Environment and Law: A Horse, a Gun, and a Plan

The legal system of the United States has historical origins in the British common law system—that is, laws derived from custom, judgment, and decrees of the courts rather than from legislation. The U.S. legal system preserved and strengthened British law to protect the individual from society—expressed best perhaps in the frontier spirit of "Just give me a little land, a horse, and a gun and leave me alone." Individual freedom—nearly unlimited discretion to use one's own property as one pleases—was given high priority, and the powers of the federal government were strictly limited.

But there is a caveat: When individual behavior infringed on the property or well-being of others, the common law provided protection through doctrines prohibiting trespass and nuisance. For example, if your land is damaged by erosion or flooding caused by your neighbor's improper management of his land, then you have recourse under common law. If the harm is more widespread through the community, creating a public nuisance, then only the government has the authority to take action—for instance, to limit certain air and water pollution.

The common law provides another doctrine, that of public trust, which both grants and limits the authority of government over certain natural areas of special character. Beginning with Roman law, navigable and tidal waters were entrusted to the government to hold for public use. More generally, "The public trust doctrine makes the government the public guardian of those valuable natural resources which are not capable of self-regeneration and for which substitutes cannot be made by man."[5] For such resources, the government has the strict responsibility of a trustee to provide protection and is not permitted to transfer such properties into private ownership. This doctrine was considerably weakened by the exaltation of private-property rights and by strong development pressures in the United States, but in more recent times it has shown increased vitality, especially concerning the preservation of coastal areas. Here is the basis for much modern environmental law, policy, regulation, and planning: common law with respect to you and your neighbors and the public trust doctrine.

The Three Stages in the History of U.S. Environmental Law

The history of federal legislation affecting land and natural resources occurred in three stages. In the first stage, the goal for public lands was to convert them to private uses. During this phase, Congress passed laws that were not intended to address environmental issues but did affect land, water, minerals, and living resources—and thereby had large effects on the environment. In 1812, Congress established the General Land Office, whose original purpose was to dispose of federal lands. The government disposed of federal lands through the Homestead Act of 1862 and other laws. As an example of Stage 1, in the 19th century the U.S. government granted rights-of-way to railroad companies to promote the development of rapid transportation. In addition to rights-of-way, the federal government granted the railroads every other square mile along each side of the railway line, creating a checkerboard pattern. The square miles in between were kept as federal land and are administered today by the Bureau of Land Management. These lands are difficult to manage for wildlife or vegetation because their artificial boundaries rarely fit the habitat needs of species, especially those of large mammals.

The second stage began in the second half of the 19th century, when Congress began to pass laws that conserved public lands for recreation, scenic beauty, and historic preservation. Late in the 19th century, Americans came to believe that the nation's grand scenery should be protected and that public lands provided benefits, some directly economic, such as rangelands for private ranching.

Federal laws created the National Park Service in the second half of the 19th century in response to Americans' growing interest in their scenic resources. Congress made Yosemite Valley a California state park in 1864 and created Yellowstone National Park in 1872 "as a public park or pleasuring-ground for the benefit and enjoyment of the people."[6] Interest in Indian ruins led soon after to the establishment in 1906 of Mesa Verde National Park, putting into public lands the prehistoric

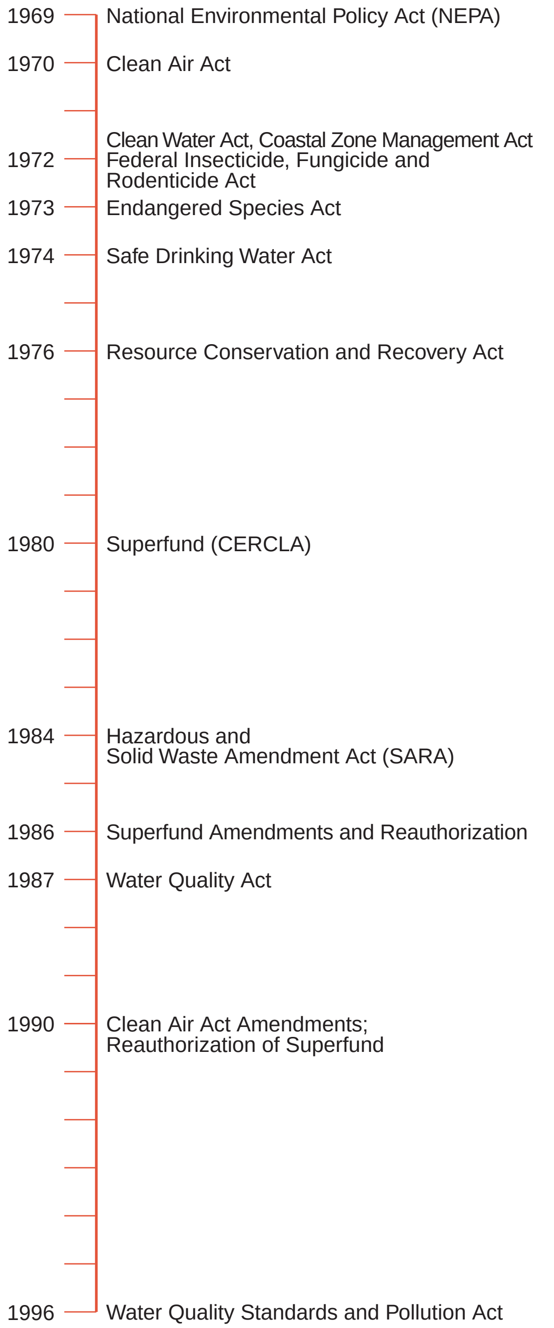


FIGURE 24.5 Major federal environmental legislation and the year enacted. Most of the important environmental legislation was adopted from 1969 to 1996. Some laws were enacted earlier in a much less comprehensive form (e.g., the Clean Air Act in 1963), and most were amended subsequently.

cliff dwellings of early North Americans and at the same time creating national monuments. The National Park System was created by Congress in 1916. Today it consists of 379 areas.

Also in the second stage, the United States Forest Service began in 1898, and President Grover Cleveland appointed Gifford Pinchot to be head of the Division of Forestry, soon renamed the U.S. Forest Service. Pinchot believed that the purpose of national forests was "the art of producing from the forest whatever it can yield for the service of man." The focus was on production of useful products.

Although the term *sustainability* had not yet become popular, in 1937 the federal government passed the Oregon and California Act, which required that timberland in western Oregon be managed to give sustained yields.[7]

In the third stage, Congress enacted laws whose primary purpose was environmental. This stage has antecedents in the 1930s but didn't get going in force until the 1960s and it continues today. The acknowledged need to regulate the use of land and resources has been filled by legislation enacted at all levels of government. In the late 1960s, public awareness and concern in the United States that our environment was deteriorating reached a high level. Congress responded by passing the National Environmental Protection Act (NEPA) in 1969 and a series of other laws in the 1970s (Figure 24.5). Federal laws relating to land management proliferated to the point where they became confusing. By the end of World War II, there were 2,000 laws about managing public lands, often contradicting one another. In 1946 Congress set up the Bureau of Land Management (BLM) to help correct this confusion.

Government regulation of land and resources has also given rise to controversy: How far should the government be allowed to go to protect what appears to be the public good against what have traditionally been private rights and interests? Today, the BLM attempts to balance the traditional uses of public lands—grazing and mining—with the environmental era's interest in outdoor recreation, scenic beauty, and biological conservation. Part of achieving a sustainable future in the United States will be finding a balance among these uses, as well as a balance between the amount of land that should be public and the amount of land that need not be.

24.4 Planning to Provide Environmental Goods and Services

One important experiment of the 20th century was regional planning. In the United States, this means planning across state boundaries. One of the best-known regional plans in the United States began in 1933, when President Franklin D. Roosevelt proposed the establishment of the Tennessee Valley Authority (TVA), a semi-independent agency responsible for promoting economic growth and social well-being for the people throughout parts of seven states, which were economically depressed at the time the authority was established. There had been rampant exploitation of timber and fossil-fuel resources in the region, and the people living there were among the poorest in the country.[8]

Today, the TVA is considered one of the world's best examples of regional planning (Figure 24.6). It is characterized by multidimensional and multilevel planning to manage land and water resources and is involved in the production and regulation of electrical power, as well as flood control, navigation, and outdoor recreation. In the midst of the Great Depression, Roosevelt sought new ways to invigorate the economy, especially in depressed rural areas. He envisioned the TVA as a corporation clothed with the power of government but with the flexibility and initiative of a private enterprise. The TVA granted legal control over land use to a multistate authority of a new kind and posed novel issues of governmental authority. The act creating the TVA contained the following stipulations:

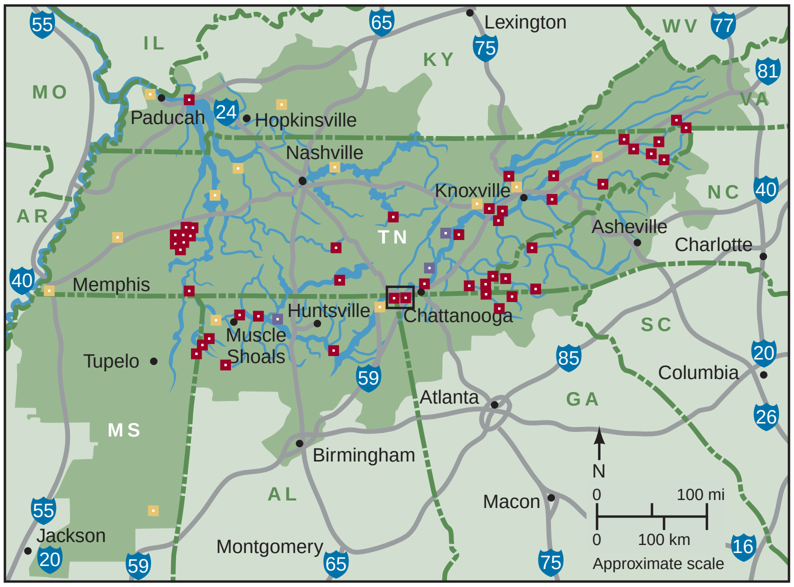
> The unified development and regulation of the Tennessee River system require that no dam, appurtenant works, or other obstruction, affecting navigation, flood control, or public lands or reservations shall be constructed, and thereafter operated or maintained across, along, or in the said river or any of its tributaries until plans for such construction, operation, and maintenance shall have been submitted to and approved by the Board; and the construction, commencement of construction, operation, or maintenance of such structures without such approval is hereby prohibited.[9]

24.5 Planning for Recreation on Public Lands

Today, management of public lands for recreational activities requires planning at a variety of levels, with considerable public input. For example, when a national forest is developing management plans, public meetings are often held to inform people about the planning process and to ask for ideas and suggestions. Maximizing public input promotes better communication between those responsible for managing resources and those using them for recreational purposes.

Government officials and scientists involved in developing plans for public lands are often faced with land-use problems so complex that no easy answers can be found. Nonetheless, because action or inaction today can have serious consequences tomorrow, it is best to have at least some plans to protect and preserve a quality environment for future generations. Plans for many of the national forests and national parks in the United States have been or are being developed, generally taking into account a spectrum of recreational activities and attempting to balance the desires of several user groups.

Severe 1996–1997 winter floods in Yosemite National Park damaged roads, campgrounds, bridges, and other structures. The flood led to a rethinking of the goals and objectives of park management, and one result was that some land claimed by the floods was returned to natural



■ Reservoirs

■■ Raccoon Mountain Dam

(a)

(b)

FIGURE 24.6 **(a)** A map showing the region encompassed by the TVA (darker area) and one of the major impoundments, the Raccoon Mountain Dam; **(b)** a large reservoir created by one of the TVA dams.

ecosystems. Another result was the elimination of private vehicles in parts of the park. Many other important policies have also been implemented in U.S. forests and parks. For example:

- In wilderness areas, only a limited number of people are admitted.
- In coastal areas, regulations may limit such activities as jet skiing and surfing in swimming areas.
- Regions that are home to endangered species, or to species that may pose a danger to people, may have more stringent regulations governing the activities of visitors. In Yellowstone National Park in Wyoming and Montana, for example, special consideration is given to grizzly bear habitats through controls on where people may venture.

Other recreational activities that are, or may become, subject to increased regulation include hiking, camping, fishing, boating, skiing, snowmobiling, and such recently popularized activities as treasure hunting, which includes panning for gold. At the extremes, certain areas have been set aside for intensive off-road-vehicle use, while other areas have been closed entirely. Activities on government lands can be more easily regulated than those occurring elsewhere. However, park management may be difficult if goals are not clear and natural processes not understood.

Who Stands for Nature? Skiing at Mineral King

Planning for recreational activities on U.S. government lands (including national forests and national parks) is controversial. At the heart of the controversy are two different moral positions, both with wide support in the United States. On one side, some argue that public land must be open to public use, and therefore the resources within those lands should be available to citizens and corporations for economic benefit. On the other side are those who argue that public lands should serve the needs of society first and individuals second, and that public lands can and must provide for land uses not possible on private lands.

FIGURE 24.7 Mineral King Valley, now part of Sequoia National Park after nearly 20 years of controversy about the development of a ski resort in the valley.

A classic example of this controversy concerned a plan by the Disney Corporation in the 1960s and 1970s to develop a ski resort with a multimillion-dollar complex of recreational facilities on federal land in a part of California's Sierra Nevada called Mineral King Valley (Figure 24.7), which had been considered a wilderness area. The Sierra Club, arguing that such a development would adversely affect the aesthetics of this wilderness, as well as its ecological balance, brought a suit against the government.

The case raised a curious question: If a wrong was being done, who was wronged? Christopher D. Stone, a lawyer, discussed this idea in an article entitled "Should Trees Have Standing? Toward Legal Rights for Natural Objects." The California courts decided that the Sierra Club itself could not claim direct harm from the development, and because the government owned the land but also represented the people, it was difficult to argue that the people in general were wronged. Stone said that the Sierra Club's case might be based, by common-law analogy, on the idea that in some cases inanimate objects have been treated as having legal standing—as, for example, in lawsuits involving ships, where ships have legal standing. Stone suggested that trees should have that legal standing, that although the Sierra Club was not able to claim direct damage to itself, it could argue on behalf of the nonhuman wilderness.

The case was taken to the U.S. Supreme Court, which concluded that the Sierra Club itself did not have a sufficient "personal stake in the outcome of the controversy" to bring the case to court. But in a famous dissenting statement, Justice William O. Douglas addressed the question of legal standing (*standing* is a legal term relating here to the right to bring suit). He proposed establishing a new federal rule that would allow "environmental issues to be litigated before federal agencies or federal courts in the name of the inanimate object about to be despoiled, defaced, or invaded by roads and bulldozers and where injury is the subject of public outrage." In other words, trees would have legal standing.

While trees did not achieve legal standing in that case, it was a landmark in that legal rights and ethical values were explicitly discussed for wilderness and natural systems. This subject in ethics still evokes lively controversy. Should our ethical values be extended to nonhuman, biological communities and even to Earth's life-support system? What position you take will depend in part on your understanding of the characteristics of wilderness, natural systems, and other environmental factors and features, and in part on your values.

FIGURE 24.8 Powell's map of water in the West.

Mineral King Valley and surrounding peaks of Mineral King, about 6,000 ha (12,600 acres), were transferred from the national forest to Sequoia National Park in September 1978. The transfer ended nearly 20 years of controversy over proposed development of a ski resort.

How Big Should Wildlands Be? Planning a Nation's Landscapes

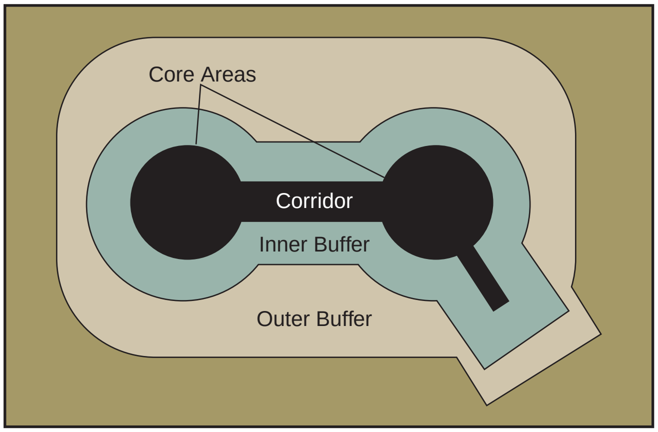
Recent thinking about the environment has focused on the big picture: What is necessary at a national scale, or at some landscape scale, to achieve our goals? We are not the first to ask this question. John Wesley Powell, the famous one-armed American explorer who was the first to lead men down the Colorado River through the Grand Canyon, observed the dry American West and suggested that the land should be organized around major watersheds rather than laid out for political and social reasons, as the states ultimately were (Figure 24.8). His utopian vision was of a landscape where farmers spent their own money on dams and canals, doing so because the land was organized politically around watersheds. They could use, but not sell, their water. This plan seemed to impose too much control from the top and never happened.[10] Instead, in 1902 Congress passed an act that began the 20th-century construction of large dams and canals funded with federal dollars. Water rights could be sold, and cities like Los Angeles could assert the right to water hundreds of miles away.

While we cannot go back to Powell's vision completely, our society is gradually thinking more and more in terms of planning around large watersheds. This regional approach may help us move closer to the dream of our ecotopia. Modern scientific studies of ecosystems and landscapes also lead to speculation about the best way to conserve biological resources. Some argue that nature can be saved only in the large. A group called the Wildlands Project argues that big predators, referred to as "umbrella species," are keys to ecosystems, and that these predators require large home ranges. The assumption is that big, wide-ranging carnivores offer a wide umbrella of land protection under which many species that are more abundant but smaller and less charismatic find safety and resources.[11] Leaders of the Wildlands Project feel that even the biggest national parks, such as Yellowstone, are not big enough, and that America needs "rewilding." They propose that large areas of the United States be managed around the needs of big predators and that we replan our landscapes to provide a combination of core areas, corridors, and inner and outer buffers (Figure 24.9). No human activities would take place in the core areas, and even in the corridors and buffers human activity would be restricted.

The Wildlands Project has created a major controversy, with some groups seeing the project as a fundamental threat to American democracy. Another criticism of the Wildlands Project is directed at its scientific foundation. These critics say that although some ecological research suggests that large predators may be important, what controls populations in all ecosystems is far from understood. Similarly, the idea of keystone species, central to the rationale of the Wildlands Project, lacks an adequate scientific base.

A related idea that developed in the last two decades was *rewilding*—that is, returning the land that was once American prairie to land without towns and cities, where bison are once again allowed to roam free. As Reed Noss, one of the founders of the Wildlands Project, has written:

> A cynic might describe rewilding as an atavistic obsession with the resurrection of Eden. A more sympathetic critic might label it romantic. We contend, however, that rewilding is simply scientific realism, assuming that our goal is to insure the long-term integrity of the land community. Rewilding with extirpated carnivores and other keystone species is a means as well as an end. The "end" is the moral obligation to protect wilderness and to sustain the remnants of the Pleistocene—animals and plants—not only for our human enjoyment, but because of their intrinsic value.[11]



Process

FIGURE 24.9 Wildlands Project diagram of land divisions.

Proposals for the environment of the future thus involve science and values, and people and nature. So what do you want? A vast area of the United States returned to what might be self-functioning ecosystems? Or some open system of conservation that integrates people and allows for more freedom of action? The choices lie with your generation and the next, and tests of those choices' validity are also yours. The implications for the environment and for people are huge.[11, 12]

24.6 How You Can Be an Actor in the Environmental Law Processes

The case of Mineral King raises the question: What is the role of our legal system—laws, courts, judges, lawyers—in achieving environmental goals? The current answer is that environmental groups working through the courts have been a powerful force in shaping the direction of environmental quality control since the early 1970s. Their influence arose in part because the courts, appearing to respond to the national sense of environmental crisis of that time, took a more activist stance and were less willing to defer to the judgment of government agencies. At the same time, citizens were granted unprecedented access to the courts and, through them, to environmental policy.

Citizen Actions

Even without specific legislative authorization for citizens' suits, courts have allowed citizen actions in environmental cases as part of a trend to liberalize standing requirements.[13]

In the 1980s, a new type of environmentalism (which some people would label radical) arose, based in part on the premise that when it comes to the defense of wilderness, there can be no compromise. Methods used by these new environmentalists have included sit-ins to block roads into forest areas where mining or timber harvesting is scheduled; sitting in trees to block timber harvesting; implanting large steel spikes in trees to discourage timber harvesting; and sabotaging equipment, such as bulldozers (a practice known as "ecotage").

Ecotage and other forms of civil disobedience have undoubtedly been responsible for millions of dollars' worth of damage to a variety of industrial activities related to the use of natural resources in wilderness areas. One result of civil disobedience by some environmental groups is that other environmental groups, such as the Sierra Club, are now considered moderate in their approach to protecting the environment. There is no doubt, however, that civil disobedience has been successful in defending the environment in some instances. For example, members of the group Earth First succeeded in halting construction of a road being built to allow timber harvesting in an area of southwestern Oregon. Earth First's tactics included blockading the road by sitting or standing in front of the bulldozers, which slowed the pace of road work considerably. In conjunction with this action, the group filed a lawsuit against the U.S. Forest Service.

Environmentalists are now relying more on the law when arguing for ecosystem protection. The Endangered Species Act has been used as a tool in attempts to halt activities such as timber harvesting and development. Although the presence of an endangered species is rarely responsible for stopping a proposed development, those species are increasingly being used as weapons in attempts to save remaining portions of relatively undisturbed ecosystems.

Mediation

The expense and delay of litigation have led people to seek other ways to resolve disputes. In environmental conflicts, an alternative that has recently received considerable attention is mediation, a negotiation process between the adversaries guided by a neutral facilitator. The task of the mediator is to clarify the issues, help each party understand the position and the needs of the other parties, and attempt to arrive at a compromise whereby each party gains enough to prefer a settlement to the risks and costs of litigation. Often, a citizens' suit, or the possibility that a suit might be filed, gives an environmental group a place at the table in mediation. Litigation, which may delay a project for years, becomes something that can be bargained away in return for concessions from a developer. Some states require mediation as an alternative or prior to litigation in the highly contentious siting of waste-treatment facilities. In Rhode Island, for example, a developer who wishes to construct a hazardous-waste treatment facility must negotiate with representatives of the host community and submit to arbitration of any issues not resolved by negotiation. The costs of the negotiation process are borne by the developer.

A classic example of a situation in which mediation could have saved millions of dollars in legal costs and years of litigation is the Storm King Mountain case, a conflict between a utility company and conservationists. In 1962, the Consolidated Edison Company of New York announced plans for a new hydroelectric project in the Hudson River Highlands, an area with thriving fisheries and also considered to have unique aesthetic value (Figure 24.10). The utility company argued that it needed the new facility, and the environmentalists fought to preserve the landscape and the fisheries. Litigation began with a suit filed in 1965 and ended in 1981 after 16 years of intense courtroom battles that left a paper trail exceeding 20,000 pages. After spending millions of dollars and untold hours, the various parties finally managed to forge an agreement with the assistance of an outside mediator. If they had been able to sit down and talk at an early stage, mediation might have settled the issue much sooner and at much less cost to the parties and to society.[14] The Storm King Mountain case is often cited as a major victory for environmentalists, but the cost was great to both sides.

24.7 International Environmental Law and Diplomacy

Legal issues involving the environment are difficult enough within a nation; they become extremely complex in international situations. International law is different from domestic law in basic concept because there is no world government with enforcement authority over nations. As a result, international law must depend on the agreement of the parties to bind themselves to behavior that many residents of a particular nation may oppose. Certain issues of multinational concern are addressed by a collection of policies, agreements, and treaties that are loosely called international environmental law. There have been encouraging developments in this area, such as agreements to reduce air pollutants that destroy stratospheric ozone (the Montreal Protocol of 1987 and subsequent discussion and agreements; see Chapter 21).

Antarctica provides a positive example of using international law to protect the environment. Antarctica, a continent of 14 million km^2, was first visited by a Russian ship in 1820, and people soon recognized that the continent contained unique landscapes and life-forms (Figure 24.11). By 1960, a number of countries had claimed parts of Antarctica to exploit mineral and fossil-fuel resources.

FIGURE 24.10 Storm King Mountain and the Hudson River Highlands in New York State were the focus of environmental conflict between a utility company and conservationists for nearly 20 years before a dispute about building a power plant was finally resolved by mediation.

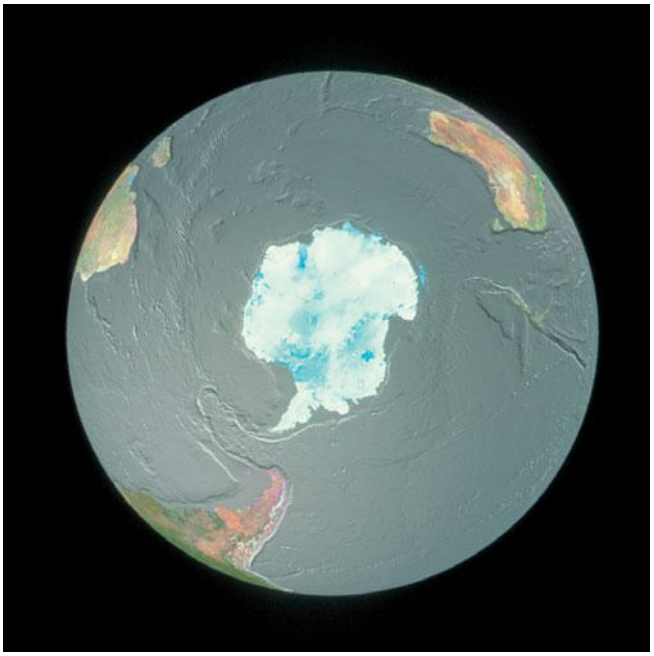
Then, in 1961, an international treaty was established designating Antarctica a "scientific sanctuary." Thirty years later, in 1991, a major environmental agreement, the Protocol of Madrid, was reached, protecting Antarctica, including islands and seas south of 60° latitude. The continent was designated "nuclear-free," and access to its resources was restricted. This was the first step in conserving Antarctica from territorial claims and establishing the "White Continent" as a heritage for all people on Earth.

Other environmental problems addressed at the international level include persistent organic pollutants (POPs), such as dioxins, DDT, and other pesticides. After several years of negotiations in South Africa and Sweden, 127 nations adopted a treaty in May 2001 to greatly reduce or eliminate the use of toxic chemicals known to contribute to cancer and harm the environment.

24.8 Global Security and Environment

The terrorist attacks on New York City and Washington, DC, on September 11, 2001, brought the realization that the United States—in fact the world—is not as safe as we had assumed. The attacks led to a war on terrorists and their financial and political networks around the world. However, for every terrorist removed, another will fill the void unless the root causes are recognized and eliminated.

Achieving sustainability in the world today has strong political and economic components, but it also has an environmental component. Terrorism comes in part from poverty, overcrowding, disease, and conflicts



(a)

(b)

FIGURE 24.11 International agreements determine environmental practices in Antarctica. **(a)** Satellite image of Antarctica and surrounding southern oceans; **(b)** emperor penguins and chicks in Antarctica.

that have environmental significance. Over 1 billion people on Earth today live in poverty with little hope for the future. In some large urban regions, tens of millions of people exist in crowded, unsanitary conditions, with unsafe drinking water and inadequate sewage disposal. In the countryside, rural people in many developing countries are being terrorized and displaced by armed conflicts over the control of valuable resources, such as oil, diamonds, and timber. Examples include oil in Nigeria, Sudan, and Colombia; diamonds in Sierra Leone, Angola, and the Democratic Republic of the Congo; and timber in Cambodia, Indonesia, and Borneo.[15]

The goal of the 1992 Rio Earth Summit on Sustainable Development was to address global environmental problems of both developed and developing countries, with an emphasis on solving conflicts between economic interests and environmental concerns. In many countries today, the gap between the rich and the poor is even wider than it was in the early 1990s. As a result, political, social, and economic security remains threatened, and serious environmental damage from overpopulation and resource exploitation continues. Environmental protection continues to be inadequately funded. Worldwatch Institute reported in 2002 that the United Nations' annual budget for the environment is about $100 million, while the governments of the world are spending $2 billion per day for military purposes.[15]

24.9 Challenges to Students of the Environment

To end this book on an optimistic note—and there *are* reasons to be optimistic—we note that the Earth Summit on Sustainable Development, held in the summer of 2002 in Johannesburg, South Africa, had the following objectives:

- To continue to work toward environmental and social justice for all the people in the world.
- To enhance the development of sustainability.
- To minimize local, regional, and global environmental degradation resulting from overpopulation, deforestation, mining, agriculture, and pollution of the land, water, and air.
- To develop and support international agreements to control global warming and pollutants, and to foster environmental and social justice.

Solving our environmental problems will help build a more secure and sustainable future. This is becoming your charge and responsibility, as you, students of the environment and our future leaders, graduate from colleges and universities. This transfer of knowledge and leadership is a major reason why we wrote this book.

CRITICAL THINKING ISSUE

Is It Possible to Derive Some Quantitative Statements about Thresholds beyond Which Unacceptable Environmental Change Will Occur?

A *threshold* is a condition or level that, if exceeded, will cause a system to change, often from one mode of operation to another, in terms of actual processes or rates of processes. In the environmental literature, thresholds are sometimes spoken of as tipping points, beyond which adverse consequences are likely to occur. Other definitions of a tipping point are: a point when a system (say the global climate) changes from one stable state to another stable state (this is a threshold); and a point where slow small changes over time results in a sudden large change (also a threshold). However, thresholds are not tipping points where change becomes catastrophic and may be irreversible. For example, some believe that if global warming continues past a particular point, say a two degree Celsius rise of temperature, then changes will become more rapid and the consequences of those changes more severe. The purpose of this critical thinking issue is to examine some of these hypotheses in more detail.[16]

In previous chapters, we discussed the major environmental problems related to human population, water, energy, and climate. In discussing human population, we introduced the concept of what Earth's carrying capacity might be. In answering that question, we posed another: "What would we *like* it to be?" It is acknowledged that human population growth is the environmental problem, but at what population level would the degree of environmental degradation become unacceptable to us? Similar limits or thresholds might be introduced for biological productivity; loss of biological diversity; use of nutrients, such as nitrogen and phosphorus; transformation of the land; and our use of freshwater resources. For this list, some scientists have tried to pinpoint thresholds beyond which environmental degradation is unacceptable (a value judgment).

Table 24.1 is based on a paper published in 2009 in the major scientific journal *Nature* and entitled "A Safe Operating Space for Humanity." You should treat these ideas as proposals for discussion, not as truths or facts. The table lists these systems in terms of parameters that may be measured, along with suggested thresholds, which are compared to the present status and also to pre-industrial levels. For example, for human population, a suggested threshold might be 5 billion people—fewer than are on Earth today and 4 billion more than the pre-industrial level of about 1 billion. This 5 billion threshold might be based on the fact that biological productivity, when it was more in balance with human needs, peaked around 1985, when the population was 5 billion people. The arbitrary choice of 5 billion is obviously linked to other factors shown in the table, as they are interrelated. Any specific number for the optimum carrying capacity of the planet will be controversial, but your evaluation will depend on the knowledge you bring to bear and your values.

With respect to climate change, Table 24.1 lists a hypothetical threshold of 350 parts per million for carbon dioxide concentration in the atmosphere, versus the present level of 390 parts per million and the pre-industrial level 280 parts per million. Setting the threshold at 350 parts per million was based on examination of the geologic record, the possible effects of previous climate change, and the likely levels of carbon dioxide in the atmosphere. This table is intended just for the sake of our discussion here. Similarly, the amount of land transformation or water use is also related to our present scientific knowledge.

Looking at Table 24.1 in more detail, we can see that some of the suggested thresholds have already been exceeded, and others have not. However, whether they actually have been exceeded will depend on how much we know about the particular system, whether the consequences are unacceptable, and whether this can be shown with some degree of certainty.

Critical Thinking Questions

1. Do you think it is a valid argument that some sorts of thresholds, or tipping points, exist beyond which unacceptable environmental degradation will occur?
2. Has science satisfactorily answered whether or not these thresholds, or tipping points, can in fact be established?
3. From your reading of *Environmental Science*, can you make other suggestions as to where thresholds or tipping points might be placed?
4. If you are not able to set thresholds, what sorts of studies might be necessary to establish them in the future? Of course, this assumes that the whole concept of thresholds, or tipping points, is a valid approach in environmental science.

Table 24.1 GLOBAL THRESHOLDS THAT, TRANSGRESSED, COULD CAUSE UNACCEPTABLE ENVIRONMENTAL CHANGE [FOR DISCUSSION PURPOSES ONLY; NOT TO BE TAKEN AS FACTS]

SYSTEM	PARAMETER	SUGGESTED THRESHOLD	PRESENT STATUS	PRE-INDUSTRIAL LEVEL
Human population	Billions of people	5.0	6.8	1.0
Climate	Carbon dioxide concentration (parts per million)	350	390	280
Biological productivity	Portion used by humans	0.6	1.2	<0.2
Biodiversity loss (extinction)	Extinction rate (number of species per million species per year)	10	>100	0.1–1.0
Nitrogen use	Amount removed from the air for human use (millions of tons per year)	35	120	0
Phosphorus use	Quantity flowing into the ocean (millions of tons per year)	11	9	-1.0
Land transformation	% of land converted to agriculture	15	12	Low
Global freshwater use	km^3/yr	4,000	2,600	415
Air pollution	Metric tons per year	To be determined	To be determined	To be determined
Water pollution	Metric tons per year	To be determined	To be determined	To be determined

Source: Modified from J. Rockström et al., 2009. "A Safe Operating Space for Humanity," *Nature* 461: 472–475. doi:10.1038/461472a.

SUMMARY

- A fundamental question, continuously debated in a democracy, is the extent to which human societies and their environment can function as self-organizing systems, and how much formal planning—laws and so on—is necessary.
- Both natural ecosystems and human societies are complex systems. The big question is how the interaction among these can lead to the long-term persistence of both, and perhaps even improvements.
- Mistakes are always likely; advance planning, including rapid response, is essential to maintaining the best environment.
- Our environmental laws have grown out of a combination of the English common law—derived from custom and judgment, rather than legislation—and American perspectives on freedom and planning.
- In the 19th and 20th centuries, America experimented with a variety of approaches to conserving nature, some involving laws, some new kinds of plans and organizations. The best combination is yet to be determined.
- International environmental law is proving useful in addressing several important environmental problems, including preservation of resources and pollution abatement.
- Global security, sustainability, and environment are linked in complex ways. Solving environmental problems will improve both sustainability and security.

STUDY QUESTIONS

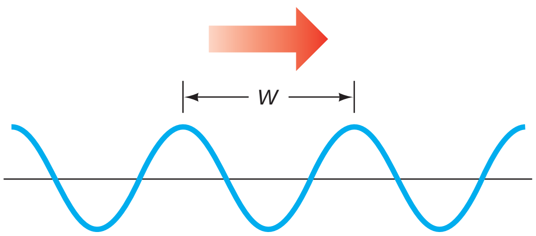
1. Based on what you have learned in this book and in your studies about environment, what would an "ecotopia" include, in addition to what is mentioned in this chapter? Which of these items, if any, do you think could be achieved during your lifetime?
2. Just how big should a wilderness be?
3. The famous ecologist Garrett Hardin argued that designated wilderness areas should not have provisions for people with handicaps, even though he himself was confined to a wheelchair. He believed that wilderness should be truly natural in the ultimate sense—that is, without any trace of civilization. Argue for or against Garrett Hardin's position. In your argument, consider the "people and nature" theme of this book.
4. How can we balance freedom of individual action with the need to sustain our environment?
5. Visit a local natural or naturalistic place, even a city park, and write down what is necessary for that area to be sustainable in its present uses.
6. Should trees—and other nonhuman organisms—have legal standing? Explain your position on this topic.
7. Since there are no international laws that are binding in the same way that laws govern people within a nation, what can be done to achieve a sustainable environment for world fisheries or other international resources?
8. Do you think the Gulf oil spill could have been prevented? If so, how?
9. Do you think Garrett Hardin is right—that there are some technologies (such as drilling in deep water) that humans are not prepared to adequately address and that there will thus be continued accidents due to human error?

Appendix

A Special Feature: Electromagnetic Radiation (EMR) Laws

Properties of Waves

- Direction of wave propagation



- W = wavelength (distance from one wave crest to the next)
- An EMR wave travels at the speed of light (C) in a vacuum, or about 300,000 km/s (3×10^8 m/s).
- The period T of a wave is the time it takes for a wave to travel a distance of one wavelength W. Then since distance is the product of speed (velocity) and time, W = CT.
- The frequency f of a wave is the number of cycles (each wavelength that passes a point is a cycle) of a wave that pass a particular point per unit time. Frequency f is measured in cycles per second (hertz). The frequency f is the inverse of T: f = 1/T and W = C/f. For example, the period T of a 6000 hertz EMF wave is: 6000 hertz = 1/T and T = 1/6000 S, or 1.7×10^{-4} S. The wavelength W = CT is 3×10^8m/s times 1.7×10^{-4} S, or 5.1×10^4 m, which according to Figure 20.18 is a long radio wave.

Absolute Temperature Scale (kelvin, K)

- Zero is really zero; there are no negative values of K
- Temperature in K = temperature in °C + 273

$$K = °C + 273$$

- Example: water freezes at °C = 0 = 273 K
  water boils at °C = 100 = 373 K

Stefan–Boltzmann Law

- All bodies with a temperature greater than absolute zero radiate EMR. These bodies are called thermal radiators. The amount of energy per second radiated from thermal radiators is called *intensity* and is given by the Stefan–Boltzmann law

$$E = aT^4$$

where E is the energy per second (intensity); T is the absolute temperature; and a is a constant (the nature of this constant involves physical ideas beyond the scope of this text).

- The Stefan–Boltzmann law states that the intensity of EMR coming from a thermal radiator is directly proportional to the fourth power of its absolute temperature.

Wien's Law

$$W_P = a/T$$

where WP is the wavelength of the peak intensity of a thermal radiator; T is temperature in K; and a is a constant. For example, Figure 20.19 shows that WP for the earth is about 10 μm. Wien's law states in a general way that the hotter a substance is, the shorter the wavelength of the emitted predominant electromagnetic radiation. That is, wavelength is inversely proportional to temperature.

B Prefix and Multiplication Factors

Number	10×, Power of 10	Prefix	Symbol
1,000,000,000,000,000,000	10^{18}	exa	E
1,000,000,000,000,000	10^{15}	peta	P
1,000,000,000,000	10^{12}	tera	T
1,000,000,000	10^{9}	giga	G
1,000,000	10^{6}	mega	M
10,000	10^{4}	myria	
1,000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deca	da
0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000 001	10^{-6}	micro	μ
0.000 000 001	10^{-9}	nano	n
0.000 000 000 001	10^{-12}	pico	p
0.000 000 000 000 001	10^{-15}	femto	f
0.000 000 000 000 000 001	10^{-18}	atto	a

C Common Conversion Gactors

LENGTH

1 yard = 3 ft, 1 fathom = 6 ft

	in	ft	mi	cm	m	km
1 inch (in) =	1	0.083	1.58×10^{-5}	2.54	0.0254	2.54×10^{-5}
1 foot (ft) =	12	1	1.89×10^{-4}	30.48	0.3048	—
1 mile (mi) =	63,360	5,280	1	160,934	1,609	1.609
1 centimeter (cm) =	0.394	0.0328	6.2×10^{-6}	1	0.01	1.0×10^{-5}
1 meter (m) =	39.37	3.281	6.2×10^{-4}	100	1	0.001
1 kilometer (km) =	39,370	3,281	0.6214	100,000	1,000	1

AREA

1 square mi = 640 acres, 1 acre = 43,560 ft^2 = 4046.86 m^2 = 0.4047 ha
1 ha = 10,000 m^2 = 2.471 acres

	in^2	ft^2	mi^2	cm^2	m^2	km^2
1 in^2 =	1	—	—	6.4516	—	—
1 ft^2 =	144	1	—	929	0.0929	—
1 mi^2 =	—	27,878,400	1	—	—	2.590
1 cm^2 =	0.155	—	—	1	—	—
1 m^2 =	1,550	10.764	—	10,000	1	—
1 km^2 =	—	—	0.3861	—	1,000,000	1

VOLUME	in³	ft³	yd³	m³	qt	liter	barrel	gal (U.S.)
1 in^3 =	1	—	—	—	—	0.02	—	—
1 ft^3 =	1,728	1	—	0.0283	—	28.3	—	7.480
1 yd^3 =	—	27	1	0.76	—	—	—	—
1 m^3 =	61,020	35.315	1.307	1	—	1,000	—	—
1 quart (qt) =	—	—	—	—	1	0.95	—	0.25
1 liter (l) =	61.02	—	—	—	1.06	1	—	0.2642
1 barrel (oil) =	—	—	—	—	168	159.6	1	42
1 gallon (U.S.) =	231	0.13	—	—	4	3.785	0.02	1

Mass and Weight

1 pound = 453.6 grams = 0.4536 kilogram = 16 ounces

1 gram = 0.0353 ounce = 0.0022 pound

1 short ton = 2000 pounds = 907.2 kilograms

1 long ton = 2240 pounds = 1008 kilograms

1 metric ton = 2205 pounds = 1000 kilograms

1 kilogram = 2.205 pounds

Energy and Power[a]

1 kilowatt-hour = 3413 Btus = 860,421 calories

2 Btu = 0.000293 kilowatt-hour = 252 calories = 1055 joules

1 watt = 3.413 Btu/hr = 14.34 calorie/min

1 calorie = the amount of heat necessary to raise the temperature of 1 gram (1 cm^3) of water 1 degree Celsius

1 quadrillion Btu = (approximately) 1 exajoule

1 horsepower = 7.457×10^2 watts

1 joule = 9.481×10^{-4} Btu = 0.239 cal = 2.778×10^{-7} kilowatt-hour

[a]Values from Lange, N. A., 1967, *Handbook of Chemistry*, New York: McGraw-Hill.

Temperature

$F = \frac{9}{5}C + 32$ — F is degrees Fahrenheit. C is degrees Celsius (centigrade).

Fahrenheit		Celsius
32	Freezing of H_20 (Atmospheric Pressure)	0
50	————	10
68	————	20
86	————	30
104	————	40
122	————	50
140	————	60
158	————	70
176	————	80
194	————	90
212	Boiling of H_20 (Atmospheric Pressure)	100

Other Conversion Factors

1 ft^3/sec = 0.0283 m^3/sec = 7.48 gal/sec = 28.32 liter/sec

1 acre-foot = 43,560 ft^3 = 1233 m^3 = 325,829 gal

1 m^3/sec = 35.32 ft^3/sec

1 ft^3/sec for one day = 1.98 acre-feet

1 m/sec = 3.6 km/hr = 2.24 mi/hr

1 ft/sec = 0.682 mi/hr = 1.097 km/hr

1 atmosphere = 14.7 lb(in.$^{-2}$) = 2116 lb(ft^{-2}) = 1.013×10^5 N(m^{-2})

D Geologic Time Scale and Biologic Evolution

Era	Approximate Age in Millions of Years Before Present	Period	Epoch	Life Form
	Less than 0.01		Recent (Holocene)	
	0.01–2	Quaternary	Pleistocene	Humans
	2			
	2–5		Pliocene	
	5–23		Miocene	
Cenozoic	23–35	Tertiary	Oligocene	
	35–56		Eocene	Mammals
	56–65		Paleocene	
	65			
	65–146	Cretaceous		
Mesozoic	146–208	Jurassic		Flying reptiles, birds
	208–245	Triassic		Dinosaurs
	245			
	245–290	Permian		Reptiles
	290–363	Carboniferous		Insects
Paleozoic	363–417	Devonian		Amphibians
	417–443	Silurian		Land plants
	443–495	Ordovician		Fish
	495–545	Cambrian		
	545			
	700			Multicelled organisms
	3,400			One-celled organisms
	4,000	Approximate age of oldest rocks discovered on Earth		
Precambrian				
	4,600	Approximate age of Earth and meteorites		

E Matter, Energy and Chemistry

Matter and Energy

The universe, as we know it, consists of two entities: matter and energy. Matter is the material that makes up our physical and biological environments (you are composed of matter). Energy is the ability to do work. The first law of thermodynamics—also known as the law of conservation of energy or the first energy law—states that energy cannot be created or destroyed but can change from one form to another. This law stipulates that the total amount of energy in the universe does not change.

Our sun produces energy through nuclear reactions at high temperatures and pressures that change mass (a measure of the amount of matter) into energy. At first glance, this may seem to violate the law of conservation of energy. However, this is not the case, because energy and matter are interchangeable. Albert Einstein first described the equivalence of energy and mass in his famous equation $E = mc^2$, where E is energy, m is mass, and c is the velocity of light in a vacuum, such as outer space (approximately 300,000 km/s or 186,000 mi/s). Because the velocity of light squared is a very large number, even a small amount of conversion of mass to energy produces very large amounts of energy. Energy, then, may be thought of as an abstract, mathematical quantity that is always conserved. This means that it is impossible to get something for nothing when dealing with energy; it is impossible to extract more energy from any system than the amount of energy that originally entered the system. In fact, the second law of thermodynamics states that you cannot break even. When energy is changed from one form to another, it always moves from a more useful form to a less useful one. Thus, as energy moves through a real system and is changed from one form to another, energy is conserved, but it becomes less useful.

Basic Chemistry

We turn next to a brief introduction to the basic chemistry of matter, which will help you in understanding biogeochemical cycles. An atom is the smallest part of a chemical element that can take part in a chemical reaction with another atom. An element is a chemical substance composed of identical atoms that cannot be separated by ordinary chemical processes into different substances. Each element is given a symbol. For example, the symbol for the element carbon is C, and that for phosphorus is P.

A model of an atom (Figure E.1) shows three subatomic particles: neutrons, protons, and electrons. The atom is visualized as a central nucleus composed of neutrons with no electrical charge and protons with a positive charge. A cloud of electrons, each with a negative charge, revolves about the nucleus. The number of protons in the nucleus is unique for each element and is the atomic number for that element. For example, hydrogen, H, has one proton in its nucleus, and its atomic number is 1. Uranium has 92 protons in its nucleus, and its atomic number is 92. A list of known elements with their atomic numbers, called the Periodic Table, is shown in Chapter 6 (Figure 6.8)

Electrons, in our model of the atom, are arranged in shells (representing energy levels), and the electrons closest to the nucleus are bound tighter to the atom than those in the outer shells. Electrons have negligible mass compared with neutrons or protons; therefore, nearly the entire mass of an atom is in the nucleus.

The sum of the number of neutrons and protons in the nucleus of an atom is known as the atomic weight. Atoms of the same element always have the same atomic number (the same number of protons in the nucleus), but they can have different numbers of neutrons and, therefore, different atomic weights. Two atoms of the same element with different numbers of neutrons in their nuclei and different atomic weights are known as isotopes of that element. For example, two isotopes of oxygen are ^{16}O and ^{18}O, where 16 and 18 are the atomic weights. Both isotopes have an atomic number of 8, but ^{18}O has two more neutrons than ^{16}O. Such study is proving very useful in learning how Earth works. For example, the study of oxygen isotopes has resulted in a better understanding of how the global climate has changed. This topic is beyond the scope of our present discussion but can be found in many basic textbooks on oceanography.

An atom is chemically balanced in terms of electric charge when the number of protons in the nucleus is equal to the number of electrons. However, an atom may lose or gain electrons, changing the balance in the electrical charge. An atom that has lost or gained electrons is called an ion. An atom that has lost one or more electrons has a net positive charge and is called a cation. For example, the potassium ion K^+ has lost one electron, and the calcium ion Ca^{2+} has lost two electrons. An atom that has gained electrons has a net negative charge and is called an anion. For example, O^{2-} is an anion of oxygen that has gained two electrons.

A compound is a chemical substance composed of two or more atoms of the same or different elements. The smallest unit of a compound is a molecule. For example, each molecule of water, H_2O, contains two atoms of hydrogen and one atom of oxygen, held together by chemical bonds. Minerals that form rocks are compounds, as are most chemical substances found in a solid, liquid, or gaseous state in the environment.

The atoms that constitute a compound are held together by *chemical bonding*. The four main types of chemical bonds are covalent, ionic, Vander Waals, and metallic. It is important to recognize that, when talking about chemical bonding of compounds, we are dealing with a complex subject. Although some compounds have a particular type of bond, many other compounds have more than one type of bond. With this caveat in mind, let's define each type of bond.

Covalent bonds result when atoms share electrons. This sharing takes place in the region between the atoms, and the strength of the bond is related to the number of pairs of electrons that are shared. Some important environmental compounds are held together solely by covalent bonds. These include carbon dioxide (CO_2) and water (H_2O). Covalent bonds are stronger than *ionic bonds*, which form as a result of attraction between cations and anions. An example of an environmentally important compound with ionic bonds is table salt (mineral halite), or sodium chloride (NaCL). Compounds with ionic bonds such as sodium chloride tend to be soluble in water and, thus, dissolve easily, as salt does. Van der Waals bonds are weak forces of attraction between molecules that are not bound to each other. Such bonding is much weaker than either covalent or ionic bonding. For example, the mineral graphite (which is the "lead" in pencils) is black and consists of sheets of carbon atoms that easily part or break from one another because the bonds are of the weak Van der Waals type. Finally, metallic bonds are those in which electrons are *c* shared, as with covalent bonds. However, they differ because, in metallic bonding, the electrons are shared by all atoms of the solid, rather than by specific atoms. As a result, the electrons can flow. For example, the mineral and element gold is an excellent conductor of electricity and can be pounded easily into thin sheets because the electrons have the freedom of movement that is characteristic of metallic bonding.

In summary, in the study of the environment, we are concerned with matter (chemicals) and energy that moves in and between the major components of the Earth system.

An example is the element carbon, which moves through the atmosphere, hydrosphere, lithosphere, and biosphere in a large variety of compounds. These include carbon dioxide (CO_2) and methane (CH_4), which are gases in the atmosphere; sugar ($C_6H_{12}O_6$) in plants and animals; and complex hydrocarbons (compounds of hydrogen and carbon) in coal and oil deposits.

Chemical Reactions

It is important to acknowledge in our discussion of how chemical cycles work that the emphasis is on chemistry. Many chemical reactions occur within and between the living and nonliving portions of ecosystems. A **chemical reaction** is a process in which new chemicals are formed from elements and compounds that undergo a chemical change. For example, a simple reaction between rainwater (H_2O) and carbon dioxide (CO_2) in the atmosphere produces weak carbonic acid (H_2CO_3):

$$H_2O + CO_2 \rightarrow H_2CO_3$$

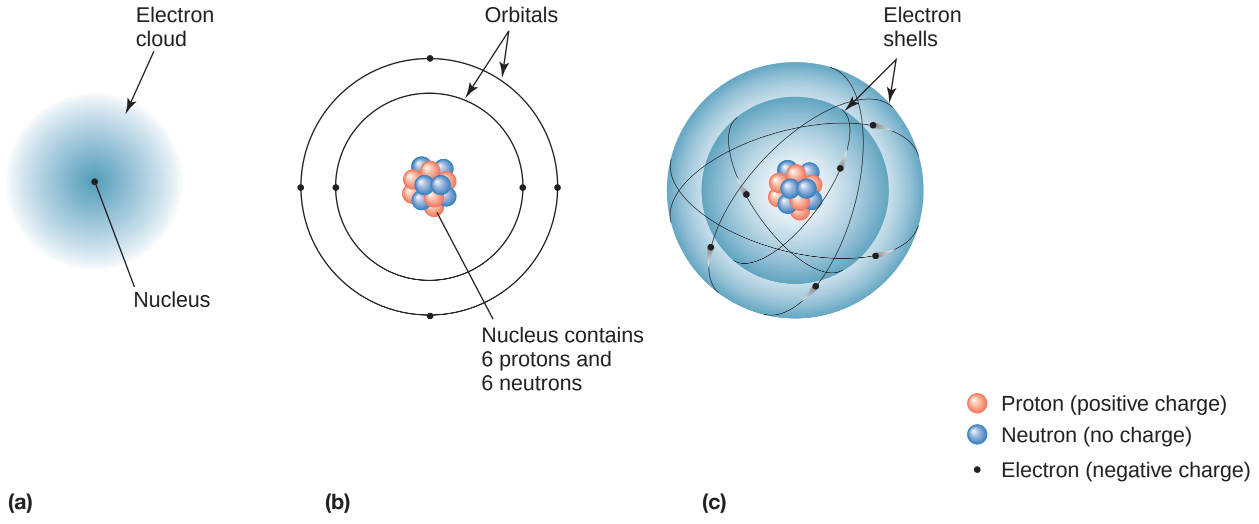
This weak acid reacts with earth materials, such as rock and soil, to release chemicals into the environment. The released chemicals include calcium, sodium, magnesium, and sulfur, with smaller amounts of heavy metals such as lead, mercury, and arsenic. The chemicals appear in various forms, such as compounds and ions in solution.

Many other chemical reactions determine whether chemicals are available to life. For example, photosynthesis is a series of chemical reactions by which living green plants, with sunlight as an energy source, convert carbon dioxide (CO_2) and water (H_2O) to sugar ($C_6H_{12}O_6$) and oxygen (O_2). The general chemical reaction for photosynthesis is:

$$6CO_2 + 6H_2O \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

Photosynthesis produces oxygen as a by-product, and that is why we have free oxygen in our atmosphere.

After considering the two chemical reactions and applying critical thinking, you may recognize that both reactions combine water and carbon dioxide, but the products are very different: carbonic acid in one combination and a sugar in the other. How can this be so? The answer lies in an important difference between the simple reaction in the atmosphere that takes place to produce carbonic acid and the production of sugar and oxygen in the series of reactions of photosynthesis. Green plants use the energy from the sun, which they absorb through the chemical chlorophyll. Thus, active solar energy is converted to a stored chemical energy in sugar.



E.1 **(a)** Idealized diagram showing the basic structure of an atom as a nucleus surrounded by a cloud of electrons. **(b)** Conceptualized model of an atom of carbon with six protons and six neutrons in the nucleus and six orbiting electrons in two energy shells. **(c)** Three-dimensional view of (b). Size of nucleus relative to size of electron shells is greatly exaggerated. [*Source*: After F. Press, and R. Siever *Understanding Earth* (New York: Freeman, 1994).]

Photo Credits

CHAPTER 1 Ch Op 1: Image Bank/Getty Images, Inc. Fig. 1.2: Corbis/SuperStock (top). Fig. 1.3: AfriPics.com/Alamy (bottom). Fig. 1.4: Images of Africa Photobank/Alamy. Fig. 1.6a: Peter Turnley/©Corbis (left). Fig. 1.6b: dbimages/Alamy (right). Fig. 1.8a: Thony Belizaire/AFP/Getty Images, Inc. (left). Fig. 1.8b: STRDEL/AFP/Getty Images, Inc. (right). Fig. 1.9a: Mira/Alamy (left). Fig. 1.9b: Comstock/Jupiter Images (right). Fig. 1.10: NASA Earth Observatory (bottom). Fig. 1.11: NASA/©Corbis. Fig. 1.12: Bill Ross/Corbis Images (top left). Fig. 1.13a: Kenneth W. Fink/Photo Researchers, Inc. (bottom left). Fig. 1.13b: © J.P. Ferrero/Jacana/Photo Researchers, Inc. (bottom right). Fig. 1.14: Courtesy Dan Botkin (top left). Fig. 1.15: Exactostock/SuperStock (top right). Fig. 1.16: Natalie Fobes/©Corbis. Fig. 1.17: Phil Dyer/iStockphoto. Fig. 1.18c: Michael Wozniak/iStockphoto.

CHAPTER 2 Ch Op 2: Dan Botkin. Fig. 2.1: Phil Schermeister/©Corbis. Fig. 2.5: Alan Root/Photo Researchers, Inc (left). Fig. 2.6: All Canada Photos/SuperStock (right). Fig. 2.8a: Gideon Mendel//Magnum Photos, Inc. (top). Fig. 2.8b: D. Hudson/©Corbis (bottom). Fig. 2.9: Visuals Unlimited.

CHAPTER 3 Ch Op 3: Lyroky/Alamy. Fig. 3.1: ©AP/Wide World Photos. Fig. 3.2: Goddard Space Flight Center Scientific Visualization Studio./Courtesy NASA (left). Fig. 3.3: Goddard Space Flight Center Scientific Visualization Studio./Courtesy NASA (right). Fig. 3.8: Morning in the Tropics, c.1858 (oil on canvas), Church, Frederic Edwin (1826-1900) / © Walters Art Museum, Baltimore, USA / The Bridgeman Art Library. Fig. 3.10a: Tim Tadder/©AP/Wide World Photos (top). Fig. 3.10c: Ed Keller (bottom). Fig. 3.13: All Canada Photos/Alamy. Fig. 3.15b: AGStockUSA/Alamy (right). Fig. 3.15c: Colin Woodbridge/Alamy (left). Fig. 3.17: Bohemian Nomad Picturemakers/©Corbis Images. Fig. 3.18: Wolfgang Kaehler/Alamy.

CHAPTER 4 Ch Op 4: AFP/Getty Images, Inc. Fig. 4.1a: ALFREDO ESTRELLA/AFP/Getty Images, Inc. (top). Fig. 4.1b: ©World Health Organization (bottom). Fig. 4.11: Jacobs Stock Photography/Photodisc/Getty Images, Inc.

CHAPTER 5 Ch Op 5: Dan Botkin. Fig. 5.1a: Alaska Stock/Alamy (top). Fig. 5.1b: David Nardini/Taxi/Getty Images, Inc. (bottom). Fig. 5.3: Farrell Grehan/Photo Researchers, Inc. Fig. 5.8a: Photographers Choice/Getty Images, Inc. (top left). Fig. 5.8b: Dan Botkin (top right). Fig. 5.9: Hubbard Brook Archives (bottom). Fig. 5.10a: Daniel Botkin (top left). Fig. 5.10b: Daniel Botkin (top right). Fig. 5.10c: Daniel Botkin (bottom left). Fig. 5.10d: Daniel Botkin (bottom right). Fig. 5.11: Mona Lisa Production/Science Photo Library. Fig. 5.14a: Masha Nordbye/Bruce Coleman, Inc. (left). Fig. 5.14b: Robert Harding Picture Library Ltd/Alamy (right). Fig. 5.15: Curlyson Photography/Flickr/Getty Images, Inc. (bottom). Fig. 5.16: Courtesy Daniel Botkin. Fig. 5.18: Michael P. Gadomski/ (left). Fig. 5.19: David B Fleetham/Photolibrary/Getty Images, Inc. (right). Fig. 5.22b: Theo Allofs/Getty Images, Inc. (left). Fig. 5.22c: David Aubrey/©Corbis Images (right).

CHAPTER 6 Ch Op 6: Mr. Eric Zimmerman. Fig. 6.1: Prof. Ed Keller. Fig. 6.2b: Prof. David Valentine (left). Fig. 6.2c: Prof. David Valentine (right). Fig. 6.4: NASA Images. Fig. 6.5: Flirt/SuperStock. Fig. 6.6a: MICHAEL AND PATRICIA FOGDEN/MINDEN PICTURES/NG Image Collection (bottom left). Fig. 6.6b: Georgette Douwma/Photo Researchers (bottom right). Fig. 6.7a: Dr. Patricia Schultz/Peter Arnold, Inc. (left). Fig. 6.7b: Kari Lounatmaa/Photo Researchers (right). Fig. 6.12a: Kim Heacox/Peter Arnold, Inc. (left). Fig. 6.12b: LUIS MARDEN/NG Image Collection (right). Fig. 6.20a: Peter Crighton/Alamy (left). Fig. 6.20b: Markus Renner/Getty Images, Inc. (right). Fig. 6.21: Melissa Farlow/NG Image Collection.

CHAPTER 7 Ch Op 7: Tom Brakefield /SuperStock. Fig. 7.1: Eric Draper/Aurora Photos/. Fig. 7.2: SuperStock. Fig. 7.3: Steve Kazlowski/Danita Delimont. Fig. 7.4: DENNIS ANDERSON/MCT/Landov LLC. Fig. 7.6: Jaime Abecasis / TopFoto/The Image Works. Fig. 7.7: Dan Botkin. Fig. 7.8: Photonica/Getty Images, Inc.

CHAPTER 8 Fig. 8.1a: Courtesy USDA (left). Fig. 8.1b: ©AP/Wide World Photos (right). Fig. 8.3: Rob Crandall/The Image Works. Fig. 8.5: Dr. Ian Woxvold of the University of Melbourne Zoology Dept. Fig. 8.6a: Oliver Meckes/Photo Researchers, Inc (left). Fig. 8.6b: Oliver Meckas/Photo Researchers, Inc (center). Fig. 8.6c: Adam Jones/Photo Researchers, Inc (right). Fig. 8.7a: Paula Bronstein / Getty Images, Inc. Fig. 8.8: All Canada Photos/Alamy. Fig. 8.10a: David Tipling/Getty Images, Inc. (left). Fig. 8.10b: Big Stock Photo (right). Fig. 8.17a: S. Greg Panosian/iStockphoto (top left). Fig. 8.17b: Jim Parkin/iStockphoto (top right). Fig. 8.17c: imagebroker/Alamy (center). Fig. 8.18a: John Carnemolla/iStockphoto (bottom left). Fig. 8.18b: Toni Angermayer/Photo Researchers (bottom center). Fig. 8.18c: Gary Unwin/iStockphoto (bottom right).

CHAPTER 9 Ch Op 9: Franz Marc Frei/Corbis Images. Fig. 9.2: Joe Raedle/Getty Images, Inc. Fig. 9.3: Cameron Davidson /Alamy (left). Fig. 9.4: Cameron Davidson/Alamy (right). Fig. 9.6: age fotostock/SuperStock. Fig. 9.7: Brand X Pictures/Getty Images, Inc. Fig. 9.8a: Nik Wheeler/©Corbis (left). Fig. 9.9: Corbis/SuperStock (top). Fig. 9.10a: Gary Crabbe/Alamy (bottom left). Fig. 9.10b: Ian Shive/Aurora Photos/Corbis Images (bottom right). Fig. 9.11a: Kaido KÑrner/Alamy (left). Fig. 9.11b: Tom Brakefield/©Photolibrary (right). Fig. 9.12: Robert Morris//Alamy (left). Fig. 9.13: Courtesy Ed Keller (right).

CHAPTER 10 Ch Op 10: ©AP/Wide World Photos. Fig. 10.1a: T. Orban/©Corbis (top). Fig. 10.1b: David & Peter Turnley/©Corbis (bottom). Fig. 10.2: Prof. Ed Keller. Fig. 10.3a: Bill Brooks/Masterfile (left). Fig. 10.3b: Greg Taylor/Alamy (right). Fig. 10.6: O. Franken/©Corbis. Fig. 10.7: Stephen Dalton/Photo Researchers. Fig. 10.9c: Martin Bond/Photo Researchers. Fig. 10.10: NANJLA TANJUNG/Reuters/Landov LLC. Fig. 10.16: (c)AP/Wide World Photos.

CHAPTER 11 Ch Op 11: Courtesy USDA. Fig. 11.1: Debbie Roos, North Carolina Cooperative Extension. Fig. 11.4: Bettmann Archive/©Corbis. Fig. 11.6: ©AP/Wide World Photos. Fig. 11.8a: Kevin Morris/Getty Images, Inc. (left). Fig. 11.8b: JC Carton/Bruce Coleman, Inc. (center). Fig. 11.8c: Du an Kosti /iStockphoto (right). Fig. 11.15: ©Corbis (top left). Fig. 11.11: SuperStock. Fig. 11.16: Daniel Valla/Alamy. Fig. 11.19: Bullit Marquez/©AP/Wide World Photos. Fig. 11.20a: Simko/Visuals Unlimited (top left). Fig. 11.20b: JAY DIRECTO/AFP/Getty Images/NewsCom (top right). Fig. 11.20c: Gaertner/Alamy (bottom). Fig. 11.21: Doug Plummer/Photo Researchers (bottom).

CHAPTER 12 Ch Op 12: Courtesy Dan Botkin. Fig. 12.1a: Courtesy Dan Botkin. Fig. 12.2: Radius/SuperStock (top). Fig. 12.1: IndexStock/SuperStock. Fig. 12.12: Global Warming Images/Alamy. Fig. 12.13a: Steve McCurry/Magnum Photos, Inc. (top). Fig. 12.13b: John Warburton-Lee Photography/Alamy (bottom). Fig. 12.14a: Photo Researchers (left). Fig. 12.14b: Gregory G. Dimijian, M.D./Photo Researchers (right). Fig. 12.15: Chee-Onn Leong/iStockphoto. Fig. 12.16a: Courtesy Dan Botkin. Fig. 12.17: Rich Reid/Getty Images, Inc.

CHAPTER 13 Ch Op 13: Courtesy Dan Botkin. Fig. 13.1: PhotoDisc, Inc. Fig. 13.2a: WILLIAM ALBERT ALLARD/NG Image Collection (top). Fig. 13.2b: Buffalo Hunt Chase (colour litho); Catlin, George (1794-1872); colour lithograph; 600 X 414; © Butler Institute of American Art, Youngstown, OH, USA; PERMISSION REQUIRED FOR NON EDITORIAL USAGE; Out of copyright (bottom). Fig. 13.4a: Ken Lucas/Visuals Unlimited. Fig. 13.6a: David South /Alamy (left). Fig. 13.6b: Jeffrey L. Rotman/©Corbis (center). Fig. 13.6c: Jeffrey Rotman/©Corbis (right). Fig. 13.9a: Courtesy NOAA. Fig. 13.10a: US Bureau of Reclamation (top). Fig. 13.11: Corbis/SuperStock, Inc. (bottom). Fig. 13.12: ©NB, Picture Archive, Cod. med. graec, fol. 164v. Fig. 13.14: John Cunningham/Visuals Unlimited. Fig. 13.15a: Francois Gohier/Photo Researchers (left). Fig. 13.15b: Denis Scott/©Corbis (right). Fig. 13.16a: Richard Elliott/Getty Images, Inc. (top). Fig. 13.16b: ©T. ULRICH / ClassicStock/The Image Works (center). Fig. 13.16c: Dianne Blell/Peter Arnold, Inc. (bottom). Fig. 13.17a: Gilbert Grant/Photo Researchers (top). Fig. 13.17b: Photo Researchers (bottom).

CHAPTER 14 Ch Op 14: ©AP/Wide World Photos. Fig. 14.1: Taxi/Getty Images, Inc.

CHAPTER 15 Ch Op 15: NASA Images (top). Ch Op 15-inset: Gerald Herbert/©AP/Wide World Photos (bottom). Fig. 15.3: Courtesy Ed Keller. Fig. 15.7a: George Hunter/Getty Images, Inc. (left). Fig. 15.7b: Ken Graham/Bruce Coleman, Inc. (right). Fig. 15.8: U.S. Fish and Wildlife Service/Liaison Agency, Inc./Getty Images. Fig. 15.9b: ©AP/Wide World Photos (left). Fig. 15.9c: U.S. Fish and Wildlife Service/Getty Images, Inc. (right). Fig. 15.13: ©AP/Wide World Photos. Fig. 15.14: IndexStock/SuperStock. Fig. 15.15a: Prof. Ed Keller (top). Fig. 15.15b: Prof. Ed Keller (bottom). Fig. 15.16: Mandel Ngan/Getty Images (top). Fig. 15.17: William P. Hines/The Scranton Times Tribune Library (bottom). Fig. 15.18: Wally Bauman/Alamy.

CHAPTER 16 Ch Op 16: age fotostock/SuperStock. Fig. 16.1: JORGE SILVA/Reuters/Landov LLC. Fig. 16.4b: JAMES P. BLAIR/NG Image Collection. Fig. 16.7a: H. Gruyaeart//Magnum Photos, Inc. (left). Fig. 16.7b: Prof. Ed Keller (right). Fig. 16.8: Courtesy Dan Botkin (bottom). Fig. 16.9a: Paul Harris/NewsCom. Fig. 16.12: Yann Arthus-Bertrand/©Corbis. Fig. 16.15: Glen Allison/Getty Images, Inc. Fig. 16.16: Kim Steele/Getty Images, Inc.

CHAPTER 17 Ch Op 17a: Courtesy Dan Botkin (top). Ch Op 17b: Courtesy Dan Botkin (bottom). Fig. 17.5a: Graham Finlayson/Getty Images, Inc. (top). Fig. 17.5: Martin Bond/Science Photo Library (bottom). Fig. 17.6: Roger Ressmeyer/Starlight/©Corbis. Fig. 17.12: ©Corbis. Fig. 17.14: Igor Kostin/©Corbis. Fig. 17.15: U.S. Department of Energy.

CHAPTER 18 Ch Op 18: Courtesy Dan Botkin. Fig. 18.1: Courtesy Ed Keller. Fig. 18.9: NASA Images (top). Fig. 18.10: AFP/EPA/NewsCom (bottom). Fig. 18.12b: USGS. Fig. 18.16a: Stephen Krasemann/Stone/Getty Images (top). Fig. 18.16b: Gregory G. Dimijian, M.D./Photo Researchers (bottom left). Fig. 18.16c: Jim Brandenburg/Minden Pictures, Inc. (bottom). Fig. 18.18: Courtesy Ed Keller. Fig. 18.19: Liu Liqun/©Corbis (top). Fig. 18.20: SuperStock (bottom). Fig. 18.21a: ©AP/Wide World Photos (left). Fig. 18.21b: STEVEN NEHL/The Oregonian/Landov LLC (right).

CHAPTER 19 Ch Op 19: Hans Pennink/©AP/Wide World Photos. Fig. 19.1: oote boe/Alamy Images. Fig. 19.2: Ben Osborne/Stone/Getty Images. Fig. 19.3: Courtesy Ed Keller (left). Fig. 19.4: McAllister/Liaison Agency, Inc./Getty Images (right). Fig. 19.7: Bohemian Nomad Picturemakers/©Corbis (top). Fig. 19.8: Thomas Del Brase/Getty Images, Inc. (bottom). Fig. 19.9: Photoshot Holdings Ltd/Alamy. Fig. 19.10: J. BLANK / ClassicStock/The Image Works (left). Fig. 19.12a: Courtesy Ed Keller (top). Fig. 19.12b: Courtesy Ed Keller (bottom). Fig. 19.18a: Courtesy John Day, Louisiana State University (top left). Fig. 19.18b: Courtesy John Day, Louisiana State University (bottom left). Fig. 19.18c: Courtesy John Day, Louisiana Stae University (right). Fig. 19.19: (c)Integrated Water Systmen, Inc (top). Fig. 19.20: Prof. Ed Keller (bottom). Fig. 19.22: John Althouse/Liaison Agency, Inc./Getty Images.

CHAPTER 20 Ch Op 20: Art Archive, The/SuperStock. Fig. 20.1: SuperStock. Fig. 20.3: NOAA. Fig. 20.12: Glasshouse Images/SuperStock. Fig. 20.12: Science Source/Photo Researchers. Fig. 20.13: Roger Ressmeyer/©Corbis. Fig. 20.14a: NASA Images (left). Fig. 20.14b: NASA Images (top). Fig. 20.14c: NASA Images (bottom). Fig. 20.24a: TORSTEN BLACKWOOD/AFP/Getty Images (left). Fig. 20.24b: Ashley Cooper/Alamy (right). Fig. 20.27: age fotostock/SUPERSTOCK. Fig. 20.28: David Tipling/Getty Images.

CHAPTER 21 Ch Op 21a: Larry Dunmire/SuperStock. Ch Op 21b: Comstock/Photolibrary. Fig. 21.1: F. Hoffman/The Image Works (left). Fig. 21.2: Courtesy Ed Keller (right). Fig. 21.8a: iStockphoto (left). Fig. 21.8b: David McNew/Getty Images, Inc. (right). Fig. 21.12a: YinYang/iStockphoto (top left). Fig. 21.12b: Natalia Bratslavsky/iStockphoto (top center). Fig. 21.12c: Lev Dolgatshjov/iStockphoto (top right). Fig. 21.12d: Eric Hood/iStockphoto (bottom left). Fig. 21.12e: oversnap/iStockphoto (bottom right). Fig. 21.18a: Andrew Syred/Photo Researchers (left). Fig. 21.18b: Oliver Meckes/Photo Researchers (right).

CHAPTER 22 Ch Op 22: Irwin Thompson/Melanie Burford/Dallas Morning News/©Corbis. Fig. 22.1a: Bettmann/©Corbis (top left). Fig. 22.1b: Courtesy Dan Botkin (bottom left). Fig. 22.1c: BEBETO MATTHEWS/AP/Wide World Photos (top right). Fig. 22.4a: U. S. Army Corps of Engineers (bottom). Fig. 22.4b: Thinkstock/Getty Images (top). Fig. 22.5a: Alamy Images (left). Fig. 22.5b: Marc Serota/Reuters/Landov LLC (right). Fig. 22.6: Tim Vasquez/Weather Graphics. Fig. 22.7: Photononstop/SUPERSTOCK. Fig. 22.9: Patrick Ward/©Corbis. Fig. 22.12: Courtesy Dan Botkin (left). Fig. 22.13: Robert Holmes/©Corbis (right). Fig. 22.15: Jim Zipp/Photo Researchers, Inc.

CHAPTER 23 Ch Op 23: Joanne Carole/©AP/Wide World Photos. Fig. 23.3: Helen Thompson/Animals Animals Earth Scenes. Fig. 23.5: Bettmann/©Corbis (top). Fig. 23.6: Ed Keller (bottom). Fig. 23.7a: Stone/Getty Images (top left). Fig. 23.7b: Craig Aurness/©Corbis (top center). Fig. 23.7c: © R. Maissonneuve/Publiphoto/Photo Researchers (top right). Fig. 23.7d: Stone/Getty Images (bottom left). Fig. 23.7e: Montana Stock Photography/Alamy (bottom right). Fig. 23.8: Courtesy of Fossil Trace Golf Course. Fig. 23.11: Ricardo Moraes/©AP/Wide World Photos. Fig. 23.14b: Courtesy EPA. Fig. 23.15: Bob Sacha/©Corbis. Fig. 23.16: Courtesy of Gloucester Fire Service & Sandhurst Area Action Group (left). Fig. 23.17: Courtesy of Gloucester Fire Service & Sandhurst Area Action Group (right). Fig. 23.21: Courtesy of Cynthia Vanderlip/Algalita Marine Research Foundation.

CHAPTER 24 Ch Op 24: United States Coast Guard. Fig. 24.1a: NOAA. Fig. 24.2a: NOAA (top left). Fig. 24.2b: Patrick Semansky/AP/Wide World Photos (top right). Fig. 24.2c: NOAA (center left). Fig. 24.2d: NOAA (center right). Fig. 24.2e: Win McNamee /Getty Images, Inc. (bottom). Fig. 24.3: John Dooley/Sipa Press/NewsCom. Fig. 24.4a: Win McNamee/Getty Images, Inc. (top). Fig. 24.4b: Spencer Platt /Getty Images, Inc. (bottom). Fig. 24.6: Tennessee Valley Authority. Fig. 24.7: B. Anthony Stewart/National Geographic/Getty Images, Inc. Fig. 24.8: Library of Congress Prints and Photographs Division. Fig. 24.10: Stone/Getty Images. Fig. 24.11a: Tom Van Sant/Photo Researchers (left). Fig. 24.11b: David W. Hamilton/The Image Bank/Getty Images (right).

Glossary

Abortion rate The estimated number of abortions per 1,000 women aged 15 to 44 in a given year. (Ages 15 to 44 are taken to be the limits of ages during which women can have babies. This, of course, is an approximation, made for convenience.)

Abortion ratio The estimated number of abortions per 1,000 live births in a given year.

Acceptable Risk The risk that individuals, society, or institutions are willing to take.

Acid mine drainage Acidic water that drains from mining areas (mostly coal but also metal mines). The acidic water may enter surface water resources, causing environmental damage.

Acid rain Rain made acid by pollutants, particularly oxides of sulfur and nitrogen. (Natural rainwater is slightly acid owing to the effect of carbon dioxide dissolved in the water.)

Active solar energy systems Direct use of solar energy that requires mechanical power; usually consists of pumps and other machinery to circulate air, water, or other fluids from solar collectors to a heat sink where the heat may be stored.

Acute disease a disease that appears rapidly in the population, affects a comparatively large percentage of it, and then declines or almost disappears for a while, only to reappear later.

Adaptive radiation The process that occurs when a species enters a new habitat that has unoccupied niches and evolves into a group of new species, each adapted to one of these niches.

Advanced wastewater treatment Treatment of wastewater beyond primary and secondary procedures. May include sand filters, carbon filters, or application of chemicals to assist in removing potential pollutants such as nutrients from the wastewater stream.

Aerobic Characterized by the presence of free oxygen.

Aesthetic justification for the conservation of nature An argument for the conservation of nature on the grounds that nature is beautiful and that beauty is important and valuable to people.

Age dependency ratio The ratio of dependent-age people (those unable to work) to working-age people. It is customary to define working-age people as those aged 15 to 65.

Age structure (of a population) A population divided into groups by age. Sometimes the groups represent the actual number of each age in the population; sometimes the groups represent the percentage or proportion of the population of each age.

Agroecosystem An ecosystem created by agriculture. Typically it has low genetic, species, and habitat diversity.

Air quality standards Levels of air pollutants that delineate acceptable levels of pollution over a particular time period. Valuable because they are often tied to emission standards that attempt to control air pollution.

Air toxics Those air pollutants known or suspected to cause cancer and other serious health problems from either long- or short-term exposure.

Allowance trading An approach to managing coal resources and reducing pollution through buying, selling, and trading of allowances to emit pollutants from burning coal. The idea is to control pollution by controlling the number of allowances issued.

Alpha particles One of the major types of nuclear radiation, consisting of two protons and two neutrons (a helium nucleus).

Alternative energy Renewable and nonrenewable energy resources that are alternatives to the fossil fuels.

Anaerobic Characterized by the absence of free oxygen.

Aquaculture Production of food from aquatic habitats.

Aquifer An underground zone or body of earth material from which groundwater can be obtained from a well at a useful rate.

Area sources Sometimes also called nonpoint sources. These are diffuse sources of pollution such as urban runoff or automobile exhaust. These sources include emissions that may be over a broad area or even over an entire region. They are often difficult to isolate and correct because of the widely dispersed nature of the emissions.

Asbestos A term for several minerals that have the form of small elongated particles. Some types of particles are believed to be carcinogenic or to carry with them carcinogenic materials.

Atmosphere Layer of gases surrounding Earth.

Atmospheric inversion A condition in which warmer air is found above cooler air, restricting air circulation; often associated with a pollution event in urban areas.

Autotroph An organism that produces its own food from inorganic compounds and a source of energy. There are photoautotrophs and chemical autotrophs.

Average residence time A measure of the time it takes for a given part of the total pool or reservoir of a particular material in a system to be cycled through the system. When the size of the pool and rate of throughput are constant, average residence time is the ratio of the total size of the pool or reservoir to the average rate of transfer through the pool.

Balance of nature An environmental myth that the natural environment, when not influenced by human activity, will reach a constant status, unchanging over time, referred to as an equilibrium state.

Barrier island An island separated from the mainland by a salt marsh. It generally consists of a multiple system of beach ridges and is separated from other barrier islands by inlets that allow the exchange of seawater with lagoon water.

Becquerel A unit commonly used for radioactive decay in the International System (IS) of measurement.

Beta particles One of the three major kinds of nuclear radiation; electrons that are emitted when one of the protons or neutrons in the nucleus of an isotope spontaneously changes.

Biochemical oxygen demand (BOD) A measure of the amount of oxygen necessary to decompose organic material in a unit volume of water. As the amount of organic waste in water increases, more oxygen is used, resulting in a higher BOD.

Biogeochemical cycle The cycling of a chemical element through the biosphere; its pathways, storage locations, and chemical forms in living things, the atmosphere, oceans, sediments, and lithosphere.

Biogeography The large-scale geographic pattern in the distribution of species, and the causes and history of this distribution.

Biohydromettalurgy Combining biological and mining processes, usually involving microbes to help extract valuable metals such as gold from the ground. May also be used to remove pollutants from mining waste.

Biological control A set of methods to control pest organisms by using natural ecological interactions, including predation, parasitism, and competition. Part of integrated pest management.

Biological diversity Used loosely to mean the variety of life on Earth, but scientifically typically used as to consisting of three components: (1) genetic diversity—the total number of genetic characteristics; (2) species diversity; and (3) habitat or ecosystem diversity—the number of kinds of habitats or ecosystems in a given unit area. Species diversity in turn includes three concepts: *species richness*, *evenness*, and *dominance*.

Biological evolution The change in inherited characteristics of a population from generation to generation, which can result in new species.

Biological production The capture of usable energy from the environment to produce organic compounds in which that energy is stored.

Biomagnification Also called *biological concentration*. The tendency for some substances to concentrate with each trophic level. Organisms preferentially store certain chemicals and excrete others. When this occurs consistently among organisms, the stored chemicals increase as a percentage of the body weight as the material is transferred along a food chain or trophic level. For example, the concentration of DDT is greater in herbivores than in plants and greater in plants than in the nonliving environment.

Biomass The amount of living material, or the amount of organic material contained in living organisms, both as live and dead material, as in the leaves (live) and stem wood (dead) of trees.

Biomass energy The energy that may be recovered from biomass, which is organic material such as plants and animal waste.

Biomass fuel A new name for the oldest fuel used by humans. Organic matter, such as plant material and animal waste, that can be used as a fuel.

Biome A kind of ecosystem. The rain forest is an example of a biome; rain forests occur in many parts of the world but are not all connected to each other.

Bioremediation A method of treating groundwater pollution problems that utilizes microorganisms in the ground to consume or break down pollutants.

Biosphere Has several meanings. One is that part of a planet where life exists. On Earth it extends from the depths of the oceans to the summits of mountains, but most life exists within a few meters of the surface. A second meaning is the planetary system that includes and sustains life, and therefore is made up of the atmosphere, oceans, soils, upper bedrock, and all life.

Biota All the organisms of all species living in an area or region up to and including the biosphere, as in "the biota of the Mojave Desert" or "the biota in that aquarium."

Biotic province A geographic region inhabited by life-forms (species, families, orders) of common ancestry, bounded by barriers that prevent the spread of the distinctive kinds of life to other regions and the immigration of foreign species into that region.

Birth control The number born divided by the total number in the population.

Birth rate The rate at which births occur in a population, measured either as the number of individuals born per unit of time or as the percentage of births per unit of time compared with the total population.

Black lung disease Often called coal miner disease because it is caused by years of inhaling coal dust, resulting in damage to the lungs.

Body burden The amount of concentration of a toxic chemical, especially radionuclides, in an individual.

Breeder reactor A type of nuclear reactor that utilizes between 40% and 70% of its nuclear fuel and converts fertile nuclei to fissile nuclei faster than the rate of fission. Thus breeder reactors actually produce nuclear fuels.

Brines With respect to mineral resources, refers to waters with a high salinity that contain useful materials such as bromine, iodine, calcium chloride, and magnesium.

Buffers Materials (chemicals) that have the ability to neutralize acids. Examples include the calcium carbonate that is present in many soils and rocks. These materials may lessen potential adverse effects of acid rain.

Burner reactors A type of nuclear reactor that consumes more fissionable material than it produces.

Capillary action The rise of water along narrow passages, facilitated and caused by surface tension.

Carbon cycle Biogeochemical cycle of carbon. Carbon combines with and is chemically and biologically linked with the cycles of oxygen and hydrogen that form the major compounds of life.

Carbon monoxide (CO) A colorless, odorless gas that at very low concentrations is extremely toxic to humans and animals.

Carbon-silicate cycle A complex biogeochemical cycle over time scales as long as one-half billion years. Included in this cycle are major geologic processes, such as weathering, transport by ground and surface waters, erosion, and deposition of crustal rocks. The carbonate-silicate cycle is believed to provide important negative feedback mechanisms that control the temperature of the atmosphere.

Carcinogen Any material that is known to produce cancer in humans or other animals.

Carnivores Organisms that feed on other live organisms; usually applied to animals that eat other animals.

Carrying capacity The maximum abundance of a population or species that can be maintained by a habitat or ecosystem without degrading the ability of that habitat or ecosystem to maintain that abundance in the future.

Cash crops Crops grown to be traded in a market.

Catastrophe A situation or event that causes great damage to people, property or society and from which recovery is a long and involved process. Also defined as a very serious disaster.

Catch per unit effort The number of animals caught per unit of effort, such as the number of fish caught by a fishing ship per day. It is used to estimate the population abundance of a species.

Channelization An engineering technique that consists of straightening, deepening, widening, clearing, or lining existing stream channels. The purpose is to control floods, improve drainage, control erosion, or improve navigation. It is a very controversial practice that may have significant environmental impacts.

Chaparral A dense scrubland found in areas with Mediterranean climate (a long warm, dry season and a cooler rainy season).

Chemical reaction The process in which compounds and elements undergo a chemical change to become a new substance or substances.

Chemoautotrophs Autotrophic bacteria that can derive energy from chemical reactions of simple inorganic compounds.

Chemosynthesis Synthesis of organic compounds by energy derived from chemical reactions.

Chimney (or stack) effect A process whereby warmer air rises in buildings to upper levels and is replaced in the lower portion of the building by outdoor air drawn through a variety of openings, such as windows, doors, or cracks in the foundations and walls.

Chlorofluorocarbons (CFCs) Highly stable compounds that have been or are being used in spray cans as aerosol propellants and in refrigeration units (the gas that is compressed and expanded in a cooling unit). Emissions of chlorofluorocarbons have been associated with potential global warming and stratospheric ozone depletion.

Chronic disease A disease that is persistent in a population, typically occurring in a relatively small but constant percentage of the population.

Chronic hunger A condition in which there is enough food available per person to stay alive, but not enough to lead a satisfactory and productive life.

Chronic patchiness A situation where ecological succession does not occur. One species may replace another, or an individual of the first species may replace it, but no overall general temporal pattern is established. Characteristic of harsh environments such as deserts.

Classical stability A system characterized by constant conditions that, if disturbed from those conditions, will return to it once the factor that disturbed the system has been removed.

Clay May refer to a mineral family or to a very fine-grained sediment. It is associated with many environmental problems, such as shrinking and swelling of soils and sediment pollution.

Clean Air Act Amendments of 1990 Comprehensive regulations (federal statute) that address acid rain, toxic emissions, ozone depletion, and automobile exhaust.

Clear-cutting In timber harvesting, the practice of cutting all trees in a stand at the same time.

Climate The representative or characteristic conditions of the atmosphere at particular places on Earth. Climate refers to the average or expected conditions over long periods; weather refers to the particular conditions at one time in one place.

Climatic change Change in mean annual temperature and other aspects of climate over periods of time ranging from decades to hundreds of years to several million years.

Climate forcing An imposed perturbation of Earth energy that balance major climatic forcings associated with global warming. Includes: greenhouse gases, such as carbon dioxide and methane; reflective aerosols in the atmosphere, black carbon. Forcing of the climate system also includes solar activity and Milankovitch Cycles.

Climax stage (or ecological succession) The final stage of ecological succession and therefore an ecological community that continues to reproduce itself over time.

Closed system A system in which there are definite boundaries to mass and energy and thus exchange of these factors with other systems does not occur.

Closed-canopy forest Forests in which the leaves of adjacent trees overlap or touch, so that the trees form essentially continuous cover.

Coal Solid, brittle carbonaceous rock that is one of the world's most abundant fossil fuels. It is classified according to energy content as well as carbon and sulfur content.

Coal gasification Process that converts coal that is relatively high in sulfur to a gas in order to remove the sulfur.

Cogeneration The capture and use of waste heat; for example, using waste heat from a power plant to heat adjacent factories and other buildings.

Cohort All the individuals in a population born during the same time period. Thus all the people born during the year 2005 represent the world human cohort for that year.

Common law Law derived from custom, judgment, or decrees of courts rather than from legislation.

Commons Land that belongs to the public, not to individuals. Historically a part of old English and New England towns where all the farmers could graze their cattle.

Community, ecological A group of populations of different species living in the same local area and interacting with one another. A community is the living portion of an ecosystem.

Community effect (community-level effect) When the interaction between two species leads to changes in the presence or absence of other species or to a large change in abundance of other species, then a community effect is said to have occurred.

Competition The situation that exists when different individuals, populations, or species compete for the same resource(s) and the presence of one has a detrimental effect on the other. Sheep and cows eating grass in the same field are competitors.

Competitive exclusion principle The idea that two populations of different species with exactly the same requirements cannot persist indefinitely in the same habitat—one will always win out and the other will become extinct.

Composting Biochemical process in which organic materials, such as lawn clippings and kitchen scraps, are decomposed to a rich, soil-like material.

Comprehensive plan An official plan adopted by local government formally stating general and long-range policies concerning future development.

Cone of depression A cone-shaped depression in the water table around a well caused by withdrawal by pumping water faster than the water can be replenished by natural groundwater flow.

Conservation With respect to resources such as energy, refers to changing our patterns of use or simply getting by with less. In a pragmatic sense the term means adjusting our needs to minimize the use of a particular resource, such as energy.

Consumptive use A type of off-stream water use. This water is consumed by plants and animals or in industrial processes or evaporates during use. It is not returned to its source.

Contamination The presence of undesirable material that makes something unfit for a particular use.

Continental drift The movement of continents in response to seafloor spreading. The most recent episode of continental drift started about 200 million years ago with the breakup of the supercontinent Pangaea.

Continental shelf The relatively shallow ocean area between the shoreline and the continental slope that extends to approximately a 600-foot (~200 m) water depth surrounding a continent.

Contour plowing Plowing land along topographic contours, as much in a horizontal plane as possible, thereby decreasing the erosion rate.

Controlled experiment A controlled experiment is designed to test the effects of independent variables on a dependent variable by changing only one independent variable at a time. For each variable tested, there are two setups (an experiment and a control) that are identical except for the independent variable being tested. Any difference in the outcome (dependent variable) between the experiment and the control can then be attributed to the effects of the independent variable tested.

Convection The transfer of heat involving the movement of particles; for example, the boiling water in which hot water rises to the surface and displaces cooler water, which moves toward the bottom.

Convergent evolution The process by which species evolve in different places or different times and, although they have different genetic heritages, develop similar external forms and structures as a result of adaptation to similar environments. The similarity in the shapes of sharks and porpoises is an example of convergent evolution.

Convergent plate boundary A boundary between two lithosphere plates in which one plate descends below the other (subduction).

Cosmopolitan species A species with a broad distribution, occurring wherever in the world the environment is appropriate.

Creative justification for the conservation of nature An argument for the conservation of nature on the grounds that people often find sources of artistic and scientific creativity in their contacts with the unspoiled natural world.

Criteria pollutants Are the sixth most common air pollutants: sulfur dioxide, nitrogen oxides, carbon monoxide, ozone and other photochemical oxidants, particulate matter, and lead.

Crop rotation A series of different crops planted successively in the same field, with the field occasionally left fallow, or grown with a cover crop.

Crude oil Naturally occurring petroleum, normally pumped from wells in oil fields. Refinement of crude oil produces most of the petroleum products we use today.

Cultural eutrophication Human-induced eutrophication that involves nutrients such as nitrates or phosphates that cause a rapid increase in the rate of plant growth in ponds, lakes, rivers, or the ocean.

Cultural justification With respect to environmental values refers to the fact that different cultures have many of the same values but differ in others.

Curie Commonly used unit to measure radioactive decay; the amount of radioactivity from 1 gram of radium 226 that undergoes about 37 billion nuclear transformations per second.

Death rate The rate at which deaths occur in a population, measured either as the number of individuals dying per unit time or as the percentage of a population dying per unit time.

Decomposers Organisms that feed on dead organic matter.

Deductive reasoning Drawing a conclusion from initial definitions and assumptions by means of logical reasoning.

Deep-well disposal Method of disposal of hazardous liquid waste that involves pumping the waste deep into the ground below and completely isolated from all freshwater aquifers. A controversial method of waste disposal that is being carefully evaluated.

Demand for food The amount of food that would be bought at a given price if it were available.

Demand-based agriculture Agriculture with production determined by economic demand and limited by that demand rather than by resources.

Demographic transition The pattern of change in birth and death rates as a country is transformed from undeveloped to developed. There are three stages: (1) in an undeveloped country, birth and death rates are high and the growth rate low; (2) the death rate decreases, but the birth rate remains high and the growth rate is high; (3) the birth rate drops toward the death rate and the growth rate therefore also decreases.

Demography The study of populations, especially their patterns in space and time.

Dependent variable See **Variable, dependent.**

Denitrification The conversion of nitrate to molecular nitrogen by the action of bacteria—an important step in the nitrogen cycle.

Density-dependent population effects Factors whose effects on a population change with population density.

Density-independent population effects Changes in the size of a population due to factors that are independent of the population size. For example, a storm that knocks down all trees in a forest, no matter how many there are, is a density-independent population effect.

Desalination The removal of salts from seawater or brackish water so that the water can be used for purposes such as agriculture, industrial processes, or human consumption.

Desertification The process of creating a desert where there was not one before.

Dioxin An organic compound composed of oxygen, hydrogen, carbon, and chlorine. About 75 types are known. Dioxin is not normally manufactured intentionally but is a by-product resulting from chemical reactions in the production of other materials, such as herbicides. Known to be extremely toxic to mammals, its effects on the human body are being intensively studied and evaluated.

Direct costs Costs borne by the producer in obtaining, processing, and distributing a product.

Direct effects With respect to natural hazards, refers to the number of people killed, injured, dislocated, made homeless or otherwise damaged by a hazardous event.

Disaster A hazardous event that occurs over a limited span of time in a defined geographic area. Loss of human life and property damage are significant.

Disprovability The idea that a statement can be said to be scientific if someone can clearly state a method or test by which it might be disproved.

Divergent evolution Organisms with the same ancestral genetic heritage migrate to different habitats and evolve into species with different external forms and structures, but typically continue to use the same kind of habitats. The ostrich and the emu are believed to be examples of divergent evolution.

Divergent plate boundary A boundary between lithospheric plates characterized by the production of new lithosphere; found along oceanic ridges.

Diversity, genetic The total number of genetic characteristics, sometimes of a specific species, subspecies, or group of species.

Diversity, habitat The number of kinds of habitats in a given unit area.

Diversity, species Used loosely to mean the variety of species in an area or on Earth. Technically, it is composed of three components: species richness—the total number of species; species evenness—the relative abundance of species; and species dominance—the most abundant species.

Dobson unit Commonly used to measure the concentration of ozone. One Dobson unit is equivalent to a concentration of 1 ppb ozone.

Dominant species Generally, the species that are most abundant in an area, ecological community, or ecosystem.

Dominants In forestry, the tallest, most numerous, and most vigorous trees in a forest community.

Dose dependency Dependence on the dose or concentration of a substance for its effects on a particular organism.

Dose–response The principle that the effect of a certain chemical on an individual depends on the dose or concentration of that chemical.

Doubling time The time necessary for a quantity of whatever is being measured to double.

Drainage basin The area that contributes surface water to a particular stream network.

Drip irrigation Irrigation of soil through tubes that drip water slowly, greatly reducing the loss of water from direct evaporation and increasing yield.

Drought A period of months or more commonly years of unusually dry weather.

Dynamic equilibrium A steady state of a system that with negative feedback will return to a quasi-equilibrium state following disturbance.

Dynamic system Characterized by a system that changes often and continually over time.

Early-successional species Species that occur only or primarily during early stages of succession.

Earth system science The science of Earth as a system. It includes understanding processes and linkages between the lithosphere, hydrosphere, biosphere, and atmosphere.

Earthquake Generation of earthquake or seismic waves when rocks under stress fracture and break, resulting in displacement along a fault.

Ecological community This term has two meanings. (1) A conceptual or functional meaning: a set of interacting species that occur in the same place (sometimes extended to mean a set that interacts in a way to sustain life). (2) An operational meaning: a set of species found in an area, whether or not they are interacting.

Ecological economics Study and evaluation of relations between humans and the economy with emphasis on long-term health of ecosystems and sustainability.

Ecological gradient A change in the relative abundance of a species or group of species along a line or over an area.

Ecological island An area that is biologically isolated so that a species occurring within the area cannot mix (or only rarely mixes) with any other population of the same species.

Ecological justification for the conservation of nature An argument for the conservation of nature on the grounds that a species, an ecological community, an ecosystem, or Earth's biosphere provides specific functions necessary to the persistence of our life or of benefit to life. The ability of trees in forests to remove carbon dioxide produced in burning fossil fuels is such a public benefit and an argument for maintaining large areas of forests.

Ecological niche The general concept is that the niche is a species' "profession"—what it does to make a living. The term is also used to refer to a set of environmental conditions within which a species is able to persist.

Ecological succession The process of the development of an ecological community or ecosystem, usually viewed as a series of stages—early, middle, late, mature (or climax), and sometimes postclimax. Primary succession is an original establishment; secondary succession is a reestablishment.

Ecology The science of the study of the relationships between living things and their environment.

Ecosystem An ecological community and its local, nonbiological community. An ecosystem is the minimum system that includes and sustains life. It must include at least an autotroph, a decomposer, a liquid medium, a source and sink of energy, and all the chemical elements required by the autotroph and the decomposer.

Ecosystem effect Effects that result from interactions among different species, effects of species on chemical elements in their environment, and conditions of the environment.

Ecosystem energy flow The flow of energy through an ecosystem—from the external environment through a series of organisms and back to the external environment.

Ecotopia A society based on sustainable development and sound environmental planning characterized by a stable human population within the carrying capacity of earth. It is thought of as an ideal state.

Ecotourism Tourism based on an interest in observing of nature.

ED-50 The effective dose, or dose that causes an effect in 50% of the population on exposure to a particular toxicant. It is related to the onset of specific symptoms, such as loss of hearing, nausea, or slurred speech.

Edge effect An effect that occurs following the forming of an ecological island; in the early phases the species diversity along the edge is greater than in the interior. Species escape from the cut area and seek refuge in the border of the forest, where some may last only a short time.

Efficiency The primary definition used in the text is the ratio of output to input. With machines, usually the ratio of work or power produced to the energy or power used to operate or fuel them. With living things, efficiency may be defined as either the useful work done or the energy stored in a useful form compared with the energy taken in.

Efficiency improvements With respect to energy, refers to designing equipment that will yield more energy output from a given amount of energy input.

Effluent Any material that flows outward from something. Examples include wastewater from hydroelectric plants and water discharged into streams from waste-disposal sites.

Effluent stream Type of stream where flow is maintained during the dry season by groundwater seepage into the channel.

El Niño Natural perturbation of the physical earth system that affects global climate. Characterized by development of warm oceanic waters in the eastern part of the tropical Pacific Ocean, a weakening or reversal of the trade winds, and a weakening or even reversal of the equatorial ocean currents. Reoccurs periodically and affects the atmosphere and global temperature by pumping heat into the atmosphere.

Electromagnetic fields (EMFs) Magnetic and electrical fields produced naturally by our planet and also by appliances such as toasters, electric blankets, and computers. There currently is controversy concerning potential adverse health effects related to exposure to EMFs in the workplace and home from such artificial sources as power lines and appliances.

Electromagnetic spectrum All the possible wavelengths of electromagnetic energy, considered as a continuous range. The spectrum includes long wavelength (used in radio transmission), infrared, visible, ultraviolet, X rays, and gamma rays.

Endangered species A species that faces threats that might lead to its extinction in a short time.

Endemic species A species that has evolved in, and lives only within, a specific location. e.g. the California condor is endemic to the Pacific coast of North America.

Energy An abstract concept referring to the ability or capacity to do work.

Energy efficiency Refers to both first-law efficiency and second-law efficiency, where first-law efficiency is the ratio of the actual amount of energy delivered to the amount of energy supplied to meet a particular need, and second-law efficiency is the ratio of the maximum available work needed to perform a particular task to the actual work used to perform that task.

Energy flow The movement of energy through an ecosystem from the external environment through a series of organisms and back to the external environment. It is one of the fundamental processes common to all ecosystems.

Entropy A measure in a system of the amount of energy that is unavailable for useful work. As the disorder of a system increases, the entropy in a system also increases.

Environment All factors (living and nonliving) that actually affect an individual organism or population at any point in the life cycle. *Environment* is also sometimes used to denote a certain set of circumstances surrounding a particular occurrence (environments of deposition, for example).

Environmental audit A process of determining the past history of a particular site, with special reference to the existence of toxic materials or waste.

Environmental economics Economic effects of the environment and how economic processes affect that environment, including its living resources.

Environmental ethics A school, or theory, in philosophy that deals with the ethical value of the environment.

Environmental geology The application of geologic information to environmental problems.

Environmental impact The effects of some action on the environment, particularly action by human beings.

Environmental impact report (EIR) Similar to the environmental impact statement, a report describing potential environmental impacts resulting from a particular project, often at the state level.

Environmental impact statement (EIS) A written statement that assesses and explores possible impacts associated with a particular project that may affect the human environment. The statement is required in the United States by the National Environmental Policy Act of 1969.

Environmental justice The principle of dealing with environmental problems in such a way as to not discriminate against people based upon socioeconomic status, race, or ethnic group.

Environmental law A field of law concerning the conservation and use of natural resources and the control of pollution.

Environmental tobacco smoke Commonly called secondhand smoke from people smoking tobacco.

Environmental unity A principle of environmental sciences that states that everything affects everything else, meaning that a particular course of action could lead to a string of events. Another way of stating this idea is that you can't do only one thing.

Environmentalism A social, political, and ethical movement concerned with protecting the environment and using its resources wisely.

Epidemic disease A disease that appears occasionally in the population, affects a large percentage of it, and declines or almost disappears for a while only to reappear later.

Equilibrium A point of rest. At equilibrium, a system remains in a single, fixed condition and is said to be in equilibrium. Compare with **Steady state**.

Eukaryote An organism whose cells have nuclei and organelles. The eukaryotes include animals, fungi, vegetation, and many single-cell organisms.

Eutrophic Referring to bodies of water having an abundance of the chemical elements required for life.

Eutrophication Increase in the concentration of chemical elements required for living things (for example, phosphorus). Increased nutrient loading may lead to a population explosion of photosynthetic algae and blue-green bacteria that become so thick that light cannot penetrate the water. Bacteria deprived of light beneath the surface die; as they decompose, dissolved oxygen in the lake is lowered and eventually a fish kill may result. Eutrophication of lakes caused by human-induced processes, such as nutrient-rich sewage water entering a body of water, is called cultural eutrophication.

Even-aged stands A forest of trees that began growth in or about the same year.

Evolution, biological The change in inherited characteristics of a population from generation to generation, sometimes resulting in a new species.

Evolution, nonbiological Outside the realm of biology, the term *evolution* is used broadly to mean the history and development of something.

Exotic species Species introduced into a new area, one in which it had not evolved.

Experimental errors There are two kinds of experimental errors, random and systematic. Random errors are those due to chance events, such as air currents pushing on a scale and altering a measurement of weight. In contrast, a miscalibration of an instrument would lead to a systematic error. Human errors can be either random or systematic.

Exponential growth Growth in which the rate of increase is a constant percentage of the current size; that is, the growth occurs at a constant rate per time period.

Exponential growth rate The annual growth rate is a constant percentage of the population.

Externality In economics, an effect not normally accounted for in the cost–revenue analysis.

Extinction Disappearance of a life-form from existence; usually applied to a species.

Facilitation During succession, one species prepares the way for the next (and may even be necessary for the occurrence of the next).

Fact Something that is known based on actual experience and observation.

Fall line The point on a river where there is an abrupt drop in elevation of the land and where numerous waterfalls occur. The line in the eastern United States is located where streams pass from harder to softer rocks.

Fallow A farm field unplanted or allowed to grow with a cover crop without harvesting for at least one season.

Fecal coliform bacteria Bacteria that occur naturally in human intestines and are used as a standard measure of microbial pollution and an indicator of disease potential for a water source.

Feedback A kind of system response that occurs when output of the system also serves as input leading to changes in the system.

First law of thermodynamics The principle that energy may not be created or destroyed but is always conserved.

First-law efficiency The ratio of the actual amount of energy delivered where it is needed to the amount of energy supplied in order to meet that need; expressed as a percentage.

Fission The splitting of an atom into smaller fragments with the release of energy.

Flood Inundation of an area by water, often produced by intense rain storms, melting of snow, storm surges from a hurricane, or tsunami, or failure of a flood-protection structure such as a dam.

Flooding, natural The process whereby waters emerge from their stream channel to cover part of the floodplain. Natural flooding is not a problem until people choose to build homes and other structures on floodplains.

Floodplain Flat topography adjacent to a stream in a river valley that has been produced by the combination of overbank flow and lateral migration of meander bends.

Fluidized-bed combustion A process used during the combustion of coal to eliminate sulfur oxides. Involves mixing finely ground limestone with coal and burning it in suspension.

Flux The rate of transfer of material within a system per unit time.

Food chain The linkage of who feeds on whom.

Food-chain concentration See **Biomagnification**.

Food web A network of who feeds on whom or a diagram showing who feeds on whom. It is synonymous with **food chain**.

Force A push or pull that affects motion. The product of mass and acceleration of a material.

Forcing With respect to global change, processes capable of changing global temperature, such as changes in solar energy emitted from the sun, or volcanic activity.

Fossil fuels Forms of stored solar energy created from incomplete biological decomposition of dead organic matter. Include coal, crude oil, and natural gas.

Fuel cell A device that produces electricity directly from a chemical reaction in a specially designed cell. In the simplest case the cell uses hydrogen as a fuel, to which an oxidant is supplied. The hydrogen is combined with oxygen as if the hydrogen were burned, but the reactants are separated by an electrolyte solution that facilitates the migration of ions and the release of electrons (which may be tapped as electricity).

Fugitive sources Type of stationary air pollution sources that generate pollutants from open areas exposed to wind processes.

Fusion, nuclear Combining of light elements to form heavier elements with the release of energy.

Gaia hypothesis The Gaia hypothesis states (1) that life has greatly altered the Earth's environment globally for more than 3 billion years and continues to do so; and (2) that these changes benefit life (increase its persistence). Some extend this, nonscientifically, to assert that life did it on purpose.

Gamma rays One of the three major kinds of nuclear radiation. A type of electromagnetic radiation emitted from the isotope similar to X-rays but more energetic and penetrating.

Garden city Land planning that considers a city and countryside together.

Gene A single unit of genetic information comprising of a complex segment of the four DNA base-paircompounds.

General circulation model (GCM) Consists of a group of computer models that focus on climate change using a series of equations, often based on conservation of mass and energy.

Genetic drift Changes in the frequency of a gene in a population as a result of chance rather than of mutation, selection, or migration.

Genetic risk Used in discussions of endangered species to mean detrimental change in genetic characteristics not caused by external environmental changes. Genetic changes can occur in small populations from such causes as reduced genetic variation, genetic drift, and mutation.

Genetically modified crops Crop species modified by genetic engineering to produce higher crop yields and increase resistance to drought, cold, heat, toxins, plant pests, and disease.

Genetically modified organisms Organisms created by genetic engineering, the altering of genes or genetic material to produce new organisms or organisms with desired characteristics, or to eliminate undesirable characteristics in organisms.

Geochemical cycles The pathways of chemical elements in geologic processes, including the chemistry of the lithosphere, atmosphere, and hydrosphere.

Geographic Information System (GIS) Technology capable of storing, retrieving, transferring, and displaying environmental data.

Geologic cycle The formation and destruction of earth materials and the processes responsible for these events. The geologic cycle includes the following subcycles: hydrologic, tectonic, rock, and geochemical.

Geometric growth See **Exponential growth**.

Geopressurized systems Geothermal systems that exist when the normal heat flow from the Earth is trapped by impermeable clay layers that act as an effective insulator.

Geothermal energy The useful conversion of natural heat from the interior of Earth.

Global circulation model (GCM) A type of mathematical model used to evaluate global change, particularly related to climatic change. GCMs are very complex and require supercomputers for their operation.

Global dimming The reduction of incoming solar radiation by reflection from suspended particles in the atmosphere and their interaction with water vapor (especially clouds).

Global forecasting Predicting or forecasting future change in environmental areas such as world population, natural resource utilization, and environmental degradation.

Global warming Natural or human-induced increase in the average global temperature of the atmosphere near Earth's surface.

Gravel Unconsolidated, generally rounded fragments of rocks and minerals greater than 2 mm in diameter.

Green building Designing buildings that have a healthy interior environment and landscape that benefits the local external environment as well.

Green plans Long-term strategies for identifying and solving global and regional environmental problems. The philosophical heart of green plans is sustainability.

Green revolution Name attached to post-World War II agricultural programs that have led to the development of new strains of crops with higher yield, better resistance to disease, or better ability to grow under poor conditions.

Greenbelt A belt of recreational parks, farmland, or uncultivated land surrounding or connecting urban communities, forming a system of countryside and urban landscapes.

Greenhouse effect Occurs when water vapor and several other gases warm the Earth's atmosphere by trapping some of the heat radiating from the Earth's atmospheric system.

Greenhouse gases The suite of gases that produce a greenhouse effect, such as carbon dioxide, methane, and water vapor.

Gross production (biology) Production before respiration losses are subtracted.

Groundwater Water found beneath the Earth's surface within the zone of saturation, below the water table.

Growth efficiency Gross production efficiency (P/C), or ratio of the material produced (P = net production) by an organism or population to the material ingested or consumed (C).

Growth rate The net increase in some factor per unit time. In ecology, the growth rate of a population, sometimes measured as the increase in numbers of individuals or biomass per unit time and sometimes as a percentage increase in numbers or biomass per unit time.

Habitat Where an individual, population, or species exists or can exist. For example, the habitat of the Joshua tree is the Mojave Desert of North America.

Half-life The time required for half the amount of a substance to disappear; the average time required for one-half of a radioisotope to be transformed to some other isotope; the time required for one-half of a toxic chemical to be converted to some other form.

Hard path Energy policy based on the emphasis of energy quantity generally produced from large, centralized power plants.

Hazardous waste Waste that is classified as definitely or potentially hazardous to the health of people. Examples include toxic or flammable liquids and a variety of heavy metals, pesticides, and solvents.

Heat energy Energy of the random motion of atoms and molecules.

Heat island Usually, a large city that is warmer air of a city than surrounding areas as a result of increased heat production and decreased heat loss because building and paving materials act as solar collectors.

Heat island effect Urban areas are several degrees warmer than their surrounding areas. During relatively calm periods there is an upward flow of air over heavily developed areas accompanied by a downward flow over nearby greenbelts. This produces an air-temperature profile that delineates the heat island.

Heat pumps Devices that transfer heat from one material to another, such as from groundwater to the air in a building.

Heat wave A period of days of weeks or unusually hot weather. A natural recurring weather phenomenon related to heating of the atmosphere and moving of air masses.

Heavy metals Refers to a number of metals, including lead, mercury, arsenic, and silver (among others); that have a relatively high atomic number (the number of protons in the nucleus of an atom). They are often toxic even at relatively low concentrations, causing a variety of environmental problems.

Herbivore An organism that feeds on an autotroph.

Heterotrophs Organisms that cannot make their own food from inorganic chemicals and a source of energy and therefore live by feeding on other organisms.

High-level radioactive waste Extremely toxic nuclear waste, such as spent fuel elements from commercial reactors.

Historical range of variation The known range of an environmental variable, such as the abundance of a species or the depth of a lake, over some past time interval.

Homeostasis The ability of a cell or organism to maintain a constant environment. Results from negative feedback, resulting in a state of dynamic equilibrium.

Hormonally active agents Chemicals in the environment able to cause reproductive and developmental abnormalities in animals, including humans.

Hot igneous systems Geothermal systems that involve hot, dry rocks with or without the presence of near-surface molten rock.

Human carrying capacity Theoretical estimates of the number of humans who could inhabit Earth at the same time.

Human demography The study of human population characteristics, such as age structure, demographic transition, total fertility, human population and environment relationships, death-rate factors, and standard of living.

Hurricane A tropical storm with circulating winds in excess of 120 km (74 mi) per hour that moves across warm ocean waters of the tropics.

Hutchinsonian niche The idea of a measured niche, the set of environmental conditions within which a species is able to persist.

Hydrocarbons Compounds containing only carbon and hydrogen. These organic compounds include petroleum products, such as crude oil and natural gas.

Hydrochlorofluorocarbons Also known as HCFCs, these are a group of chemicals containing hydrogen, chlorine, fluorine, and carbon, produced as a potential substitute for chlorofluorocarbons (CFCs).

Hydrofluorocarbons Chemicals containing hydrogen, fluorine, and carbons, produced as potential substitutes for chlorofluorocarbons (CFCs).

Hydrologic cycle Circulation of water from the oceans to the atmosphere and back to the oceans by way of evaporation, runoff from streams and rivers, and groundwater flow.

Hydrology The study of surface and subsurface water.

Hydroponics The practice of growing plants in a fertilized water solution on a completely artificial substrate in an artificial environment such as a greenhouse.

Hydrothermal convection systems A type of geothermal energy characterized by circulation of steam and/or hot water that transfers to the surface.

Hypothesis In science, an explanation set forth in a manner that can be tested and disproved. A tested hypothesis is accepted until and unless it has been disproved.

Igneous rocks Rocks made of solidified magma. They are extrusive if they crystallize on the surface of Earth and intrusive if they crystallize beneath the surface.

Incineration Combustion of waste at high temperature, consuming materials and leaving only ash and noncombustibles to dispose of in a landfill.

Independent variable See **Variable, independent.**

Indirect effects In regards to natural hazards, effects disaster. Include donations of money and goods as well as providing shelter for people and paying taxes that will help finance recovery and relief of emotional distress caused by natural hazardous events.

Inductive reasoning Drawing a general conclusion from a limited set of specific observations.

Industrial ecology The process of designing industrial systems to behave more like ecosystems where waste from one part of the system is a resource for another part.

Inference (1) A conclusion derived by logical reasoning from premises and/or evidence (observations or facts), or (2) a conclusion, based on evidence, arrived at by insight or analogy, rather than derived solely by logical processes.

Inflection point The point where a graphed curve or an equation representing that curve changes from convex to concave, or from concave to convex.

Influent stream Type of stream that is everywhere above the groundwater table and flows in direct response to precipitation. Water from the channel moves down to the water table, forming a recharge mound.

Input With respect to basic concepts of systems, refers to material or energy that enters a system.

Inspirational justification for the conservation of nature An argument for the conservation of nature on the grounds that direct experience of nature is an aid to spiritual or mental well-being.

In-stream use A type of water use that includes navigation, generation of hydroelectric power, fish and wildlife habitat, and recreation.

Intangible factor In economics, an intangible factor is one you can't touch directly, but you value it.

Integrated energy management Use of a range of energy options that vary from region to region, including a mix of technology and sources of energy.

Integrated pest management Control of agricultural pests using several methods together, including biological and chemical agents. A goal is to minimize the use of artificial chemicals; another goal is to prevent or slow the buildup of resistance by pests to chemical pesticides.

Integrated waste management (IWM) Set of management alternatives including reuse, source reduction, recycling, composting, landfill, and incineration.

Interference When, during succession, one species prevents the entrance of later-successional species into an ecosystem. For example, some grasses produce such dense mats that seeds of trees cannot reach the soil to germinate. As long as these grasses persist, the trees that characterize later stages of succession cannot enter the ecosystem.

Island arc A curved group of volcanic islands associated with a deep oceanic trench and subduction zone (convergent plate boundary).

Isotope Atoms of an element that have the same atomic number (the number of protons in the nucleus of the atom) but vary in atomic mass number (the number of protons plus neutrons in the nucleus of an atom).

Keystone species A species, such as the sea otter, that has a large effect on its community or ecosystem so that its removal or addition to the community leads to major changes in the abundances of many or all other species.

Kinetic energy The energy of motion. For example, the energy in a moving car that results from the mass of the car traveling at a particular velocity.

Kwashiorkor Lack of sufficient protein in the diet, which leads to a failure of neural development in infants and therefore to learning disabilities.

Lag time The delay in time between the cause and appearance of an effect in a system.

Land application Method of disposal of hazardous waste that involves intentional application of waste material to surface soil. Useful for certain biodegradable industrial waste, such as oil and petroleum waste, and some organic chemical waste.

Land ethic A set of ethical principles that affirm the right of all resources, including plants, animals, and earth materials, to continued existence and, at least in some locations, to continued existence in a natural state.

Landscape perspective The concept that effective management and conservation recognizes that ecosystems, populations, and species are interconnected across large geographic areas.

Landslide Comprehensive term for earth materials moving downslope.

Land-use planning A complex process involving development of a land-use plan to include a statement of land-use issues, goals, and objectives; a summary of data collection and analysis; a land-classification map; and a report that describes and indicates appropriate development in areas of special environmental concern.

Late-successional species Species that occur only or primarily in, or are dominant in, late stages in succession.

Law of the minimum (Liebig's law of the minimum) The concept that the growth or survival of a population is directly related to the single life requirement that is in least supply (rather than due to a combination of factors).

LD-50 A crude approximation of a chemical toxicity defined as the dose at which 50% of the population dies on exposure.

Leachate Noxious, mineralized liquid capable of transporting bacterial pollutants. Produced when water infiltrates through waste material and becomes contaminated and polluted.

Leaching Water infiltration from the surface, dissolving soil materials as part of chemical weathering processes and transporting the dissolved materials laterally or downward.

Lead A heavy metal that is an important constituent of automobile batteries and other industrial products. Lead is a toxic metal capable of causing environmental disruption and health problems to people and other living organisms.

Liebig's law of the minimum See **Law of the minimum**.

Life expectancy The estimated average number of years (or other time period used as a measure) that an individual of a specific age can expect to live.

Limiting factor The single requirement for growth available in the least supply in comparison to the need of an organism. Originally applied to crops but now often applied to any species.

Linear process With respect to systems, refers to the addition or subtraction of anything to a compartment in a system where the amount will always be the same, no matter how much you have added before and what else has changed about the system and the environment. For example, if you collect stones from a particular site and place them in a basket and place one stone per hour, you will have placed 6 stones in 6 hours and 24 in 24 hours, and the change is linear with time.

Lithosphere The outer layer of Earth, approximately 100 km thick, of which the plates that contain the ocean basins and the continents are composed.

Little Ice Age (LIA) A period of approximately 300 years from the mid 1400 to 1700 where the Earth was a bit cooler than it is today. During the Little Ice Age, glaciers expanded in mountainous regions. Cold, wet years during the Little Ice Age, may have contributed to the devastation caused by the Black Plague.

Littoral drift Movement caused by wave motion in nearshore and beach environment.

Local extinction The disappearance of a species from part of its range but continued persistence elsewhere.

Logistic carrying capacity In terms of the logistic curve, the population size at which births equal deaths and there is no net change in the population.

Logistic equation The equation that results in a logistic growth curve; that is, the growth rate $dN/dt = rN[(K - N)/N]$, where r is the intrinsic rate of increase, K is the carrying capacity, and N is the population size.

Logistic growth curve The S-shaped growth curve that is generated by the logistic growth equation. In the logistic, a small population grows rapidly, but the growth rate slows down, and the population eventually reaches a constant size.

Low-level radioactive waste Waste materials that contain sufficiently low concentrations or quantities of radioactivity so as not to present a significant environmental hazard if properly handled.

Luz solar electric generating system Solar energy farms comprising a power plant surrounded by hundreds of solar collectors (curved mirrors) that heat a synthetic oil, which flows through heat exchangers to drive steam turbine generators.

Macronutrients Elements required in large amounts by living things. These include the big six—carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur.

Made lands Man-made areas created artificially with fill, sometimes as waste dumps of all kinds and sometimes to make more land available for construction.

Magma A naturally occurring silica melt, a good deal of which is in a liquid state.

Malnourishment The lack of specific components of food, such as proteins, vitamins, or essential chemical elements.

Manipulated variable See **Variable, independent**.

Marasmus Progressive emaciation caused by a lack of protein and calories.

Marginal cost In environmental economics, the cost to reduce one additional unit of a type of degradation; for example, pollution.

Marginal land An area of Earth with minimal rainfall or otherwise limited severely by some necessary factor, so that it is a poor place for agriculture and easily degraded by agriculture. Typically, these lands are easily converted to deserts even when used for light grazing and crop production.

Mariculture Production of food from marine habitats.

Marine evaporites With respect to mineral resources, refers to materials such as potassium and sodium salts resulting from the evaporation of marine waters.

Materially closed system Characterized by a system in which no matter moves in and out of the system, although energy and information may move across the system's boundaries. For example, Earth is a materially closed system for all practical purposes.

Materials management In waste management, methods consistent with the ideal of industrial ecology, making better use of materials and leading to more sustainable use of resources.

Matter Anything that occupies space and has mass. It is the substance of which physical objects are composed.

Maximum lifetime Genetically determined maximum possible age to which an individual of a species can live.

Maximum sustainable population The largest population size that can be sustained indefinitely.

Maximum sustainable yield (MSY) The maximum usable production of a biological resource that can be obtained in a specified time period without decreasing the ability of the resource to sustain that level of production.

Mediation A negotiation process between adversaries, guided by a neutral facilitator.

Medieval Warming Period (MWP) A period of approximately 300 years from A.D. 950 to 1250 when Earth's surface was considerably warmer than the normal that we experience today. The warming was particularly relevant and important in Western Europe and the Atlantic Ocean where the MWP was a time of flourishing culture and activity, as well as expansion of population.

Megacities Urban areas with at least 8 million inhabitants.

Meltdown A nuclear accident in which the nuclear fuel forms a molten mass that breaches the containment of the reactor, contaminating the outside environment with radioactivity.

Methane (CH_4) A molecule of carbon and four hydrogen atoms. It is a naturally occurring gas in the atmosphere, one of the so-called greenhouse gases.

Methane hydrate A white icelike compound made up of molecules of methane gas trapped in "cages" of frozen water in the sediments of the deep seafloor.

Microclimate The climate of a very small local area. For example, the climate under a tree, near the ground within a forest, or near the surface of streets in a city.

Micronutrients Chemical elements required in very small amounts by at least some forms of life. Boron, copper, and molybdenum are examples of micronutrients.

Micropower The production of electricity using smaller distributed systems rather than relying on large central power plants.

Migration The movement of an individual, population, or species from one habitat to another or more simply from one geographic area to another.

Migration corridor Designated passageways among parks or preserves allowing migration of many life-forms among several of these areas.

Mineral A naturally occurring inorganic material with a definite internal structure and physical and chemical properties that vary within prescribed limits.

Mineral resources Elements, chemical compounds, minerals, or rocks concentrated in a form that can be extracted to obtain a usable commodity.

Minimum viable population The minimum number of individuals that have a reasonable chance of persisting for a specified time period.

Missing carbon sink The unknown location of substantial amounts of carbon dioxide released into the atmosphere but apparently not reabsorbed and thus remaining unaccounted for.

Mitigated negative declaration A special type of negative declaration that suggests that the adverse environmental aspects of a particular action may be mitigated through modification of the project in such a way as to reduce the impacts to near insignificance.

Mitigation A process that identifies actions to avoid, lessen, or compensate for anticipated adverse environmental impacts.

Mobile sources Sources of air pollutants that move from place to place; for example, automobiles, trucks, buses, and trains.

Model A deliberately simplified explanation, often physical, mathematical, pictorial, or computer-simulated, of complex phenomena or processes.

Monitoring Process of collecting data on a regular basis at specific sites to provide a database from which to evaluate change. For example, collection of water samples from beneath a landfill to provide early warning should a pollution problem arise.

Monoculture (Agriculture) The planting of large areas with a single species or even a single strain or subspecies in farming.

Moral justification for the conservation of nature An argument for the conservation of nature on the grounds that aspects of the environment have a right to exist, independent of human desires, and that it is our moral obligation to allow them to continue or to help them persist.

Multiple use Literally, using the land for more than one purpose at the same time. For example, forestland can be used to produce commercial timber but at the same time serve as wildlife habitat and land for recreation. Usually multiple use requires compromises and trade-offs, such as striking a balance between cutting timber for the most efficient production of trees at a level that facilitates other uses.

Mutation Stated most simply, a chemical change in a DNA molecule. It means that the DNA carries a different message than it did before, and this change can affect the expressed characteristics when cells or individual organisms reproduce.

Mutualism See **Symbiosis**.

Natural capital Ecological systems that provide public service benefits.

Natural catastrophe Sudden catastrophic change in the environment, not the result of human actions.

Natural gas Naturally occurring gaseous hydrocarbon (predominantly methane) generally produced in association with crude oil or from gas wells; an important efficient and clean-burning fuel commonly used in homes and industry.

Natural hazard Any natural process that is a potential threat to human life and property.

Natural selection A process by which organisms whose biological characteristics better fit them to the environment are represented by more descendants in future generations than those whose characteristics are less fit for the environment.

Nature preserve An area set aside with the primary purpose of conserving some biological resource.

Negative declaration A document that may be filed if an agency has determined that a particular project will not have a significant adverse effect on the environment.

Negative feedback A type of feedback that occurs when the system's response is in the opposite direction of the output. Thus negative feedback is self-regulating.

Net growth efficiency Net production efficiency (P/A), or the ratio of the material produced (P) to the material assimilated (A) by an organism. The material assimilated is less than the material consumed because some food taken in is egested as waste (discharged) and never used by an organism.

Net production (biology) The production that remains after utilization. In a population, net production is sometimes measured as the net change in the numbers of individuals. It is also measured as the net change in biomass or in stored energy. In terms of energy, it is equal to the gross production minus the energy used in respiration.

New forestry The name for a new variety of timber harvesting practices to increase the likelihood of sustainability, including recognition of the dynamic characteristics of forests and of the need for management within an ecosystem context.

Niche (1) The "profession," or role, of an organism or species; or (2) all the environmental conditions under which the individual or species can persist. The fundamental niche is all the conditions under which a species can persist in the absence of competition; the realized niche is the set of conditions as they occur in the real world with competitors.

Nitrogen cycle A complex biogeochemical cycle responsible for moving important nitrogen components through the biosphere and other Earth systems. This is an extremely important cycle because nitrogen is required by all living things.

Nitrogen fixation The process of converting inorganic, molecular nitrogen in the atmosphere to ammonia. In nature it is carried out only by a few species of bacteria, on which all life depends.

Nitrogen oxides Occur in several forms: NO, NO_2, and NO_3. Most important as an air pollutant is nitrogen dioxide, which is a visible yellow brown to reddish brown gas. It is a precursor of acid rain and produced through the burning of fossil fuels.

Noise pollution A type of pollution characterized by unwanted or potentially damaging sound.

Non-linear process Characterized by system operation in which the effect of adding a specific amount of something changes, depending upon how much has been added before.

Nonmarine evaporites With respect to mineral resources, refers to useful deposits of materials such as sodium and calcium bicarbonate, sulfate, borate, or nitrate produced by evaporation of surficial waters on the land, as differentiated from marine waters in the oceans.

Nonpoint sources Pollution sources that are diffused and intermittent and are influenced by factors such as land use, climate, hydrology, topography, native vegetation, and geology.

Nonrenewable energy Energy sources, including nuclear and geothermal, that are dependent on fuels, or a resource that may be used up much faster than it is replenished by natural processes.

Nonrenewable resource A resource that is cycled so slowly by natural Earth processes that once used, it is essentially not going to be made available within any useful time framework.

No-till agriculture A combination of farming practices that includes not plowing the land and using herbicides to keep down weeds.

Nuclear cycle The series of processes that begins with the mining of uranium to be processed and used in nuclear reactors and ends with the disposal of radioactive waste.

Nuclear energy The energy of the atomic nucleus that, when released, may be used to do work. Controlled nuclear fission reactions take place within commercial nuclear reactors to produce energy.

Nuclear fuel cycle Processes involved with producing nuclear power from the mining and processing of uranium to control fission, reprocessing of spent nuclear fuel, decommissioning of power plants, and disposal of radioactive waste.

Nuclear reactors Devices that produce controlled nuclear fission, generally for the production of electric energy.

Obligate symbionts A symbiotic relationship between two organisms in which neither by themselves can exist without the other.

Observations Information obtained through one or more of the five senses or through instruments that extend the senses. For example, some remote sensing instruments measure infrared intensity, which we do not see, and convert the measurement into colors, which we do see.

Ocean thermal conversion Direct utilization of solar energy using part of a natural oceanic environment as a gigantic solar collector.

Off-site effect An environmental effect occurring away from the location of the causal factors.

Off-stream use Type of water use where water is removed from its source for a particular use.

Oil shale A fine-grained sedimentary rock containing organic material known as kerogen. On distillation, it yields significant amounts of hydrocarbons, including oil.

Oil spill The accidental release of oil from a ship transporting oil, an oil pipeline leak, or release of oil from a well during or after drilling.

Old-growth forest A nontechnical term often used to mean a virgin forest (one never cut), but also used to mean a forest that has been undisturbed for a long, but usually unspecified, time.

Oligotrophic Referring to bodies of water having a low concentration of the chemical elements required for life.

Omnivores Organisms that eat both plants and animals.

On-site effect An environmental effect occurring at the location of the causal factors.

Open dump An area where solid waste is disposed of by simply dumping it. It often causes severe environmental problems, such as water pollution, and creates a health hazard. Illegal in the United States and in many other countries around the world.

Open system A type of system in which exchanges of mass or energy occur with other systems.

Open woodlands Areas in which trees are a dominant vegetation form but the leaves of adjacent trees generally do not touch or overlap, so that there are gaps in the canopy. Typically, grasses or shrubs grow in the gaps among the trees.

Operational definitions Definitions that tell you what you need to look for or do in order to carry out an operation, such as measuring, constructing, or manipulating.

Optimal carrying capacity A term that has several meanings, but the major idea is the maximum abundance of a population or species that can persist in an ecosystem without degrading the ability of the ecosystem to maintain (1) that population or species; (2) all necessary ecosystem processes; and (3) the other species found in that ecosystem.

Optimum sustainable population (OSP) The population size that is in some way best for the population, its ecological community, its ecosystem, or the biosphere.

Optimum sustainable yield (OSY) The largest yield of a renewable resource achievable over a long time period without decreasing the ability of the resource, its ecosystem or its environment to maintain this level of yield. OSY differs from maximum sustainable yield (MSY) by taking the ecosystem of a resource into account.

Ore deposits Earth materials in which metals exist in high concentrations, sufficient to be mined.

Organelle Specialized parts of cells that function like organs in multi-celled organisms.

Organic compound A compound of carbon; originally used to refer to the compounds found in and formed by living things.

Organic farming Farming that is more "natural" in the sense that it does not involve the use of artificial pesticides and, more recently, genetically modified crops. In recent years governments have begun to set up legal criteria for what constitutes organic farming.

Output With respect to basic operation of system, refers to material or energy that leaves a particular storage compartment.

Overdraft Groundwater withdrawal when the amount pumped from wells exceeds the natural rate of replenishment.

Overgrazing Exceeding the carrying capacity of land for an herbivore, such as cattle or deer.

Overshoot and collapse Occurs when growth in one part of a system over time exceeds carrying capacity, resulting in a sudden decline in one or both parts of the system.

Ozone (O_3) A form of oxygen in which three atoms of oxygen occur together. It is chemically active and has a short average lifetime in the atmosphere. Forms a natural layer high in the atmosphere (stratosphere) that protects us from harmful ultraviolet radiation from the sun, is an air pollutant when present in the lower atmosphere above the National Air Quality Standards.

Ozone shield Stratospheric ozone layer that absorbs ultraviolet radiation.

Pandemic A worldwide disease outbreak.

Particulate matter Small particles of solid or liquid substances that are released into the atmosphere by many activities, including farming, volcanic eruption, and burning fossil fuels. Particulates affect human health, ecosystems, and the biosphere.

Passive solar energy system Direct use of solar energy through architectural design to enhance or take advantage of natural changes in solar energy that occur throughout the year without requiring mechanical power.

Pasture Land plowed and planted to provide forage for domestic herbivorous animals.

Peak oil Refers to the time in the future when one-half of Earth's oil has been exploited. Peak oil is expected to occur sometime between 2020 and 2050.

Pebble A rock fragment between 4 and 64 mm in diameter.

Pedology The study of soils.

Pelagic ecosystem An ecosystem that occurs in the floating part of an ocean or sea, without any physical connections to the bottom of the ocean or sea.

Pelagic whaling Practice of whalers taking to the open seas and searching for whales from ships that remained at sea for long periods.

Per-capita availability The amount of a resource available per person.

Per-capita demand The economic demand per person.

Per-capita food production The amount of food produced per person.

Permafrost Permanently frozen ground.

Persistent organic pollutants Synthetic carbon-based compounds, often containing chlorine, that do not easily break down in the environment. Many were introduced decades before their harmful effects were fully understood and are now banned or restricted.

Pesticides, broad-spectrum Pesticides that kill a wide variety of organisms. E.g. arsenic, one of the first elements used as a pesticide, is toxic to many life-forms, including people.

Phosphorus cycle A major biogeochemical cycle involving the movement of phosphorus throughout the biosphere and lithosphere. This cycle is important because phosphorus is an essential element for life and often is a limiting nutrient for plant growth.

Photochemical oxidants Result from atmospheric interactions of nitrogen dioxide and sunlight. Most common is ozone (O_3).

Photochemical smog Sometimes called L.A.-type smog or brown air. Directly related to automobile use and solar radiation. Reactions that occur in the development of the smog are complex and involve both nitrogen oxides and hydrocarbons in the presence of sunlight.

Photosynthesis Synthesis of sugars from carbon dioxide and water by living organisms using light as energy. Oxygen is given off as a by-product.

Photovoltaics Technology that converts sunlight directly into electricity using a solid semiconductor material.

Physiographic province A region characterized by a particular assemblage of landforms, climate, and geomorphic history.

Pioneer species Species found in early stages of succession.

Placer deposit A type of ore deposit found in material transported and deposited by agents such as running water, ice, or wind. Examples include gold and diamonds found in stream deposits.

Plantations In forestry, managed forests, in which a single species is planted in straight rows and harvested at regular intervals.

Plate tectonics A model of global tectonics that suggests that the outer layer of Earth, known as the lithosphere, is composed of several large plates that move relative to one another. Continents and ocean basins are passive riders on these plates.

Point sources Sources of pollution such as smokestacks, pipes, or accidental spills that are readily identified and stationary. They are often thought to be easier to recognize and control than are area sources. This is true only in a general sense, as some very large point sources emit tremendous amounts of pollutants into the environment.

Polar amplification Processes in which global warming causes greater temperature increases at polar regions.

Polar stratospheric clouds Clouds that form in the stratosphere during the polar winter.

Polar vortex Arctic air masses that in the winter become isolated from the rest of the atmosphere and circulate about the pole. The vortex rotates counterclockwise because of the rotation of Earth in the Southern Hemisphere.

Policy instruments The means to implement a society's policies. Such instruments include moral suasion (jawboning—persuading people by talk, publicity, and social pressure); direct controls, including regulations; and market processes affecting the price of goods, subsidies, licenses, and deposits.

Pollutant In general terms, any factor that has a harmful effect on living things or their environment.

Pollution The process by which something becomes impure, defiled, dirty, or otherwise unclean.

Pollution prevention Identifying ways to avoid the generation of waste rather than finding ways to dispose of it.

Pool (in a stream) A stream bed produced by scour.

Population A group of individuals of the same species living in the same area or interbreeding and sharing genetic information.

Population age structure The number of individuals or the proportion of the population in each age class.

Population dynamics The causes of changes in population size.

Population momentum or lag effect The continued growth of a population after replacement-level fertility is reached.

Population regulation See **Density-dependent population effects** and **Density-independent population effects.**

Population risk A term used in discussions of endangered species to mean random variation in population—birth rates and death rates—possibly causing species in low abundance to become extinct.

Positive feedback A type of feedback that occurs when an increase in output leads to a further increase in output. This is sometimes known as a vicious cycle, since the more you have, the more you get.

Potential energy Energy that is stored. Examples include the gravitational energy of water behind a dam; chemical energy in coal, fuel oil, and gasoline; and nuclear energy (in the forces that hold atoms together).

Power The amount of energy used per unit of time.

Precautionary principle The idea that even full scientific certainty is not available to prove cause and effect, we should still take cost-effective precautions to solve environmental problems when appears to be a threat of potential serious and irreversible environmental damage.

Predation-parasitism Interaction between individuals of two species in which the outcome benefits one and is detrimental to the other.

Predator An organism that feeds on other live organisms, usually of other species. The term is usually applied to animals that feed on other animals.

Premises In science, initial definitions and assumptions.

Primary pollutants Air pollutants emitted directly into the atmosphere. Included are particulates, sulfur oxides, carbon monoxide, nitrogen oxides, and hydrocarbons.

Primary production See **Production, primary.**

Primary succession The initial establishment and development of an ecosystem.

Primary treatment (of wastewater) Removal of large particles and organic materials from wastewater through screening.

Probability The likelinood that an event will occur.

Production, ecological The amount of increase in organic matter, usually measured per unit area of land surface or unit volume of water, as in grams per square meter (g/m^2). Production is divided into *primary* (that of autotrophs) and *secondary* (that of heterotrophs). It is also divided into *net* (that which remains stored after use) and *gross* (that added before any use).

Production, primary The production by autotrophs.

Production, secondary The production by heterotrophs.

Productivity, ecological The *rate* of production; that is, the amount of increase in organic matter per unit time (for example, grams per meter squared per year).

Prokaryote A kind of organism that lacks a true cell nucleus and has other cellular characteristics that distinguish it from the *eukaryotes*. Bacteria are prokaryotes.

Pseudoscientific Describes ideas that are claimed to have scientific validity but are inherently untestable and/or lack empirical support and/or were arrived at through faulty reasoning or poor scientific methodology.

Public service functions Functions performed by ecosystems that benefit other forms of life in other ecosystems. Examples include the cleansing of the air by trees and removal of pollutants from water by infiltration through the soil.

Public trust Grants and limits the authority of government over certain natural areas of special character.

Qualitative data Data distinguished by qualities or attributes that cannot be or are not expressed as quantities. For example, blue and red are qualitative data about the electromagnetic spectrum.

Quantitative data Data expressed as numbers or numerical measurements. For example, the wavelengths of specific colors of blue and red light (460 and 650 nanometers, re-spectively) are quantitative data about the electromagnetic spectrum.

R-to-C ratio A measure of the time available for finding the solutions to depletion of nonrenewable reserves, where R is the known reserves (for example, hundreds of thousands of tons of a metal) and C is the rate of consumption (for example, thousands of tons per year used by people).

Radiation absorbed dose (RAD) Energy retained by living tissue that has been exposed to radiation.

Radioactive decay A process of decay of radioisotopes that change from one isotope to another and emit one or more forms of radiation.

Radioactive waste Type of waste produced in the nuclear fuel cycle; generally classified as high-level or low-level.

Radioisotope A form of a chemical element that spontaneously undergoes radioactive decay.

Radionuclides Atoms with unstable nuclei that undergo radioactive decay.

Radon A naturally occurring radioactive gas. Radon is colorless, odorless, and tasteless and must be identified through proper testing.

Rangeland Land used for grazing.

Rare species Species with a small total population, or restricted to a small area, but not necessarily declining or in danger of extinction.

Realms (ecological) Major biogeographic regions of Earth in which most animals have some common genetic heritage.

Record of decision Concise statement prepared by the agency planning a proposed project; it outlines the alternatives considered and discusses which alternatives are environmentally preferable.

Recreational justification for the conservation of nature An argument for the conservation of nature on the grounds that direct experience of nature is inherently enjoyable and that the benefits derived from it are important and valuable to people.

Recycle To collect and reuse resources in the waste stream.

Reduce With respect to waste management, refers to practices that will reduce the amount of waste we produce.

Reduce, reuse, and recycle The three Rs of integrated waste management.

Renewable energy Alternative energy sources, such as solar, water, wind, and biomass, that are more or less continuously available in a time framework useful to people.

Renewable resource A resource, such as timber, water, or air, that is naturally recycled or recycled by artificial processes within a time frame useful for people.

Replacement-level fertility The fertility rate required for the population to remain a constant size.

Representative natural areas Parks or preserves set aside to represent presettlement conditions of a specific ecosystem type.

Reserves Known and identified deposits of earth materials from which useful materials can be extracted profitably with existing technology and under present economic and legal conditions.

Resource-based agriculture Agricultural practices that rely on extensive use of resources, so that production is limited by the availability of resources.

Resources Reserves plus other deposits of useful earth materials that may eventually become available.

Respiration The complex series of chemical reactions in organisms that make energy available for use. Water, carbon dioxide, and energy are the products of respiration.

Responding variable See **Variable, dependent.**

Restoration ecology The field within the science of ecology whose goal is to return damaged ecosystems to ones that are functional, sustainable, and more natural in some meaning of this word.

Reuse With respect to waste management, refers to finding ways to reuse products and materials so they need not be disposed of.

Riffle A section of stream channel characterized at low flow by fast, shallow flow. Generally contains relatively coarse bed-load particles.

Risk The product of the probability of an event occurring and the consequences should that event occur.

Risk assessment The process of determining potential adverse environmental health effects to people following exposure to pollutants and other toxic materials. It generally includes four steps: identification of the hazard, dose-response assessment, exposure assessment, and risk characterization.

Risk-benefit analysis In environmental economics, weighing the riskiness of the future against the value we place on things in the present.

Rock (engineering) Any earth material that has to be blasted in order to be removed.

Rock (geologic) An aggregate of a mineral or minerals.

Rock cycle A group of processes that produce igneous, metamorphic, and sedimentary rocks.

Rotation time Time between cuts of a stand or area of forest.

Rule of climatic similarity Similar environments lead to the evolution of organisms similar in form and function (but not necessarily in genetic heritage or internal makeup) and to similar ecosystems.

Ruminants Animals having a four-chambered stomach within which bacteria convert the woody tissue of plants to proteins and fats that, in turn, are digested by the animal. Cows, camels, and giraffes are ruminants; horses, pigs, and elephants are not.

Sand Grains of sediment between 1/16 and 2 mm in diameter; often sediment composed of quartz particles of this size.

Sand dune A ridge or hill of sand formed by wind action.

Sanitary landfill A method of disposal of solid waste without creating a nuisance or hazard to public health or safety. Sanitary landfills are highly engineered structures with multiple barriers and collection systems to minimize environmental problems.

Savanna An area with trees scattered widely among dense grasses.

Scientific method A set of systematic methods by which scientists investigate natural phenomena, including gathering data, formulating and testing hypotheses, and developing scientific theories and laws.

Scientific theory A grand scheme that relates and explains many observations and is supported by a great deal of evidence, in contrast to a guess, a hypothesis, a prediction, a notion, or a belief.

Scoping The process of early identification of important environmental issues that require detailed evaluation.

Scrubbing A process of removing sulfur from gases emitted from power plants burning coal. The gases are treated with a slurry of lime and limestone, and the sulfur oxides react with the calcium to form insoluble calcium sulfides and sulfates that are collected and disposed of.

Second growth A forest that has been logged and regrown.

Secondary enrichment A weathering process of sulfide ore deposits that may concentrate the desired minerals.

Secondary pollutants Air pollutants produced through reactions between primary pollutants and normal atmospheric compounds. An example is ozone that forms over urban areas through reactions of primary pollutants, sunlight, and natural atmospheric gases.

Secondary production See **Production, secondary.**

Secondary succession The reestablishment of an ecosystem where there are remnants of a previous biological community.

Secondary treatment (of wastewater) Use of biological processes to degrade wastewater in a treatment facility.

Second-law efficiency The ratio of the minimum available work needed to perform a particular task to the actual work used to perform that task. Reported as a percentage.

Second law of thermodynamics The law of thermodynamics which states that *no use of energy in the real (not theoretical) world can ever be 100% efficient.*

Secure landfill A type of landfill designed specifically for hazardous waste. Similar to a modern sanitary landfill in that it includes multiple barriers and collection systems to ensure that leachate does not contaminate soil and other resources.

Sediment pollution By volume and mass, sediment is our greatest water pollutant. It may choke streams, fill reservoirs, bury vegetation, and generally create a nuisance that is difficult to remove.

Seed-tree cutting A logging method in which mature trees with good genetic characteristics and high seed production are preserved to promote regeneration of the forest. It is an alternative to clear-cutting.

Seismic Referring to vibrations in Earth produced by earth-quakes.

Selective cutting In timber harvesting, the practice of cutting some, but not all, trees, leaving some on the site. There are many kinds of selective cutting. Sometimes the biggest trees with the largest market value are cut, and smaller trees are left to be cut later. Sometimes the best trees are left to provide seed for future generations. Sometimes trees are left for wildlife habitat and recreation.

Shelterwood cutting A logging method in which dead and less desirable trees are cut first; mature trees are cut later. This ensures that young, vigorous trees will always be left in the forest. It is an alternative to clear-cutting.

Sick building syndrome A condition associated with a particular indoor environment that appears to be unhealthy for the human occupants.

Silicate minerals The most important group of rock-forming minerals.

Silt Sediment between 1/16 and 1/256 mm in diameter.

Silviculture The practice of growing trees and managing forests, traditionally with an emphasis on the production of timber for commercial sale.

Single stream recycling Recycling process in which paper, plastic, glass, and metals are not separated prior to collection.

Sink With respect to systems operation, refers to a component or storage cell within a system that is receiving a material, such as a chemical. The donating compartment is called a source, and there generally is a flux or rate of transfer between the source and sink.

Sinkhole A surface depression formed by the solution of limestone or the collapse over a subterranean void such as a cave.

Site (in relation to cities) Environmental features of a location that influence the placement of a city. For example, New Orleans is built on low-lying muds, which form a poor site, while New York City's Manhattan is built on an island of strong bedrock, an excellent site.

Site quality Used by foresters to mean an estimator of the maximum timber crop the land can produce in a given time.

Situation (in relation to cities) The relative geographic location of a site that makes it a good location for a city. For example, New Orleans has a good situation because it is located at the mouth of the Mississippi River and is therefore a natural transportation junction.

Smog A term first used in 1905 for a mixture of smoke and fog that produced unhealthy urban air. There are several types of fog, including photochemical smog and sulfurous smog.

Soft path Energy policy that relies heavily on renewable energy resources as well as other sources that are diverse, flexible, and matched to the end-use needs.

Soil The top layer of a land surface where the rocks have been weathered to small particles. Soils are made up of inorganic particles of many sizes, from small clay particles to large sand grains. Many soils also include dead organic material.

Soil (in engineering) Earth material that can be removed without blasting.

Soil (in soil science) Earth material modified by biological, chemical, and physical processes such that the material will support rooted plants.

Soil fertility The capacity of a soil to supply the nutrients and physical properties necessary for plant growth.

Soil horizon A layer in soil (A, B, C) that differs from another layer in chemical, physical, and biological properties.

Solar cell (photovoltaic) A device that directly converts light into electricity.

Solar collector A device for collecting and storing solar energy. For example, home water heating is done by flat panels consisting of a glass cover plate over a black background on which water is circulated through tubes. Short-wave solar radiation enters the glass and is absorbed by the black background. As long-wave radiation is emitted from the black material, it cannot escape through the glass, so the water in the circulating tubes is heated, typically to temperatures of 38° to 93°C.

Solar energy Energy from the sun.

Solar pond A shallow pond filled with water and used to generate relatively low-temperature water.

Solar power tower A system of collecting solar energy that delivers the energy to a central location where the energy is used to produce electric power.

Source With respect to storage compartments within a system, such as the atmosphere or land, refers to a compartment that donates to another compartment. The donating compartment is the source; the receiving compartment the sink.

Source reduction A waste-management process to reduce the amounts of materials that must be handled in the waste stream.

Species A group of individuals capable of interbreeding.

Stable equilibrium A condition in which a system will remain if undisturbed and to which it will return when displaced.

Stand An informal term used by foresters to refer to a group of trees.

Stationary sources Air pollution sources that have a relatively fixed location, including point sources, fugitive sources, and area sources.

Steady state When input equals output in a system, there is no net change and the system is said to be in a steady state. A bathtub with water flowing in and out at the same rate maintains the same water level and is in a steady state. Compare with **equilibrium**.

Stratosphere Overlies the troposphere and the atmosphere from approximately 20-70 kilometers above the Earth. The stratosphere contains the higher concentrations of ozone at about 25 kilometers above the Earth known as the ozone layer.

Stress Force per unit area. May be compression, tension, or shear.

Strip cutting In timber harvesting, the practice of cutting narrow rows of forest, leaving wooded corridors.

Strip mining Surface mining in which the overlying layer of rock and soil is stripped off to reach the resource. Large strip mines are some of the world's largest excavations by people.

Subduction A process in which one lithospheric plate descends beneath another.

Subsidence A sinking, settling, or otherwise lowering of parts of crust.

Subsistence crops Crops used directly for food by a farmer or sold locally where the food is used directly.

Succession The process of establishment and development of an ecosystem.

Sulfur dioxide (SO_2) A colorless and odorless gas normally present at Earth's surface in low concentrations. An important precursor to acid rain, its major anthropogenic source is burning fossil fuels.

Sulfurous smog Produced primarily by burning coal or oil at large power plants. Sulfur oxides and particulates combine under certain meteorological conditions to produce a concentrated form of this smog.

Suppressed In forestry, describes tree species growing in the understory, beneath the dominant and intermediate species.

Surface impoundment Method of disposal of some liquid hazardous waste. This method is controversial, and many sites have been closed.

Sustainability Management of natural resources and the environment with the goals of allowing the harvest of resources to remain at or above some specified level, and the ecosystem to retain its functions and structure.

Sustainable development The ability of a society to continue to develop its economy and social institutions and also maintain its environment for an indefinite time.

Sustainable ecosystem An ecosystem that is subject to some human use but at a level that leads to no loss of species or of necessary ecosystem functions.

Sustainable energy development A type of energy management that provides for reliable sources of energy while not causing environmental degradation and while ensuring that future generations will have a fair share of the Earth's resources.

Sustainable forestry Managing a forest so that a resource in it can be harvested at a rate that does not decrease the ability of the forest ecosystem to continue to provide that same rate of harvest indefinitely.

Sustainable harvest An amount of a resource that can be harvested at regular intervals indefinitely.

Sustainable water use Use of water resources that does not harm the environment and provides for the existence of high-quality water for future generations.

Symbiont Each partner in symbiosis.

Symbiosis An interaction between individuals of two different species that benefits both. For example, lichens contain an alga and a fungus that require each other to persist. Sometimes this term is used broadly, so that domestic corn and people could be said to have a symbiotic relationship—domestic corn cannot reproduce without the aid of people, and some people survive because they have corn to eat.

Symbiotic Relationships that exist between different organisms. Mutually beneficial.

Synergism Cooperative action of different substances such that the combined effect is greater than the sum of the effects taken separately.

Synergistic effect When the change in availability of one resource affects the response of an organism to some other resource.

Synfuels Synthetic fuels, which may be liquid or gaseous, derived from solid fuels, such as oil from kerogen in oil shale, or oil and gas from coal.

Synthetic organic compounds Compounds of carbon produced synthetically by human industrial processes, as for example pesticides and herbicides.

System A set of components that are linked and interact to produce a whole. For example, the river as a system is composed of sediment, water, bank, vegetation, fish, and other living things that all together produce the river.

Systematic errors Errors that occur consistently in scientific experiments, such as those resulting from incorrectly calibrated instruments.

Taiga Forest of cold climates of high latitudes and high altitudes, also known as boreal forest.

Tangible factor In economics, something one you can touch, buy and sell.

Tar sands Sedimentary rocks or sands impregnated with tar oil, asphalt, or bitumen.

Taxa Categories that identify groups of living organisms based on evolutionary relationships or similarity of characters.

Taxon A grouping of organisms according to evolutionary relationships.

TD-50 The toxic dose defined as the dose that is toxic to 50% of a population exposed to the toxin.

Tectonic cycle The processes that change Earth's crust, producing external forms such as ocean basins, continents, and mountains.

Terminator gene A genetically modified crop that has a gene to cause the plant to become sterile after the first year.

Tertiary treatment (of wastewater) An advanced form of wastewater treatment involving chemical treatment or advanced filtration. An example is chlorination of water.

Theories Scientific models that offer broad, fundamental explanations of related phenomena and are supported by consistent and extensive evidence.

Thermal (heat) energy The energy of the random motion of atoms and molecules.

Thermal pollution A type of pollution that occurs when heat is released into water or air and produces undesirable effects on the environment.

Thermodynamic equilibrium With respect to systems, is a physical concept of equilibrium where everything is at the lowest energy level in the system, and matter and energy are dispersed randomly.

Thermodynamic system Formed by an energy source, ecosystem, and energy sink, where the ecosystem is said to be an intermediate system between the energy source and the energy sink.

Thermodynamics, first law of See **First law of thermodynamics.**

Thermodynamics, second law of See **Second law of thermodynamics.**

Thinning The timber-harvesting practice of selectively removing only smaller or poorly formed trees.

Threatened species Species experiencing a decline in the number of individuals to a degree that raises concern about the possibility of extinction of that species.

Threshold A point in the operation of a system at which a change occurs. With respect to toxicology, it is a level below which effects are not observable and above which effects become apparent.

Tidal power Energy generated by ocean tides in places where favorable topography allows for construction of a power plant.

Time series The set of estimates of some variable over a number of years.
Tolerance The ability to withstand stress resulting from exposure to a pollutant or other harmful condition.
Tornado A funnel-shaped cloud of violently rotating air that extends downward from large thunder storms to contact the surface of earth.
Total fertility rate (TFR) The average number of children expected to be born to a woman during her lifetime. (Usually defined as the number born to a woman between the ages of 15 and 44, taken conventionally as the lower and upper limit of reproductive ages for women.)
Toxic Harmful, deadly, or poisonous.
Toxicology The science concerned with the study of poisons (or toxins) and their effects on living organisms. The subject also includes the clinical, industrial, economic, and legal problems associated with toxic materials.
Transuranic waste Radioactive waste consisting of human-made radioactive elements heavier than uranium. Includes clothing, rags, tools, and equipment that has been contaminated.
Trophic level In an ecological community, all the organisms that are the same number of food-chain steps from the primary source of energy. For example, in a grassland the green grasses are on the first trophic level, grasshoppers are on the second, birds that feed on grasshoppers are on the third, and so forth.
Trophic level efficiency The ratio of the biological production of one trophic level to the biological production of the next lower trophic level.
Troposphere The atmospheric zone from the surface of the Earth to an altitude of approximately 20 kilometers above the Earth. The troposphere is the zone of the atmosphere we are most familiar with because we spend most of our lives in it.
Tundra The treeless land area in alpine and arctic areas characterized by plants of low stature and including bare areas without any plants and areas covered with lichens, mosses, grasses, sedges, and small flowering plants, including low shrubs.
Ubiquitous species Species that are found almost anywhere on Earth.
Ultraviolet A (UVA) The longest wavelength of ultraviolet radiation (0.32–0.4 micrometers), not affected by stratospheric ozone, and transmitted to the surface of Earth.
Ultraviolet B (UVB) Intermediate-wavelength radiation which is the ozone problem. Wavelengths are approximately 0.28–0.32 micrometers and are the most harmful of the ultraviolet radiation types. Most of this radiation is absorbed by stratospheric ozone, and depletion of ozone has led to increased ultraviolet B radiation reaching Earth.
Ultraviolet C (UVC) The shortest wavelength of the ultraviolet radiation with wavelengths of approximately 0.2–0.28 micrometers. It is the most energetic of the ultraviolet radiation and is absorbed strongly in the atmosphere. Only a negligible amount of Ultraviolet C reaches the surface of Earth.
Ultraviolet (UV) index An index based on the exposure to ultraviolet radiation to humans. Varies from low to extreme and is useful for people wishing recommendation of how much exposure to the sun they should incur and how much sun block to use.
Undernourishment The lack of sufficient calories in available food, so that one has little or no ability to move or work.
Uneven-aged stands A forest stand with at least three distinct age classes.
Unified soil classification system A classification of soils, widely used in engineering practice, based on the amount of coarse particles, fine particles, or organic material.
Uniformitarianism The principle stating that processes that operate today operated in the past. Therefore, observations of processes today can explain events that occurred in the past and leave evidence, for example, in the fossil record or in geologic formations.
Urban dust dome Polluted urban air produced by the combination of lingering air and abundance of particulates and other pollutants in the urban air mass.
Urban forestry The practice and profession of planting and maintaining trees in cities, including trees in parks and other public areas.
Urban-runoff naturalization An emerging bioengineering technology with the objective to treat urban runoff before it reaches streams, lakes, or the ocean.
Utilitarian justification for the conservation of nature An argument for the conservation of nature on the grounds that the environment, an ecosystem, habitat, or species provides individuals with direct economic benefit or is directly necessary to their survival.
Utility Value or worth in economic terms.
UVA **See Ultraviolet A**.
UVB **See Ultraviolet B**.
UVC **See Ultraviolet C**.
Vadose zone Zone or layer above the water table where water may be stored as it moves laterally or down to the zone of saturation. Part of the vadose zone may be saturated part of the time.
Variable, dependent A variable that changes in response to changes in an independent variable; a variable taken as the outcome of one or more other variables.
Variable, independent In an experiment, the variable that is manipulated by the investigator. In an observational study, the variable that is believed by the investigator to affect an outcome, or dependent, variable.
Variable, manipulated See **Variable, independent**.
Variable, responding See **Variable, dependent**.
Virgin forest A forest that has never been cut.
Virtual water The amount of water necessary to produce a product, such as rice or, in industry, an automobile.
Volcanic eruption Extrusion at the surface of Earth of molten rock (magma). May be explosive and violent or less energetic lava flows.
Vulnerable species Another term for *threatened species*—species experiencing a decline in the number of individuals.
Waldsterben German phenomenon of forest death as the result of acid rain, ozone, and other air pollutants.

Wallace's realms Six biotic provinces, or biogeographic regions, divided on the basis of fundamental inherited features of the animals found in those areas, suggested by A. R. Wallace (1876). His realms are Nearctic (North America), Neotropical (Central and South America), Palearctic (Europe, northern Asia, and northern Africa), Ethiopian (central and southern Africa), Oriental (the Indian subcontinent and Malaysia), and Australian.

Wastewater renovation and conservation cycle The practice of applying wastewater to the land. In some systems, treated wastewater is applied to agricultural crops, and as the water infiltrates through the soil layer, it is naturally purified. Reuse of the water is by pumping it out of the ground for municipal or agricultural uses.

Wastewater treatment The process of treating wastewater (primarily sewage) in specially designed plants that accept municipal wastewater. Generally divided into three categories: primary treatment, secondary treatment, and advanced wastewater treatment.

Water budget Inputs and outputs of water for a particular system (a drainage basin, region, continent, or the entire Earth).

Water conservation Practices designed to reduce the amount of water we use.

Water power An alternative energy source derived from flowing water. One of the world's oldest and most common energy sources. Sources vary in size from microhydropower systems to large reservoirs and dams.

Water reuse The use of wastewater following some sort of treatment. Water reuse may be inadvertent, indirect, or direct.

Water table The surface that divides the zone of aeration from the zone of saturation, the surface below which all the pore space in rocks is saturated with water.

Watershed An area of land that forms the drainage of a stream or river. If a drop of rain falls anywhere within a watershed, it can flow out only through that same stream or river.

Weather What is happening in the atmosphere over a short time period or what may be happening now in terms of temperature, pressure, cloudiness, precipitation, and winds. The average of weather over longer periods and regions refers to the climate.

Weathering Changes that take place in rocks and minerals at or near the surface of Earth in response to physical, chemical, and biological changes; the physical, chemical, and biological breakdown of rocks and minerals.

Wetlands A comprehensive term for landforms such as salt marshes, swamps, bogs, prairie potholes, and vernal pools. Their common feature is that they are wet at least part of the year and as a result have a particular type of vegetation and soil. Wetlands form important habitats for many species of plants and animals, while serving a variety of natural service functions for other ecosystems and people.

Wilderness An area unaffected now or in the past by human activities and without a noticeable presence of human beings.

Wildfire Self-sustaining rapid oxidation that releases light, heat, carbon dioxide, and other gases as it moves across the landscape. Also known as a fire in the natural environment that may be initiated by natural processes such as lighting strike or deliberately set by humans.

Wind power Alternative energy source that has been used by people for centuries. More recently, thousands of windmills have been installed to produce electric energy.

Work (physics) Force times the distance through which it acts. When work is done we say energy is expended.

Zero population growth Results when the number of births equals the number of deaths so that there is no net change in the size of the population.

Zone of aeration The zone or layer above the water table in which some water may be suspended or moving in a downward migration toward the water table or laterally toward a discharge point.

Zone of saturation Zone or layer below the water table in which all the pore space of rock or soil is saturated.

Zooplankton Small aquatic invertebrates that live in the sunlit waters of streams, lakes, and oceans and feed on algae and other invertebrate animals.

Index

Entries followed by an f may be found in figures, those followed by a t may be found in tables.

F

O

P

Q

R

T

U

Y

Z

Notes

Chapter 1 Notes

1. Western, D., and C. Van Prat. 1973. Cyclical changes in habitat and climate of an East African ecosystem. *Nature* 241(549):104–106.
2. Dunne, T., and L.B. Leopold. 1978. *Water in Environmental Planning*. San Francisco: Freeman.
3. Altmann, J., S.C. Alberts, S.A. Altman, and S.B. Roy. 2002. Dramatic change in local climate patterns in the Amboseli basin, Kenya. *African Journal of Ecology* 40:248–251.
4. Maclennan, S.D., R.J. Groom, D.W. Macdonald, and L.G. Frank. 2009. Evaluation of a compensation scheme to bring about a pastoralist tolerance of lions. *Bio Conserve*. (in Press).
5. Frank, L., S. Maclennan, L. Mazzah, R. Bonham, and T. Hill. 2006. Lion killing in the Amboseli-Tsavo ecosystem, 2001–2006, and its implications for Kenya's lion population. *Report by the Kilimanjaro Lion Conservation Project and Museum of Vertebrate Zoology*, University of California, Berkeley.
6. Deevey, E.S. 1960. The human population. *Scientific American* 203:194–204.
7. Keyfitz, N. 1989. The growing human population. *Scientific American* 261: 118–126.
8. Gottfield, R.S. 1983. *The Black Death: Natural and Human Disaster in Medieval Europe.* New York: Free Press.
9. Field, J.O., ed. 1983. *The Challenge of Famine: Recent Experience, Lessons Learned.* Hartford, CT: Kumarian Press.
10. Glantz, M.H., ed. 1987. *Drought and Hunger in Africa: Denying Famine a Future.* Cambridge: Cambridge University Press.
11. Seavoy, R.E. 1989. *Famine in East Africa: Food Production and Food Politics.* Westport, CT: Greenwood.
12. Levinson, F.J., and Bassett. 2007. *Malnutrition is Still a Major Contributor to Child Deaths*. Washington, DC: Population Reference Bureau.
13. Gower, B.S. 1992. What do we owe future generations? In D.E. Cooper and J.A. Palmers, eds., *The Environment in Question: Ethics and Global Issues*, pp. 1–12. New York: Routledge.
14. Haub, C. 2007. *World Population Data Sheet.* Washington, DC: Population Reference Bureau.
15. Bartlett, A.A. 1997–1998. Reflections on sustainability, population growth, and the environment, revisited. *Renewable Resources Journal* 15(4):6–23.
16. Hawken, P., A. Lovins, and L.H. Lovins. 1999. *Natural Capitalism.* Boston: Little, Brown.
17. Hubbard, B.M. 1998. *Conscious Evolution.* Novato, CA: New World Library.
18. Botkin, D.B., M. Caswell, J.E. Estes, and A. Orio, eds. 1989. *Changing the Global Environment: Perspectives on Human Involvement.* New York: Academic Press.
19. Montgmery, D.R. 2007. *Dirt: The Erosion of Civilizations.* Berkeley: University of California Press.
20. World Resources Institute. 1998. *Teacher's Guide to World Resources: Exploring Sustainable Communities.* Washington, DC: World Resources Institute. http://www.igc.org/wri/wr-98–99/citygrow.htm.
21. World Resources Institute. 1999. *Urban Growth.* Washington, DC: World Resources Institute.
22. Starke, L., ed. 2007. *State of the World: Our Urban Future.* Worldwatch Institute. New York: W. W. Norton.
23. Foster, K.R., P. Vecchia, and M.H. Repacholi. 2000. Science and the Precautionary Principle. *Science* 288:979–981.
24. Easton, T.A., and T.D. Goldfarb, eds. 2003. *Taking Sides, Environmental Issues*, 10th ed. Issue 5: Is the Precautionary Principle a sound basis for international policy? pp. 76–101. Guilford, CT: McGraw-Hill/Dushkin.
25. Rolett, B., and J. Diamond. 2004. Environmental predictors of pre-European deforestation on Pacific Islands. *Nature* 431:443–446.
26. Stokstad, E. 2004. Heaven or hellhole? Islands' destinies were shaped by geography. *Science* 305:1889.
27. Hunt, T.L. 2006. Rethinking the fall of Easter Island. *American Scientist* 94(5): 412–419.
28. Hunt,T.L, and C.P. Lipo. 2008. Evidence for a shorter chronology on Rapa Nui (Easter Island). *Journal of Island and Coastal Archaeology* 3:140–148.
29. Brown, L.R., and C. Flavin. 1999. A new economy for a new century. In L. Star, ed., *State of the World*, pp. 3–21. New York: W.W. Norton.

Chapter 2 Notes

1. Wiens, J.A., D.T. Pattern, and D.B. Botkin. 1993. Assessing ecological impact assessment: Lessons from Mono Lake, California. *Ecological Applications* 3(4): 595—609; and Botkin, D.B., W.S. Broecker, L.G. Everett, J. Shapiro, and J.A. Wiens. 1988. *The Future of Mono Lake* (Report No. 68). Riverside: California Water Resources Center, University of California and http://www.monolake.org; accessed June 17, 2008.
2. Botkin, D.B. 2001. *No Man's Garden: Thoreau and a New Vision for Civilization and Nature*. Washington, DC: Island Press.
3. Lerner, L.S., and W.J. Bennetta. 1988 (April). The treatment of theory in textbooks. *The Science Teacher*, pp. 37–41.
4. Vickers, B., ed. *English Science: Bacon to Newton* (Cambridge English Prose Texts). 1987 (Paperback)
5. Kuhn, T.S. 1970. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.
6. Pease, C.M., and J.J. Bull. 1992. Is science logical? *Bioscience* 42:293–298.

7. Schmidt, W.E. 1991 (September 10). "Jovial con men" take credit(?) for crop circles. *New York Times*, p. 81.
8. This information about crop circles is from *Crop Circle News*, http://cropcirclenews.com.
9. Heinselman, H.M. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Journal of Quaternary Research* 3:329–382.
10. Trefil, J.S. 1978. A consumer's guide to pseudoscience. *Saturday Review* 4:16–21.

Chapter 3 Notes

1. Botkin, D.B. 1999. *Passage of Discovery: The American Rivers Guide to the Missouri River of Lewis and Clark*. New York: Perigee Books (a Division of Penguin-Putnam).
2. Botkin, D.B. 2004. *Beyond the Stony Mountains: Nature in the American West from Lewis and Clark to Today*. New York: Oxford University Press.
3. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York: Oxford University Press.
4. The discussion of basic systems responses in from Botkin, D.B. and K. Woods, *Fundamentals of Ecology* (in press).
5. Dunne, T., and L.B. Leopold. 1978. *Water in Environmental Planning*. San Francisco: Freeman.
6. Leach, M.K., and T.J. Givnich. 1996. Ecological determinants of species loss in remnant prairies. *Science* 273:1555–1558.
7. Lovelock, J. 1995. *The Ages of Gaia: A Biography of Our Living Earth*, rev. ed. New York: Norton.

Chapter 3 Critical Thinking Issue References

Barlow, C. 1993. *From Gaia to Selfish Genes.* Cambridge, MA: MIT Press.

Kirchner, J.W. 1989. The Gaia hypothesis: Can it be tested? *Reviews of Geophysics* 27:223–235.

Lovelock, J.E. 1995. *Gaia: A New Look at Life on Earth.* New York: Oxford University Press.

Lyman, F. 1989. What hath Gaia wrought? *Technology Review* 92(5): 55–61.

Resnik, D.B. 1992. Gaia: From fanciful notion to research program. *Perspectives in Biology and Medicine* 35(4):572–582.

Schneider, S.H. 1990. Debating Gaia. *Environment* 32(4):4–9, 29–32.

Chapter 3 Working It Out 3.1 Reference

Bartlett, A. A. 1993. The arithmetic of growth: Methods of calculation. *Population and Environment* 14(4):359–387.

Chapter 4 Notes

1. World Health Organization: http://www.who.int/csr/don/2009_05_14/en/index.html. Accessed May 14, 2009.
2. U.S. Centers for Disease Control. West Nile virus statistics, surveilance, and control. http://www.cdc.gov/ncidod/dvbid/westnile/surv&controlCaseCount07_detailed.htm.
3. U.S. Centers for Disease Control Web site, available at http:// www.cdc.gov/ncidod/sars/factsheet.htm and http://www.cdc.gov/ncidod/dvbid/westnile/qa/overview.htm.
4. Xinhua News Agency, 2002 (December 31). China's cross-border tourism prospers in 2002. From the Population Reference Bureau Web site, available at http://www.prb.org/Template.cfm? Section=PRB&template=/ContentManagement/Content_Display. cfm&ContentID=8661.
5. Graunt, J. (1662). 1973. *Natural and Political Observations Made upon the Bill of Mortality*. London, 662.
6. Barry, J.M. 2005. *The Great Influenza: The Story of the Deadliest Pandemic in History* (New York: Penguin Books, paperback).
7. Keyfitz, N. 1992. Completing the worldwide demographic transition: The relevance of past experience. *Ambio* 21:26–30.
8. U.S. Census Bureau. International Data Base, http://www.census.gov/ipc/www/idb/idbsprd.html. Accessed May 14, 2009.
9. Graunt, J. *Natural and Political Observations Made upon the Bill of Mortality*.
10. Dumond, D.E. 1975. The limitation of human population: A natural history. *Science* 187:713–721.
11. All population growth rate data are from U.S. Census Bureau, http://www.census.gov/ipc/www/idb/country/usportal.html. Accessed May 12, 2009.
12. Population Reference Bureau. 2005. World Population Data Sheet.
13. Ibid.
14. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York: Oxford University Press.
15. Zero Population Growth. 2000. U.S. population. Washington, DC.: Zero Population Growth.
16. World Bank. 1984. World Development Report 1984. New York: Oxford University Press.
17. McNeil, Donald G. Jr. 2008 (June 15). Malthus redux: Is doomsday upon us, again? *New York Times*.
18. Malthus, T.R. (1803). 1992. An essay on the principle of population. Selected and introduced by Donald Winch. Cambridge, England: Cambridge University Press.
19. *Source:* U.S. Census Bureau, International Data Base. http://www.census.gov/cgi-bin/ipc/idbagg.
20. U.S. Census Bureau. International Data Base, http://www.census.gov/ipc/www/idb/idbsprd.html. Accessed May 14, 2009.
21. Bureau of the Census, 1990. *Statistical Abstract of the United States* 1990. Washington, DC: U.S. Department of Commerce.
22. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York: Oxford University Press.
23. Erhlich, P.R. 1971. *The Population Bomb, rev. ed.* New York: Ballantine.
24. Central Intelligence Agency. 1990. *The World Factbook*. Washington, DC: CIA.
25. Naess, Arne. 1989. *Ecology, Community and Lifestyle: Outline of an Ecosophy*. New York: Cambridge University Press.

26. World Bank. 1992. World Development Report. The Relevance of Past Experience. Washington, DC: World Bank.
27. Guz, D., and J. Hobcraft. 1991. Breastfeeding and fertility: A comparative analysis. *Population Studies* 45:91–108.
28. Fathalla, M.F. 1992. Family planning: Future needs, *AMBIO* 21: 84–87.
29. Alan Guttmacher Institute. 1999. Sharing Responsibility: Women, *Society and Abortion Worldwide.* New York: AGI.
30. Xinhua News Agency, March 13, 2002, untitled, available at http://www.16da.org.cn/english/archiveen/28691.htm.
31. Xinhua News Agency, March 13, 2002, untitled, available at http://www.16da.org.cn/english/archiveen/28691.htm.
32. Revkin, A.C. 2008 (March 14). *Earth 2050: Population Unknowable?* **Dot Earth** (a Web page of the *New York Times*). http://dotearth.blogs.nytimes.com/2008/03/14/earth-2050-population-unknowable/?scp=2-b&sq =human+population+growth&st=nyt.

Chapter 5 Notes

1. Kvitek, R.G., J.S. Oliver, A.R. DeGange, and B.S. Anderson. 1992. Changes in Alaskan soft-bottom prey communities along a gradient in sea otter predation. *Ecology* 73:413–428.
2. Paine, R.T. 1969. A note on trophic complexity and community stability. *American Naturalist* 100:65–75.
3. Duggins, D.O. 1980. Kelp beds and sea otters: An experimental approach. *Ecology* 61:447–453.
4. Kenyon, K.W. 1969. The sea otter in the eastern Pacific Ocean. North American Fauna, no. 68. Washington, DC: Bureau of Sports Fisheries and Wildlife, U.S. Department of the Interior.
5. Sea otter 2008 population size from the following: U.S. Geological Survey, Western Ecological Research Center, Santa Cruz Field Station, Spring 2008 Mainland California Sea Otter Survey Results. Brian Hatfield and Tim Tinker, brian_hatfield@usgs.gov, ttinker@usgs.gov June, 24 2008, U.S. Geological Survey, http://www.werc.usgs.gov/otters/ca-surveydata.html.
6. IUCN otter specialist group. 2006. http://www.otterspecialistgroup.org/Species/Enhydra_lutris.html#Distribution. The current worldwide population estimate for *E. lutris* is approximately 108,000.
7. Kvitek et al. Changes in Alaskan soft-bottom prey communities.
8. Morowitz, H.J. 1979. *Energy Flow in Biology.* Woodbridge, CT: Oxbow Press.
9. Brock, T.D. 1967. Life at high temperatures. *Science* 158:1012–1019.
10. NOAA Office of Protected Resources, http://www.nmfs.noaa.gov/pr/species/mammals/pinnipeds/harpseal.htm, accessed June 26, 2009.
11. Lavigne, D.M., W. Barchard, S. Innes, and N.A. Oritsland. 1976. *Pinniped bioenergetics.* ACMRR/MM/SC/12. Rome: United Nations Food and Agriculture Organization.
12. Estes, J.A., and J.F. Palmisano. 1974. Sea otters: Their role in structuring nearshore communities. *Science* 185:1058–1060.
13. Schrödinger, Erwin, 1944. *What Is Life? The Physical Aspect of the Living Cell.* Cambridge: The University Press. Based on lectures delivered under the auspices of the Institute of Trinity College, Dublin, in February 1943. Widely reprinted since then and available as a PDF file on the Internet.
14. Peterson, R.O. 1995. *The Wolves of Isle Royale: A Broken Balance.* Minocqua, WI: Willow Creek Press.
15. Mitchell, W. Colgan. 1987 (December). Coral Reef Recovery on Guam (Micronesia) after Catastrophic Predation by *Acanthaster Planci. Ecology*, 68, No. 68 (6): 1592–1605.
16. Tissot, Brian N. 2005. The Hawaiian reef ecosystem. Hawai'i Coral Reef Network, http://www.coralreefnetwork.com/reefs/ecology/ecology.htm.
17. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century.* New York: Oxford University Press.
18. Connell, J.H., and R.O. Slatyer. 1977. Mechanism of succession in natural communities and their role in community stability and organization. *American Naturalist* 111:1119–1144.
19. Pickett, S.T.A., S.L. Collins, and J.J. Armesto. 1987. Models, mechanisms and pathways of succession. *Botanical Review* 53:335–371.
20. Gomez-Pompa, A., and C. Vazquez-Yanes. 1981. Successional studies of a rain forest in Mexico. In D.C. West, H.H. Shugart, and D.B. Botkin eds., *Forest Succession: Concepts and Application,* pp. 246–266. New York: Springer-Verlag.
21. Gorham, E., P.M. Vitousek, and W.A. Reiners. 1979. The regulation of chemical budgets over the course of terrestrial ecosystem succession. *Annual Review Ecology and Systematics* 10:53–84.
22. MacMahon, J.A. 1981. Successional processes: Comparison among biomes with special reference to probable roles of and influences on animals. In D.C. West, H.H. Shugart, and D.B. Botkin, eds., *Forest Succession: Concepts and Application,* pp. 277–304. New York: Springer-Verlag.

Chapter 6 Notes

1. Mau, S., D.L. Valentine, J.F. Clark, J. Reed, R. Camilli, and L. Washburn, 2007. Dissolved methane distributions and air-sea flux in the plume of a massive seep field, Coal Oil Point, California. *Geophysical Research Letters*, 34, L22603, doi:10.1029/2007GL031344, 20.
2. Ding, H., and D.L. Valentine. 2008. Methanotrophic bacteria occupy benthic microbial mats in shallow marine hydrocarbon seeps, Coal Oil Point, California. *Journal of Geophysical Research Biogeosciences* 113 (GI) G01015.
3. Leifer, I., B.P. Luyendyk , J. Boles, and J.F. Clark, 2006. Natural marine seepage blowout: Contribution to atmospheric methane. *Global Biogeochemical Cycles*, 20, GB3008, doi:10.1029/2005GB002668.

4. Christian, D. 2004. *Maps of Time.* Berkeley: University of California Press.
5. Gaddis, J.L. 2002. *The Landscape of History*. New York, Oxford University Press.
6. Lovelock, J. 1995. *The Ages of Gaia: A Biography of the Earth*. Oxford: Oxford University Press.
7. Lane, Nick. 2009. *Oxygen: The Molecule That Made the World*. Oxford: Oxford University Press.
8. This section is based on, and used with permission, Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York, Oxford University Press.
9. Henderson, Lawrence J. 1913 reprinted 1958 by the same publisher. *The Fitness of the Environment*. Boston: Beacon Press.
10. Ehrlich, P.R., A.H. Ehrlich, and J.P. Holdren. 1970. *Ecoscience: Population, Resources, Environment.* San Francisco: W.H. Freeman, p. 1051.
11. Post, W.M., T. Peng, W.R. Emanuel, A.W. King, V.H. Dale, and D.L. De Angelis. 1990. The global carbon cycle. *American Scientist* 78:310–326.
12. Kasting, J.F., O.B. Toon, and J.B. Pollack. 1988. How climate evolved on the terrestrial planets. *Scientific American* 258:90–97.
13. Berner, R.A. 1999. A new look at the long-term carbon cycle. *GSA Today* 9(11):2–6.
14. Peter M. Vitousek, Chair, John Aber, Robert W. Howarth, Gene E. Likens, Pamela A. Matson, David W. Schindler, William H. Schlesinger, and G. David Tilman. 2000. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences. *Issues in Ecology—Human Alteration of the Global Nitrogen Cycle*. ESA publication http://esa.sdsc.edu/tilman.htm 30/08/2000.
15. Chameides, W.L., and E.M. Perdue. 1997. *Biogeochemical Cycles.* New York: Oxford University Press.
16. Carter, L.J. 1980. Phosphate: Debate over an essential resource. *Science* 209:4454.
17. Vaccari, D.A. 2009. Phosphorus: A looming crisis. *Scientific American* 300(6):54–59.
18. Smil, V. 2000. Phosphorus in the environment: Natural flows and human interference. *Annual Review of Environment and Resources*, 25:53–88.
19. U.S. Geological Survey. 2009. http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/mcs-2009-phosp.pdf.
20. Ibid.
21. Asner, G.P., T.R. Seastedt, and A.R. Townsend. 1997 (April). The decoupling of terrestrial carbon and nitrogen cycles. *Bioscience* 47 (4):226–234.
22. Hellemans, A. 1998 (February 13). Global nitrogen overload problem grows critical. *Science,* 279:988–989.
23. Smil, V.1997 (July). Global populations and the nitrogen cycle. *Scientific American,* 76–81.
24. Vitousek, P.M., J. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger, and G.D. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. *Issues in Ecology.* http://esa.sdsc.edu/.

Chapter 7 Notes

1. EPA. 2009. *Cap and Trade Essentials*. Adobe pdf file available at http://www.epa.gov/captrade/documents/ctessentials.pdf accessed June 16, 2009.
2. Loris, Nicolas and Ben Lieberman. 2009. *Cap and trade: A handout for corporations and a huge tax on consumers.*" Thomas A. Roe Institute for Economic Policy Studies. Washington, DC: Heritage Foundation.
3. Tarlock, Dan. 1994. The nonequilibrium paradigm in ecology and the partial unraveling of environmental law." Loyola of Los Angeles Law Review **2**(1121): 1–25.
4. Senate Resolution 580 2007, Recognizing the importance of pollinators to ecosystem health and agriculture in the United States and the value of partnership efforts to increase awareness about pollinators and support … (Agreed to by Senate). http://www.ucs.iastate.edu/mnet/_repository/2005/plantbee/pdf/Senate_Resolution_580.pdf.
5. The North American Pollinator Protection Campaign and the Pollinator Partnership. http://www.pollinator.org. Accessed July 18, 2009.
6. National Biological Information Infrastructure. 2009. http://www.nbii.gov/portal/community/Communities/Ecological_Topics/Pollinators/Pollinator_Species/Invertebrates/. Accessed July 18, 2009.
7. Hills, S. 2008. Study sheds light on bee decline threatening crops. Food Navigator USA.com 20-Aug-2008. http://www.foodnavigator-usa.com/Product-Categories/Fruit-vegetable-nut-ingredients. Accessed July 18, 2009.
8. Costanza, R., et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253–260.
9. Hardin, G. 1968. The tragedy of the commons. *Science* 162:1243–1248.
10. State of Vermont. http://www.anr.state.vt.us/air/htm/woodstoverebate.htm Accessed July 18, 2009.
11. Clark, C.W. 1973. The economics of overexploitation. *Science* 181:630–634.
12. Bockstoce, J.R., D.B. Botkin, A. Philp, B.W. Collins, and J.C. George, 2007. The geographic distribution of Bowhead Whales in the Bering, Chukchi, and Beaufort seas: Evidence from whaleship records, 1849–1914. 2007 *Marine Fisheries Review* 67 (3): 1–43.
13. Freudenburg, W.R. 2004. Personal communication.
14. Gunn, J.M., ed. 1995. *Restoration and Recovery of an Industrial Region: Progress in Restoring the Smelter-damaged Landscape near Sudbury, Canada*. New York: Springer-Verlag.
15. Litton, R.B. 1972. Aesthetic dimensions of the landscape. In J.V. Krutilla, ed. *Natural Environments*. Baltimore: Johns Hopkins University Press.
16. Schwing, R.C. 1979. Longevity and benefits and costs of reducing various risks *Technological Forecasting and Social Change* 13:333–345.
17. Gori, G.B. 1980. The regulation of carcinogenic hazards. *Science* 208:256–261.
18. Cairns, J., Jr., 1980. Estimating hazard. *BioScience* 20:101–107.

Chapter 8 Notes

1. Dowdy, Alan K. 2008. Current issues in invasive species management. *PowerPoint Presentation* USDA, APHIS Plant Protection and Quarantine, Emergency and Domestic Programs. Provided courtesy of Dowdy.
2. Botkin, D.B. 2001. *No Man's Garden: Thoreau and a New Vision for Civilization and Nature*. Washington, DC: Island Press.
3. Woese, C.R., O. Kandler, and M.L. Wheelis. 1990. Towards a natural system of organisms: Proposals for the domains Archaea, Bacteria, and Eucharya. *Proceedings of the National Academy of Sciences* (USA) 87:4576–4579.
4. Cicero. *The Nature of the Gods* (44 B.C.). Reprinted by Penguin Classics. New York, 1972.
5. *Christian Science Monitor*. 2008. *Complete DNA Coding Opens New Ways to Beat Malaria:* Published: 10/2/2002. © Guardian News & Media 2008 Boston.
6. United Nations World Health Organization. 2003. http://www. who.int/mediacentre/releases/2003/pr33/en.
7. World Health Organization. 2008. World malaria 2008.
8. World Health Organization. 2008. World malaria 2008; and U.S. Centers for Disease Control. Malaria, April 11, 2007. http://www.cdc.gov/malaria/facts.htm; United Nations World Health Organization. 2003. http://www. who.int/ mediacentre/releases/2003/pr33/en/; World Health Organization. 2000. Overcoming antimicrobial resistance: World Health Report on Infectious Diseases 2000.
9. James, A.A. 1992. Mosquito molecular genetics: The hands that feed bite back. *Science* 257:37–38; Kolata, G., 1984. The search for a malaria vaccine. *Science* 226:679–682; Miller, L.H. 1992. The challenge of malaria. *Science* 257:36–37; World Health Organization. 1999 (June). Using malaria information. News Release No. 59. WHO; World Health Organization. 1999 (July). Sequencing the *Anopheles gambiae genome.* News Release No. 60. WHO.
10. Darwin, C.R.1859. *The Origin of Species by Means of Natural Selection or the Preservation of Favored Races in the Struggle for Life.* London: Murray. (Originally published as: Darwin, C. 1859. *On the Origin of Species by Means of Natural Selection.* London: John Murray.)
11. Grant, P.R. 1986. *Ecology and Evolution of Darwin's Finches*. Princeton, NJ: Princeton University Press.
12. Cox, Call., I.N. Healey, and P.D. Moore. 1973. *Biogeography.* New York: Halsted.
13. Hedrick, P.W., G.A. Gutierrez-Espeleta, and R.N. Lee. 2001. Founder effect in an island population of bighorn sheep. *Molecular Ecology* 10: 851–857.
14. Hutchinson, G.E. 1965. *The Ecological Theater and the Evolutionary Play.* New Haven, CT: Yale University Press.
15. Hardin, G. 1960. The competitive exclusion principle. *Science* 131:1292–1297.
16. British Forestry Commission. http://www.forestry.gov.uk/ forestry/Redsquirrel. May 20, 2008.
17. Miller, R.S. 1967. Pattern and process in competition. *Advances in Ecological Research* 4:1–74.
18. Elton, C.S. 1927. *Animal Ecology.* New York: Macmillan.
19. Hutchinson, G.E. 1958. Concluding remarks. *Cold Spring Harbor Symposium in Quantitative Biology* 22:415–427.
20. Botkin, D.B. 1985. The need for a science of the biosphere. *Interdisciplinary Science Reviews* 10:267–278.
21. Wallace, A.R. 1896. *The Geographical Distribution of Animals.* Vol. 1. New York: Hafner. Reprinted 1962.
22. Pielou, E.C. 1979. *Biogeography.* New York: Wiley.
23. Takhtadzhian, A.L. 1986. *Floristic Regions of the World.* Berkeley: University of California Press; and Udvardy, M. 1975. *A Classification of the Biogeographical Provinces of the World.* IUCN Occasional Paper 18. Morges, Switzerland: IUCN.
24. Lentine, J.W. 1973. Plates and provinces, a theoretical history of environmental discontinuity. In N.F. Hughes, ed., *Organisms and Continents through Time,* pp. 79–92. Special Papers in Paleontology 12.
25. Mather, J.R., and G.A. Yoshioka. 1968. The role of climate in the distribution of vegetation. *Annals of the Association of American Geography,* 58:29–41; and Prentice, I.C., W. Cramer, S.P. Harrison, R. Leemans, R.A. Monserud, and A.M. Solomon. 1992. A global biome model based on plant physiology and dominance, soil properties and climate. *Journal of Biogeography* 19:117–134.
26. Wilson, E.O. and R.H. MacArthur 2001. *The Theory of Island Biogeography*. Princeton, NJ: Princeton University Press.
27. Tallis, J.H. 1991. *Plant Community History.* London: Chapman & Hall.

Chapter 9 Notes

1. Comprehensive Everglades Restoration Plan. www. evergladesplan.org. Accessed March 11, 2006.
2. Society for Ecological Restoration. 2004. The SER international primer on ecological restoration. www.ser.org. Accessed March 11, 2006.
3. Riley, A.L. 1998. *Restoring Streams in Cities*. Washington, DC: Island Press.
4. South Florida Water Management District. Kissimmee River restoration. www.sfwmd.gov. Accessed March 11, 2006.
5. Ripple, J.W., and Robert L. Beschta, 2004. Wolves and the ecology of fear: Can predation risk structure ecosystems? *BioScience* 54(8):755–66.
6. Smith, D.W., R.O. Smith, and D.B. Houston, 2003. Yellowstone after wolves. *BioScience* 53(4):330–340.
7. CNN News, Tuesday, February 22, 2005. Posted: 2:28 PM EST (1928) GMT, http://www.cnn.com/2005/TECH/ science/02/22/iraq.marshes/index.html. Accessed April 10, 2006.
8. UNEP project to help manage and restore the Iraq Marshlands, Iraqi Marshlands Observation System (IMOS). 2006. http://imos.grid.unep.ch.

9. Collins, S.L., A.K. Knapp, J.M. Briggs, J.M. Blair, and E.M. Steinauer, 1998. Modulation of diversity by grazing and mowing in native tallgrass prairie. *Science* 280:745–747.
10. Roemer, G.W., A.D. Smith, D.K. Garcelon, and R.K. Wayne 2001. The behavioral ecology of the Island Fox (*Urocyon littoralis*). *Journal of Zoology* 255:1–14.
11. Roemer, G.W., T.J. Coonan, D.K. Garcelon, J. Dascompte, and L. Laugrin 2001. Feral pigs facilitate hyperpredation by golden eagles and indirectly cause the decline of island fox. *Animal Conservation* 4:307–318.
12. Taylor, P. 2000. Nowhere to run, nowhere to hide. *National Wildlife* 38(5).
13. Wathern, Peter. 1986. Restoring derelict lands in Great Britain. In G. Orians, ed., *Ecological Knowledge and Environmental Problem-solving: Concepts and Case Studies*, pp. 248–274. Washington, DC: National Academy Press.
14. Pacific Estuarine Research Laboratory (PERL). 1997 (November). The status of constructed wetlands at Sweetwater Marsh National Wildlife Refuge. Annual Report to the California Department of Transportation.
15. Malakoff, D. 1998 (April 17). Restored wetlands flunk real-world test. *Science* 280:371–372.
16. Zedler, J.B. 1997. Adaptive management of coastal ecosystems designed to support endangered species. *Ecology Law Quarterly* 24:735–743.
17. Zedler, J.B., and A. Powell. 1993. Problems in managing coastal wetlands: Complexities, compromises, and concerns. *Oceanus* 36(2):19–28.

Chapter 10 Notes

1. Whitworth, K.W., E. Symanski, and A.L. Coker. 2008. Childhood lymphohematopoietic cancer incidence and hazardous air pollutants in southeast Texas, 1995–2004. *Environmental Health Perspectives* 116(11):1576–1580.
2. US Department of Labor. 1,3-Butadiene. Health Effects. Accessed April 28, 2008, www.osha.gov.
3. Selinus, O., ed. 2005. *Essentials of Medical Geology*. Burlington, MA: Elsevier Academic Press.
4. Rubonowitz-Lundun, E., and K.M. Hiscock. 2005. Water hardness and health effects. In O. Selinus, ed., *Essentials of Medical Geology*, Ch. 13. Burlington, MA: Elsevier Academic Press.
5. Han, H. 2005. The grey zone. In C. Dawson and G. Gendreau. *Healing Our Planet, Healing Ourselves*. Santa Rosa, CA: Elite Books.
6. Warren, H.V., and R.E. DeLavault. 1967. A geologist looks at pollution: Mineral variety. *Western Mines* 40:23–32.
7. Evans, W. 1996. Lake Nyos. Knowledge of the fount and the cause of disaster. *Science* 379:21.
8. Krajick, K. 2003. Efforts to tame second African killer Lake Begin. *Science* 379:21.
9. Gunn, J., ed. 1995. *Restoration and Recovery of an Industrial Region: Progress in Restoring the Smelter-damaged Landscape near Sudbury, Canada*. New York: Springer-Verlag.
10. Blumenthal, D.S., and J. Ruttenber. 1995. *Introduction to Environmental Health*, 2nd ed. New York: Springer.
11. U.S. Geological Survey. 1995. *Mercury Contamination of Aquatic Ecosystems*. USGS FS 216–95.
12. Greer, L., M. Bender, P. Maxson, and D. Lennett. 2006. Curtailing mercury's global reach. In L. Starke, ed., *State of the World 2006*, pp. 96–114. New York: Norton.
13. Ehrlich, P.R., A.H. Ehrlich, and J.P. Holdren. 1970. *Ecoscience: Population, Resources, Environment*. San Francisco: Freeman.
14. Waldbott, G.L. 1978. *Health Effects of Environmental Pollutants*, 2nd ed. Saint Louis: Moseby.
15. McGinn, A.P. 2000 (April 1). POPs culture. *World Watch*, pp. 26–36.
16. Carlson, E.A. 1983. International symposium on herbicides in the Vietnam War: An appraisal. *BioScience* 33:507–512.
17. Cleverly, D., J. Schaum, D. Winters, and G. Schweer. 1999. Inventory of sources and releases of dioxin-like compounds in the United States. Paper presented at the 19th International Symposium on Halogenated Environmental Organic Pollutants and POPs, September 12–17, Venice, Italy. Short paper in *Organohalogen Compounds* 41:467–472.
18. Roberts, L. 1991. Dioxin risks revisited. *Science* 251: 624–626.
19. Kaiser, J. 2000. Just how bad is dioxin? *Science* 5473: 1941–1944.
20. Johnson, J. 1995. SAB Advisory Panel rejects dioxin risk characterization. *Environmental Science & Technology* 29:302A.
21. National Research Council Committee on EPA's Exposure and Human Health Reassessment of TCDD and Related Compounds.2006. *Health Risks from Dioxin and Related Compounds*. Washington, DC: National Academy Press.
22. Thomas, V.M., and T.G. Spiro.1996. The U.S. dioxin inventory: Are there missing sources? *Environmental Science &Technology* 30:82A–85A.
23. U.S. Environmental Protection Agency. 1994 (June). Estimating exposure to dioxinlike compounds. Review draft. Office of Research and Development, EPA/600/6–88/005 Ca-c.
24. Krimsky, S. 2001. Hormone disrupters: A clue to understanding the environmental cause of disease. *Environment* 43(5):22–31.
25. Committee on Hormonally Active Agents in the Environment, National Research Council, National Academy of Sciences. 1999. *Hormonally Active Agents in the Environment*. Washington, DC: National Academy Press.
26. Royte, E. 2003. Transsexual frogs. *Discover* 24(2):26–53.
27. Hayes, T.B., K. Haston, M. Tsui, A. Hong, C. Haeffele, and A. Vock. 2002. Hermaphrodites beyond the cornfield. Atrozine-induced testicular oogenesis in leopard frogs (Rana pipiens). *Nature* 419:895–896.
28. Hanes, T.B., et al. 2002. Hermaphroditic demasculinized frogs after exposure to the herbicide atrozine at low ecologi-

cally relevant doses. *Proceedings of the National Academy (PNAS)* 99(8):5476–5480.
29. Ross, M. 1990. Hazards associated with asbestos minerals. In B.R. Doe, ed., *Proceedings of a U.S. Geological Survey Workshop on Environmental Geochemistry*, pp. 175–176. U.S. Geological Survey Circular 1033.
30. Agency for Toxic Substances & Disease Registry. 2002. Mortality from Asbestosis in Libby, Montana, 1979–1998. www.atsdr.cdc.gov.
31. Pool, R. 1990. Is there an EMF-cancer connection? *Science* 249:1096–1098.
32. Linet, M.S., E.E. Hatch, R.A. Kleinerman, L.L. Robison, W.T. Kaune, D.R. Friedman, R.K. Severson, C.M. Haines, C.T. Hartsock, S. Niwa, S. Wacholder, and R.E. Tarone. 1997. Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. *New England Journal of Medicine* 337(1):1–7.
33. Kheifets, L.I., E.S. Gilbert, S.S. Sussman, P. Guaenel, S.D. Sahl, D.A. Savitz, and G. Thaeriault. 1999. Comparative analyses of the studies of magnetic fields and cancer in electric utility workers: Studies from France, Canada, and the United States. *Occupational and Environmental Medicine* 56(8):567–574.
34. Ahlbom, A., E. Cardis, A. Green, M. Linet, D. Savitz, and A. Swerdlow. 2001. Review of the epidemiologic literature on EMF and health. *Environmental Perspectives* 109(6):911–933.
35. World Health Organization, International Agency for Research on Cancer. Volume 80: Non-ionizing radiation, Part 1, Static and extremely low-frequency (ELF) electric and magnetic fields. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. 2002: Lyon, France.
36. Kleinerman, R.A., W.T. Kaune, E.E. Hatch, et al. 2000. Are children living near high voltage power lines at increased risk of acute lymphocytic leukemia? *American Journal of Epidemiology* 15:512–515.
37. Greenland, S., A.R. Sheppard, W.T. Kaune, C. Poole, and M.A. Kelsh. 2000. A pooled analysis of magnetic fields, wire codes, and childhood leukemia. Childhood Leukemia-EMF Study Group. *Epidemiology* 11(6):624–634.
38. Schoenfeld, E.R., E.S. O'Leary, K. Henderson, et al. 2003. Electromagnetic fields and breast cancer on Long Island: A case-control study. *American Journal of Epidemiology* 158:47–58.
39. Kabat, G.C., E.S. O'Leary, E.R. Schoenfeld, et al. 2003. Electric blanket use and breast cancer on Long Island. *Epidemiology* 14(5):514–520.
40. Kliukiene, J., T. Tynes, and A. Andersen. 2004. Residential and occupational exposures to 50-Hz magnetic fields and breast cancer in women: A population-based study. *American Journal of Epidemiology* 159(9):852–861.
41. Zhu, K., S. Hunter, K. Payne-Wilks, et al. 2003. Use of electric bedding devices and risk of breast cancer in African-American women. *American Journal of Epidemiology* 158: 798–806.
42. Francis, B.M. 1994. *Toxic Substances in the Environment*. New York: John Wiley & Sons.
43. Poisons and poisoning. 1997. *Encyclopedia Britannica*. Vol. 25, p. 913. Chicago: Encyclopedia Britannica.
44. Air Risk Information Support Center (Air RISC), U.S. Environmental Protection Agency. 1989. *Glossary of Terms Related to Health Exposure and Risk Assessment*. EPA/450/_3–88/016. Research Triangle Park, NC.
45. Needleman, H.L., J.A. Riess, M.J. Tobin, G.E. Biesecker, and J.B. Greenhouse. 1996. Bone lead levels and delinquent behavior. *Journal of the American Medical Association* 275:363–369.
46. Centers for Disease Control. 1991. *Preventing Lead Poisoning in Young Children*. Atlanta: Public Health Service, Centers for Disease Control.
47. Goyer, R.A. 1991. Toxic effects of metals. In M.O. Amdur, J. Doull, and C.D. Klaassen, eds., *Toxicology*, pp. 623–680. New York: Pergamon.
48. Bylinsky, G. 1972. Metallic nemesis. In B. Hafen, ed., *Man, Health and Environment*, pp. 174–185. Minneapolis: Burgess.
49. Hong, S., J. Candelone, C.C. Patterson, and C.F. Boutron. 1994. Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations. *Science* 265:1841–1843.

Chapter 11 Notes

1. Etter, L. 2007. With corn prices rising, pigs switch to fatty snacks on the menus: Trail mix, cheese curls, tater tots; Farmer Jones's ethanol fix. _*Wall Street Journal*.
2. Farm Photos of the Week, August 1, 2005. Photos by Debbie Roos, Agricultural Extension Agent. Co-op member John Bonitz demonstrates how to catch the seeds that shatter during harvest. He is harvesting mustard, one of the many oilseed crops that can be used to create biodiesel fuel. http://www.ces.ncsu.edu/chatham/ag/SustAg/farmphotoaugust0105.html.
3. The North Carolina Biodiesel Trade Group was started in 2007 and has its own Web site. http://news.biofuels.coop/2008/01/15/north-carolina-biodiesel-trade-group-launched.
4. UN News Central UN predicts rise in global cereal production but warns prices will remain high 14 February 2008, The United Nations Food and *Agriculturel Organization* (FAO) http://www.un.org/apps/news/story.asp?NewsID=25621&Cr=cereal&Cr1=.
5. BBC news about a new UN FAO report February 18th, 2008. http://news.bbc.co.uk/2/hi/business/7148374.stm.
6. UN News Central UN predicts rise in global cereal production but warns prices will remain high 14 February 2008, The United Nations Food and *Agricultural Organization* (FAO) http://www.un.org/apps/news/story.asp?NewsID=25621&Cr=cereal&Cr1=.
7. Vocke, Gary. 2007, Global production shortfalls bring record wheat prices. AmberWaves November 2007.

8. U.S. Department of Agriculture (USDA). 2007. National Resources Inventory 2003 Annual NRI Soil erosion report February 2007. Accessed December 23, 2008 from http://www.nrcs.usda.gov/technical/NRI/2003/SoiIErosion mrb.pdf.
9. Land area in agriculture is from United Nations Food and *Agricultural Organization*, Statistics 2006, http://faostat.fao.org/faostat.
10. Information on African wars is from Globalsecurity.org http://www.globalsecurity.org/military/world/war/index.html, accessed June 16, 2008. Information on African coups is from http://www.crisisgroup.org/home/index.cfm?id=4040.
11. Field, J.O., ed. 1993. *The Challenge of Famine: Recent Experience, Lessons Learned.* Hartford, CT.: Kumarian Press.
12. World Food Programme. 1998. *Tackling Hunger in a World Full of Food: Tasks Ahead for Food Aid*; and U.N. FAO. "FAOSTAT" 2003 Web site.
13. UNFAO. 1998 (September). Global information.
14. USDA, National Resources Inventory. 2003. Annual NRI. http://www.nrcs.usda.gov/technical/NRI/2003/nri03eros-mrb.html
15. Trimble, S.W., and P. Crosson. July 2000. U.S. soil erosion rates myth and reality. *Science* 289:248–250; and Trimble, S.W. 2000. Soil conservation and soil erosion in the upper Midwest. *Environmental Review* 7(1):3–9.
16. USDA, National Resources Inventory. 2003. Annual NRI. http://www.nrcs.usda.gov/technical/NRI/2003/ images/eros chart.
17. Lashof, J. C., ed. 1979. *Pest Management Strategies in Crop Protection*. Vol. 1. Washington, D.C.: Office of Technology Assessment, U.S. Congress; and Baldwin, F.L., and P.W. Santelmann. 1980. Weed science in integrated pest management. *BioScience* 30:675–678.
18. Barfield, C.S., and J.L. Stimac. 1980. Pest management: An entomological perspective. *BioScience* 30:683–688.
19. EBRD and FAO call for bold steps to contain soaring food prices, UN FAO http://www.fao.org/newsroom/en/news/2008/1000808/index.html, FAO news room, March 10, 2008.
20. USDA, National Agricultural Statistics Service Research and Development Division. 1997 Census of Agriculture acreage by state for harvested cropland, corn, soybeans, wheat, hay, and cotton" http://www.nass.usda.gov/research/sumpant.htm. Accessed March 10, 2008.
21. USDA. U.S. organic farming emerges in the 1990s. Available at http://www.ers.usda.gov/publications/aib770/aib770.pdf.
22. PEW Biotechnology Initiative, Pew Charitable Trusts. Web site. http://pewagbiotech.org/resources/factsheets/display.php3? FactsheetID.
23. California Agricultural Statistics Service. 1999. California agricultural statistics. Sacramento, Calif.
24. USDA. July 2000. Magriet Caswell interview.
25. USDA. 2003. Alternative Farming Systems Information Center. Available at http://www.nal.usda.gov/afsic/ofp/.
26. IPCC, 2007: Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Martin L. Parry, Osvaldo F. Canziani, Jean P. Palutikof, Paul J. van der Linden, and Clair E. Hanson (eds.). Cambridge, UK: Cambridge University Press, 1,000 pp.

Chapter 12 Notes

1. Lloyd, E.C. 2007. Jamaica Bay Watershed Protection Plan Volume I—Regional Profile, New York City Department of Environmental Protection, Emily Lloyd, Commissioner, October 1, 2007.
2. Lloyd, E.C. 2007. Jamaica Bay Watershed Protection Plan Volume I—Regional Profile, New York City Department of Environmental Protection, Emily Lloyd, Commissioner, October 1, 2007.
3. United Nations Food and Agriculture Organization. 2001. Rome: UN FAO. Available at ftp://ftp.fao.org/docrep/fao/003/y0900e/ y0900e02.pdf.
4. Suming Jin. 2006. Effects of forest ownership and change on forest harvest rates, types and trends in northern Maine. *Science Direct* Available online May 2, 2006. http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6T6X-4JVTCCJ-4&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrld=1050312920&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=5c36bcd396911d59aff4583aec8d9095.
5. United Nations Food and Agriculture Organization. 2001. Rome: UN FAO. ftp://ftp.fao.org/docrep/fao/003/y0900e/y0900e02.pdf.
6. USFS. 2008. Forest Ownership Patterns and Family Forest Highlights from the National Woodland Owner Survey USDA, Northern Research Station.
7. USFS. 2008. Forest Ownership Patterns and Family Forest Highlights from the National Woodland Owner Survey USDA, Northern Research Station.
8. Busby, F.E., et al. 1994. *Rangeland Health: New Methods to Classify Inventory and Monitor Rangelands*. Washington, D.C.: National Academy Press.
9. UNFAO. 2006. Global Forest Resources Assessment 2005: Progress toward Sustainable Forest Management. Rome, United Nations Food and Agriculture Organization. p.122, Table 7.8.
10. World Firewood Supply, World Energy Council website. www. worldenergy.org. April 24, 2006. Accessed 6/01/08.
11. World Resources Institute. 1993. *World Resources 1992–93*. New York: Oxford University Press.
12. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. NewYork: Oxford University Press.
13. Likens. G.E., F.H. Borman, R.S. Pierce, J.S. Eaton, and N.M. Johnson. 1977. *The Biogeochemistry of a Forested Ecosystem*. New York: Springer-Verlag.

14. The Hubbard Brook ecosystem continues to be one of the most active and long-term ecosystem studies in North America. An example of a recent publication is: Bailey, S. W., D.C. Buso, and G.E. Likens. 2003. Implications of sodium mass balance for interpreting the calcium cycle of a forested ecosystem. *Ecology* 84(2):471–484.
15. Swanson, F.J., and C.T. Dyrness. 1975. Impact of clearcutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. *Geology* 3:393–396.
16. Fredriksen, R.L. 1971. Comparative chemical water quality—natural and disturbed streams following logging and slash burning. In *Forest Land Use and Stream Environments*, pp. 125–137. Corvallis: Oregon State University.
17. Sedjo, R.A., and D.B. Botkin. 1997. Using forest plantations to spare the natural forest environment 39(10):14–20.
18. http://www.google.com/imgres?imgurl=http://www.scienceimage.csiro.au/index.cfm%3Fevent%3Dsite.image.thumbnail%26id%3D4808%26viewfile%3Df%26divid%3DBU&imgrefurl=http://www.scienceimage.csiro.au/index.cfm%3Fevent%3Dsite.image.detail%26id%3D4808&h=270&w=270&sz=51&tbnid=pRK6RyGx2HvnnM:&tbnh=113&tbnw=113&prev=/images%3Fq%3Dforest%2Bplantation%2Bphoto&usg=__iTa9J6H8DL3gHqq5Nb8pp-VjO_E=&ei=RSjeSufqMZXVlAevoYSoAw&sa=X&oi=image_result&resnum=1&ct=image&ved=0CAsQ9QEwAA
19. Kimmins, H. 1995. Proceedings of the conference on certification of sustainable forestry practices. Malaysia.
20. Jenkins, Michael B. 1999. *The Business of Sustainable Forestry*. Washington, D.C.: Island Press.
21. World Resources Institute. *Disappearing Land: Soil Degradation*. Washington, D.C.: WRI.
22. Manandhar, A. 1997. *Solar Cookers as a Means for Reducing Deforestation in Nepal*. Nepal: Center for Rural Technology.
23. Council on Environmental Quality and U.S. Department of State. 1981. The Global 2000 Report to the President: Entering the Twenty-first Century. Washington, D.C.: Council on Environmental Quality.
24. Perlin, J. 1989. *A Forest Journey: The Role of Wood in the Development of Civilization.* New York: Norton.
25. Botkin, D.B. 1992. Global warming and forests of the Great Lakes states. In J. Schrnandt, ed., *The Regions and Global Warming: Impacts and Response Strategies.* New York: Oxford University Press.
26. Runte, A. 1997. *National Parks: The American Experience.* Lincoln: Bison Books of the University of Nebraska.
27. Runte, A.1997. *National Parks: The American Experience.* Lincoln: Bison Books of the University of Nebraska.
28. National Park Service Web site, http://www/wilderness.net/index.cfm?fuse=NWPS&sec=fastfacts.
29. Quotations from Alfred Runte cited by the Wilderness Society on its Web site, available at http://www.wilderness.org/NewsRoom/ Statement/20031216.cm.
30. Voyageurs National Park Web site, http://www.npsgov/voya/home.htm.
31. Costa Rica's TravelNet.National parks of Costa Rica. 1999. Costa Rica: Costa Rica's TravelNet.
32. Kenyaweb. 1998. National parks and reserves. Kenya.
33. National Park Service Web site, http://www/wilderness.net/index.cfm?fuse=NWPS&sec=fastfacts.
34. The National Wilderness Preservation System. 2006. http://nationalatlas. gov/articles/boundaries/a_nwps.html.
35. Hendee, J.C., G.H. Stankey, and R.C. Lucas. 1978. Wilderness management. *United States Forest Service Misc. Pub.* No. 1365.

Chapter 13 Notes

1. Botkin, D.B. 2004. *Beyond the Stony Mountains: Nature in the American West from Lewis and Clark to Today.* New York: Oxford University Press.
2. Mattson, D.J., and M.W. Reid. 1991. Conservation of the Yellowstone grizzly bear. *Conservation Biology* 5:364–372.
3. The National Zoo. April 10, 2006. http://nationalzoo.si.edu/support/adoptspecies/Animalinfo/biosn/default.cfm.
4. www.bisoncentral.com. April 10, 2006.
5. Haines, F. 1970. *The Buffalo.* New York: Thomas Y. Crowell.
6. Miller, R.S., D.B. Botkin, and R. Mendelssohn. 1974. The whooping crane (*Grus americana*) population of North America, *Biol. Conservation* 6: 106–111.
7. Stehn, Tom. 2009. Whooping crane recovery activities. U.S. Fish and Wildlife Service. Aransas Pass, TX, U.S. Fish and Wildlife Service: 27 pp.
8. Stehn, Tom. 2009. Whooping crane recovery activities. U.S. Fish and Wildlife Service. Aransas Pass, TX, U.S. Fish and Wildlife Service: 27pp.
9. The National Zoo. April 10, 2006. http://nationalzoo.si.edu/support/adoptspecies/Animalinfo/biosn/default.cfm.
10. Martin, P.S. 1963. *The Last 10,000 Years.* Tucson: University of Arizona Press.
11. http://www.defenders.org/wildlife/dolphin/tundolph.html.
12. April 9, 2009, New York Times, National Briefing | West, California: Agency Calls Off Chinook Salmon Fishing Season, by the Associated Press.
13. Specific data obtained from National Marine Fisheries Service. http://swr.nmfs.noaa.gov/biologic.htm.
14. Pacific Fishery Management Council. 2008, February. *Preseason Report I, Stock Abundance Analysis for 2008 Ocean Salmon Fisheries,* Chapter 2.
15. FAO Statistics. 2006. http://www.fao.org/waicent/portal/statistics_en.asp.
16. Species Survival Commission. 2006. *Red List of Threatened Species*. Geneva: IUCN.
17. Botkin, D.B., and L.M. Talbot. 1992. Biological diversity and forests. In N. Sharma, ed., *Contemporary Issues in Forest Management: Policy Implications.* Washington, D.C: World Bank.
18. Botkin, D. B. 2001. *No Man's Garden: Thoreau and a New Vision for Civilization and Nature*, Island Press.

19. O'Donnell, James J. 2008. *The Ruin of the Roman Empire*. New York: ECCO Press (HarperCollins), p. 190.
20. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York: Oxford University Press.
21. Michigan Department of Natural Resources. 2008. Michigan's 2008 Kirtland's Warbler Population Reaches Another Record High.
22. NOAA's Coral Reef Conservation Program: Medicine. http://coralreef.noaa.gov/aboutcorals/values/medicine.
23. Bruckner, A. 2002. Life-Saving Products from Coral Reefs: *Issues in Science and Technology*. Spring Ed.
24. Naess, A. 1989. *Ecology, Community, and Lifestyle.* Cambridge, England: Cambridge University Press.
25. Regan, H.M., R. Lupia, A.N. Drinnan, and M.A. Burgman. 2001. The currency and tempo of extinction. *American Naturalist* 157(1):1–10.
26. Martin, P.S. 1963. *The Last 10,000 Years.* Tucson: University of Arizona Press.
27. http://www.defenders.org/wildlife/dolphin/tundolph.html.
28. U.S. Fish and Wildlife Service Delisting Report http://ecos.fws.gov/tess_public/DelistingReport.do)
29. Friends of the Earth. 1979. *The Whaling Question: The Inquiry by Sir Sidney Frost of Australia.* San Francisco: Friends of the Earth.
30. United Nations Food and Agriculture Organization. 1978. *Mammals in the Seas.* Report of the FAO Advisory Committee on Marine Resources Research, Working Party on Marine Mammals. FAO Fisheries Series 5, vol. 1. Rome: UNFAO.
31. NOAA. 2003. World fisheries. Available at http://www.st.nmfs. gov/st1/fus/current/04_world2002.pdf.
32. United Nations Food and Agriculture Organization. 1978. *Mammals in the Seas.* Report of the FAO Advisory Committee on Marine Resources Research, Working Party on Marine Mammals. FAO Fisheries Series 5, vol. 1. Rome: UNFAO.
33. Stenn, T. 2003. Whooping Crane Report, Arkansas National Wildlife Refuge, December 10, 2003. Available at http://www.birdrockport. com/tom_stehn_whooping_crane__report.htm
34. Regan, H.M., R. Lupia, A.N. Drinnan, and M.A. Burgman. 2001. The currency and tempo of extinction. *American Naturalist* 157(1):1–10.
35. Impacts of California sea lion and Pacific Harbor Seal on Salmonids and west coast ecosystems, U.S Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, February 10, 1999; p. Appendix-7.
36. NOAA delisted species, http://www.nmfs.noaa.gov/pr/species/ esa.htm#delisted and U.S. Fish and Wildlife Service Threatened and Endangered Species System (TESS).
37. California Department of Fish and Game. http://www.dfg.ca.gov/news/issues/lion/lion_faq.html, mountain lion abundances.
38. U.S. Department of Defense and U.S. Fish and Wildlife Service. 2006. Red-cockaded Woodpecker *(Picoides borealis).* http://www.fws. gov/endangered/pdfs/DoD/RCW_fact_sheet-Aug06.pdf, accessed 12128108.

Chapter 14 Notes

1. McKibben, B. 2007. Energizing America. *Sierra* 92(1): 30–38; 112–113.
2. Butti, K., and J. Perlin. 1980. *A Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto, CA: Cheshire Books.
3. Morowitz, H.J. 1979. *Energy Flow in Biology.* New Haven, CT: Oxbow Press.
4. Ehrlich, P.R., A.H. Ehrlich, and J.P. Holdren. 1970. *Ecoscience: Population, Resources, Environment.* San Francisco: W.H. Freeman.
5. Feynman, R.P., R.B. Leighton, and M. Sands. 1964. *The Feynman Lectures on Physics.* Reading, MA: Addison-Wesley.
6. Alekett, K. 2006. Oil: A bumpy road ahead. *World Watch* 19(1):10–12.
7. Cavanay, R. 2006. Global oil about to peak? A recurring myth. *World Watch* 19(1):13–15.
8. Miller, P. 2009. Saving energy. *National Geographic* 251(3): 60–81.
9. Lindley, D. 2009. The energy should always work twice. *Nature* 458(7235): 138–141.
10. Flavin, C. 1984. *Electricity's Future: The Shift to Efficiency and Small-scale Power.* Worldwatch Paper 61. Washington, DC: Worldwatch Institute.
11. Consumers' Research. 1995. Fuel economy rating: 1996 mileage estimates. *Consumers' Research* 78:22–26.
12. Lovins, A.B. 1979. *Soft Energy Paths: Towards a Durable Peace.* New York: Harper & Row.
13. Duval, J. 2007. The fix. *Sierra* 92(1):40–41.
14. Wald, M.L. 2009. The power of renewables. *Scientific American* 300(3):57–61.
15. Flavin, C. 2008. *Low-Carbon Energy: A Roadmap*. Worldwatch report 178. Worldwatch Institute. Washington, DC.
16. California Energy Commission. 1991.*California's Energy Plan: Biennial Report.* Sacramento, CA.
17. Flavin, C., and S. Dunn. 1999. Reinventing the energy system. In L.R. Brown et al., eds., *State of the World 1999: A Worldwatch Institute Report on Progress toward a Sustainable Society.* New York: W.W. Norton.
18. Dunn, S. 2000. *Micropower, the Next Electrical Era.* Worldwatch Paper 151. Washington, DC: Worldwatch Institute.
19. U.S. Energy Information Administration. International Energy Outlook 2009. Accessed January 18, 2010. www.eia.doe.gov

Chapter 15 Notes

1. Alekett, K. 2006. Oil: A bumpy road ahead. *World Watch* 19(1):10–12.
2. Roberts, P. 2008. Tapped out. *National Geographic* 213(6):86–91

3. Cavanay, R. 2006. Global oil about to peak? A recurring myth. *World Watch* 19(1):13–15.
4. McKibben, B. 2007. Energizing America. *Sierra* 92(1):30–38; 112–113.
5. Van Koevering, T.E., and N.J. Sell. 1986. *Energy: A Conceptual Approach*. Englewood Cliffs, NJ: Prentice-Hall.
6. McCulloh, T.H. 1973. In D.A. Brobst and W.P. Pratt, eds., *Oil and Gas in United States Mineral Resources*, pp. 477–496. U.S. Geological Survey Professional Paper 820.
7. British Petroleum Company. 2009. *B.P. Statistical Review of World Energy 2008*. London: British Petroleum Company.
8. Maugeri, L. 2004. Oil: Never cry wolf—when the petroleum age is far from over. *Science* 304:1114–1115.
9. Kerr, R.A. 2000. USGS optimistic on world oil prospects. *Science* 289:237.
10. Youngquist, W. 1998. Spending our great inheritance. Then what? *Geotimes* 43(7):24–27.
11. Edwards, J.D. 1997. Crude oil and alternative energy production forecast for the twenty-first century: The end of the hydrocarbon era. *American Association of Petroleum Geologists Bulletin* 81(8):1292–1305.
12. Darmstadter, J., H.H. Landsberg, H.C. Morton, and M.J. Coda. 1983. *Energy Today and Tomorrow: Living with Uncertainty*. Englewood Cliffs, NJ: Prentice-Hall.
13. Nuccio, V. 2000. *Coal-bed Methane: Potential Environmental Concerns*. U.S. Geological Survey. USGS Fact Sheet. FS-123-00.
14. Wood, T. 2003 (February 2). Prosperity's brutal price. *Los Angeles Time Magazine.*
15. Milici, R. C. and Swezey, C. S. 2006. Assessment of Appalachian Basin Oil and Gas Resources: Devonian Shale-Middle and Upper Paleozoic Total Petroleum System. *U.S. Geological Survey Open File Report* 2006-1237. Reston, VA.
16. Suess, E., G. Bohrmann, J. Greinert, and E. Lauch. 1999. Flammable ice. *Scientific American* 28(5):76–83.
17. U.S. Energy Administration 2008. Annual Coal Report 2007. Accessed July 20, 2009 at http://www.eia.doe.gov.
18. Rahn, P.H. 1996. *Engineering Geology: An Environmental Approach*, 2d ed. New York: Elsevier.
19. Stewart Burns, S. 2009. Mountain top removal in Central Appalachia. *Southern Spaces*, September 30.
20. Webber, M.E. 2009. Coal-to-liquids: The good, the bad and the ugly. *Earth* 54(4):44–47.
21. Berlin Snell, M. 2007. Can coal be clean? *Sierra* 92(1): 32–33.
22. Corcoran, E. 1991. Cleaning up coal. *Scientific American* 264:106–116.
23. Environmental Protection Agency. 2009. EPAs response to the TVA Kingston Fossil Plant Fly ash release. Accessed March 15, 2009 at http://www.epa.gov/region4/kingston.
24. Knapp, D.H. 1995. Non-OPEC oil supply continues to grow. *Oil & Gas Journal* 93:35–45.
25. Dyni, J.R. 2006. Geology and resources of some world oil-shale deposits. *U.S. Geological Survey Scientific Investigations Report 2005-5294*. Reston, VA.
26. Kunzig, R. 2009. The Canadian oil boom. *National Geographic* 215(3):34–59.
27. EIS. 2008. About tar sands. Accessed May 27, 2008 at http://ostseis.anl.gov.
28. Sachs, J.D. 2008. Surging food prices and global stability. *Scientific American* 298(6):40.

Chapter 16 Notes

1. Eaton, W.W. 1978. Solar energy. In L.C. Ruedisili and M.W. Firebaugh, eds., *Perspectives on Energy,* 2nd ed., pp. 418–436. New York: Oxford University Press.
2. Brown, L.R. 1999 (March–April). Crossing the threshold. *Worldwatch,* pp. 12–22.
3. U.S. Energy Information "Administration, Form EIA-63B 2008 (December). Annual Photovoltaic Module/Cell Manufacturers Survey."
4. Starke, L., ed. 2005. *Vital Signs 2005.* New York: Norton.
5. Berger, J.J. 2000. *Beating the Heat.* Berkeley, CA: Berkeley Hills Books.
6. Demeo, E.M., and P. Steitz. 1990. The U.S. electric utility industry's activities in solar and wind energy. In K.W. Böer, ed., *Advances in Solar Energy,* Vol. 6, pp. 1–218. New York: American Solar Energy Society.
7. Johnson, J.T. 1990 (May). The hot path to solar electricity. *Popular Science,* pp. 82–85.
8. Kartha, S., and P. Grimes. 1994. Fuel cells: Energy conversion for the next century. *Physics Today* 47:54–61.
9. Kartha, S., and P. Grimes. 1994. Fuel cells: Energy conversion for the next century. *Physics Today* 47:54–61.
10. Piore, A. 2002 (April 15). Hot springs eternal: Hydrogen power. *Newsweek,* pp.32H.
11. Demeo, E.M., and P. Steitz. 1990. The U.S. electric utility industry's activities in solar and wind energy. In K.W. Böer, ed., *Advances in Solar Energy,* Vol. 6, pp. 1–218. New York: American Solar Energy Society.
12. Schatz Solar Hydrogen Project. N. D. Pamphlet. Arcata, CA: Humboldt State University.
13. Fuel cell buses. http://www.fuelcells.org/info/charts/buses.pdf, created by Fuel Cells 2000.
14. Fuel Cell Bus Programs Worldwide. http://www.cleanairnet.org/infopool/1411/propertyvalue19516.html.
15. Schatz Solar Hydrogen Project. N. D. Pamphlet. Arcata, CA: Humboldt State University.
16. World Firewood Supply. World Energy Council. 2006 (April 24). www.worldenergy.org.
17. Botkin, D.B., 2010 *Powering the Future: A Scientist's Guide to Energy Independence* (Indianapolis In: Pearson FT Press Science).
18. Showstack, R. 2003. Re-examining potential for geothermal energy in United States. *EOS* 84(23):214.

19. Piore, 2002 (April 15). Hot springs Eternal: Hydrogen power. *newsweek*, P.32H.
20. Anonymous. 2009. *World Wind Energy Report 2008*. Bonn, Germany, World Wind Energy Association. http://www.wwindea.org/home/index.php.
21. Electric Power: Energy Information Administration, Form EIA-923, Power Plant Operations Report, and predecessor forms: Form EIA-906, Power Plant Report, and Form EIA-920, Combined Heat and Power Plant Report.
22. Botkin, D.B. 2010. *Powering the Future: A Scientist's Guide to Energy Independence* (Indianapolis, IN: Pearson FT Press).
23. Top 50 Cities in the U.S. by Population and Rank. Infoplease. © 2000–2007 Pearson Education, publishing as Infoplease. June 17, 2008. http://www.infoplease.com/ipa/A0763098.html.
24. Quinn, R. 1997 (March). Sunlight brightens our energy future. *The World and I,* pp. 156–163.
25. Anonymous. 2009. *World Wind Energy Report 2008*. Bonn, Germany, World Wind Energy Association. http://www.wwindea.org/home/index.php.
26. Anonymous. 2009. *World Wind Energy Report 2008*. Bonn, Germany, World Wind Energy Association.
27. Botkin, 2010.
28. Botkin, 2010.
29. Botkin, 2010.
30. Wright, P. 2000. Geothermal energy. *Geotimes* 45(7):16–18.
31. Wright, P. 2000. Geothermal energy. *Geotimes* 45(7):16–18.
32. Botkin, 2010.
33. Duffield, W.A., J.H. Sass, and M.L. Sorey. 1994. Tapping the Earth's natural heat. U.S. Geological Survey Circular 1125.
34. Botkin, 2010.
35. Johnson, J.T. 1990 (May). The hot path to solar electricity. *Popular Science,* pp. 82–85.
36. Reuters, 2008, (January 15). Wind Farm Clears Hurdle.
37. Galbraith, Kate, 2006 (September 25). Texas is more hospitable than Mass. to wind farms economy, culture fueling a boom, *The Boston Globe*.
38. Cassidy, P. 2008, April 19. Floating wind farm plan dealt blow, *Cape Cod Times.*
39. Zezima, K. 2010. Interior secretary sees little hope for consensus on wind farm. New York Times.

Chapter 17 Notes

1. Rosa, E.A., and R.E. Dunalp. 1994. Nuclear power: Three decades of public opinion. *Public Opinion Quarterly* 58(2):295–324.
2. New York Times Topics > Subjects > I > Indian Point Nuclear Power Plant (NY). Updated: May 6, 2009. http://topics.nytimes.com/top/reference/timestopics/subjects/i/indian_point_nuclear_power_plant_ny/index.html?=8qa&scp=1-spot&sq=indian+point&st=nyt
3. Botkin, D.B., 2010, *Powering the Future*: *A Scientist's Guide to Energy Independence* (Indianapolis IN: Pearson FT Press).
4. European Nuclear Society. Accessed February 26, 2010 at http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-world-wide.htm.
5. Till, O.E. 1989. Advanced reactor development. *Annals of Nuclear Energy* 16(6):301–305.
6. Churchill, A.A. 1993 (July). Review of WEC Commission: Energy for tomorrow's world. *World Energy Council Journal*, pp. 19–22.
7. Duderstadt, J.J. 1978. Nuclear power generation. In L. C. Ruedisili and M. W. Firebaugh, eds., *Perspectives on Energy*, 2d ed., pp. 249–273. New York: Oxford University Press.
8. Brenner, D.J. 1989. *Radon: Risk and Remedy*. New York: Freeman.
9. Ehrlich, P.R., A.H. Ehrlich, and J.P. Holdren. 1970. *Ecoscience: Population, Resources, Environment*. San Francisco: Freeman.
10. *New Encyclopedia Britannica*. 1997. *Radiation*, 26, p. 487.
11. Brenner,1989.
12. Waldbott, G.L. 1978. *Health Effects of Environmental Pollutants*, 2d ed. St. Louis: C.V. Moseby.
13. U.S. Department of Energy. 1999. Radiation (in) waste isolation pilot plant. Carlsbad, New Mexico. Accessed at www.wipp. carlsbad.nm.us
14. New Encyclopedia Britannica. 1997. *Radiation*, 26, p. 487.
15. Waldbott, G.L. 1978. *Health Effects of Environmental Pollutants*, 2d ed. St. Louis: C.V. Moseby.
16. Ehrlich et al. 1970.
17. University of Maine and Maine Department of Human Services. 1983 (February). Radon in water and air. *Resource Highlights*.
18. Brenner, 1989.
19. Ibid., 1989.
20. Till, O.E. 1989. Advanced reactor development. *Annals of Nuclear Energy* 16(6):301–305.
21. MacLeod, G.K. 1981. Some public health lessons from Three Mile Island: A case study in chaos. *Ambio* 10:18–23.
22. Anspaugh, L.R. , R.J. Catlin, and M. Goldman. 1988. The global impact of the Chernobyl reactor accident. *Science* 242: 1513–1518.
23. Nuclear Energy Agency. 2002. Chernobyl Assessment of Radiological and Health Impacts: 2002 Update of Chernobyl: Ten Years On.
24. Anspaugh, L.R. , R.J. Catlin, and M. Goldman. 1988. The global impact of the Chernobyl reactor accident. *Science* 242: 1513–1518.
25. Nuclear Energy Agency. 2002.
26. U.S. Department of Energy. 1979. *Environmental Development Plan*, *Magnetic Fusion*. DOE/ER-0052. Washington, DC: U.S. Department of Energy.
27. Cohen, B.L. 1990. *The Nuclear Energy Option: An Alternative for the 90s*. New York: Plenum.
28. Fletcher, M. 2000 (November 14). The last days of Chernobyl. *Times 2* London, pp. 3–5.

29. Cohen, B.L. 1990. *The Nuclear Energy Option: An Alternative for the 90s*. New York: Plenum.
30. U.S. Nuclear Regulatory Commissions Accessed March 17, 2010 at http://www.nrc.gov/reading rm/doc collections/fact sheets/radwaste.html.
31. Office of Industry Relations. 1974. *Development, Growth and State of the Nuclear Industry*. Washington, DC: U.S. Congress, Joint Committee on Atomic Energy.
32. Ibid.
33. Weisman, J. 1996. Study inflames Ward Valley controversy. *Science* 271:1488.
34. DOE Waste Isolation Pilot Plant "WIPP Chronology." Accessed February 26, 2010 http://www.wipp.energy.gov/fctshts/factsheet.htm.
35. Waste Isolation_Pilot_Plant (2047). The Remote Handled Transuranic Waste Program.
36. Weart, W.D., M.T. Rempe, and D.W. Powers. 1998 (October). The waste isolation plant. *Geotimes*.
37. U.S. Department of Energy. 1999. Waste isolation pilot plant, Carlsbad, NM. Accessed at www.wipp.carlsbad.nm.us.
38. Ibid.
39. Roush, W. 1995. Can nuclear waste keep Yucca Mountain dry— and safe? *Science* 270:1761.
40. Hanks, T.C., I.J. Winograd, R.E. Anderson, T.E. Reilly, and E.P. Weeks. 1999. *Yucca Mountain as a Radioactive Waste Repository*. U.S. Geological Survey Circular 1184.
41. *New York Times*. Nevada: A Shift at Yucca Mountain. New York, Associated Press.
42. Ibid.
43. Hanks et al., 1999. *New York Times*. Nevada: A Shift at Yucca Mountain. Nuclear Regulatory Commission. 2000 NRC's high level waste program. Accessed July 18, 2000 at http://www.nrc.gov/NMSS/ DWM/hlw.htm.
44. *New York Times*, Nevada: A shift at Yucca Mountain.
45. Nuclear Regulatory Commission, 2000 NRC's high level waste program.
46. Ibid.
47. Botkin, 2010.
48. Cohen, 1990.
49. Botkin, D.B. The limits of nuclear power 2008 (October 20). *International Herald Tribune*.
50. Starke, L., ed. 2005. *Vital Signs* 2005. New York: W.W. Norton p. 139.
51. U.S. Nuclear Regulatory Commission, 2008. Backgrounder on New Nuclear Plant Designs, Accessed February 24, 2010 at http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/new-nuc-plant-des-bg.html.
52. A.C. Kadak, R.G. Ballinger, T. Alvey, C.W. Kang, P. Owen, A. Smith, M. Wright and X. Yao. 1998. Nuclear Power Plant Design Project: A Response to the Environmental and Economic Challenge Of Global Warming Phase 1 Review of Options & Selection of Technology of Choice. http://web.mit.edu/pebble-bed/background.html
53. Anonymous, 2010. Vermont Senate Votes to Close Nuke Plant in 2012. *New York Times*.

Chapter 18 Notes

1. Frank, R. What drought? Palm Beach. Wall Street Journal online November 16, 2007, accessed April 28, 2008 @ wsj.com
2. Palm Beach County. Reclaimed water. Accessed April 28, 2008 @ www. pbcgov.com.
3. Henderson, L.J. 1913. *The Fitness of the Environment: An Inquiry into the Biological Significance of the Properties of Matter.* New York: Macmillan.
4. Water Resources Council. 1978. The Nation's Water Resources, 1975–2000, Vol. 1. Washington, DC.
5. Winter, T.C.. J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. *Groundwater and Surface Water: A Single Resource.* U.S. Geological Survey Circular 1139.
6. Micklin, P., and Aladin, N.V. 2008. Reclaiming the Aral Sea. *Scientific American*, 298(4):64–71.
7. Kenny, J.F., et al. 2010. *Estimated Use of Water in the United States in 2005.* U.S. Geological Survey Circular 1344.
8. Alexander, G. 1984 (February/March). Making do with less. *National Wildlife*, special report, pp. 11–13.
9. U.S. General Accounting Office. 2003. *Freshwater Supply: States' View of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages.* Report GAO-03-514.
10. Gfeick, P.H., P. Loh, S.V. Gomez, and J. Morrison. 1995. *California Water 2020, A Sustainable Vision*. Oakland, CA: Pacific Institute for Studies in Development, Environment and Security.
11. Alley, W.M., T.E. Reilly, and O.L. Franke. 1999. *Sustainability of Ground-Water Resources*. U.S. Geological Survey Circular.
12. Leopold, L.B. 1977. A reverence for rivers. *Geology* 5: 429–430.
13. Allen, 1998. Virtual water: A strategic resource, global solutions to regional deficits. *Groundwater* 36(4): 545–546.
14. Hoekstra, A.Y. and A.K. Chapagain. 2008. *Globalization of Water*. Malden MA: Blackwell Publishing.
15. Smil, V. 2008.Water news: Bad, good and virtual. *American Scientist* 96:399–407
16. Hoekstra, A.Y ed. 2003. Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series 12. IHE Delft. The Netherlands.
17. Holloway, M. 1991. High and dry. *Scientific American* 265:16–20.
18. Levinson, M. 1984 (February/March). Nurseries of life. *National Wildlife*, special report, pp. 18–21.
19. Nichols, F.H., J.E. Cloern, S.N. Luoma, and D.H. Peterson. 1986. The modification of an estuary. *Science* 231:567–573.
20. Day, J.W., Jr., J.M. Rybczyk, L. Carboch, W.H. Conner, P. Delgado-Sanchez, R.I. Partt, and A. Westphal. 1998. A review of recent studies of the ecology and economic aspects of the

application of secondary treated municipal effluent to wetlands in southern Louisiana. From L.P. Rozas et al., eds., *Symposium on Recent Research in Coastal Louisiana*, February 3–5, 1998, Louisiana Sea Grant College Program, pp. 1–12.

21. Hileman, B. 1995. Rewrite of Clean Water Act draws praise, fire. *Chemical & Engineering News* 73:8.
22. Kaiser, J. 2001. Wetlands restoration: Recreated wetlands no match for original. *Science* 293:25a.
23. Gurardo, D., M.L. Fink, T.D. Fontaine, S. Newman, M. Chimney, R. Bearxotti, and G. Goforth. 1995. Large-scale constructed wetlands for nutrient removal from stormwater runoff: An Everglades restoration project. *Environmental Management* 19:879–889.
24. Pearce, M. 1995 (January). The biggest dam in the world. *New Scientist*, pp. 25–29.
25. Zich, R. 1997. China's Three Gorges: Before the flood. *National Geographic* 192(3):2–33.
26. Dolan, R., A. Howard, and A. Gallenson. 1974. Man's impact on the Colorado River and the Grand Canyon. *American Scientist* 62:392–401.
27. Hecht, J. 1996. Grand Canyon flood a roaring success. *New Scientist* 151 (2045):8.
28. Wright, S.A., Schmidt, J.C., Melis, T.S., Topping, D.J., and D.M. Rubin. 2008. Is there enough sand? Evaluating the fate of Grand Canyon sandbars. *GSA Today*. 18 (8):4–10.
29. Grant, G. 2001. Dam removal: Panacea or Pandora for rivers. *Hydrological Processes* 15:1531–1532.
30. State of Maine. 2001. A brief history of the Edwards Dam. Accessed January 15, 2000 at http://janus.state.me.us/spo/edwares/_timeline.htm.
31. O'Connor, J., Major, J., and G. Grant. 2008. The dams come down. *Geotimes* 53(3):22–28.
32. American Rivers. Elwha River Restoration accessed March 1, 2006 at www.americanrivers.org.
33. Brown, L.R. 2003. *Plan B: Rescuing a Planet under Stress and a Civilization in Trouble*. New York: Norton.
34. Hoekstra, A.Y. 2009. A comprehensive introduction to water footprints. Accessed August 25, 2009 at http: //www.waterfootprint.org.

Chapter 19 Notes

1. Environmental Protection Agency, American Heritage Rivers, Hudson River. Accessed February 19, 2005 www.epa.gov/rivers/98rivers/hudson.html .
2. Bopp, R.F., and H.J. Simpson, 1989. *Contamination of the Hudson River: The Sediment Record in Contaminated Marine Sediments, an Assessment and Remediation*. Washington, DC: National Academy Press.
3. Wall, G.R., Riva-Murray, K., Phillips, P.J. 1998. and , A.C. 2009. Water quality in the Hudson River Basin. New York and adjacent states, 1992–95.
4. Morrison, J. 2005. How much is clean water worth? *National Wildlife* 43(2):22–28.
5. Gleick, P.H. 1993. An introduction to global fresh water issues. In P. H. Gleick, ed., *Water in Crisis*, pp. 3–120 New York: Oxford University Press.
6. Hileman, B. 1995. Pollution tracked in surface and groundwater. *Chemical & Engineering News* 73:5.
7. Lewis, S.A. 1995. Trouble on tap. *Sierra* 80:54–58.
8. Smith, R.A. 1994. Water quality and health. *Geotimes* 39:19–21.
9. MacKenzie, W.R., et al. 1994. A massive outbreak in Milwaukee of Cryptosporidium infection transmitted through the public water supply. *New England Journal of Medicine* 331:161–167.
10. Kluger, J. 1998. Anatomy of an outbreak. *Time* 152 (5): 56–62.
11. Maugh, T.H. 1979. Restoring damaged lakes. *Science* 203:425–127.
12. Mitch, W.J., J.W. Day, Jr., J.W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N. Wang. 2001. The Gulf of Mexico hypoxia— approaches to reducing nitrate in the Mississippi River or reducing a persistent large-scale ecological problem. *Bioscience* (in Press).
13. Hinga, K.R. 1989. Alteration of phosphorus dynamics during experimental eutrophication of enclosed-marine ecosystems. *Marine Pollution Bulletin* 20:624–628.
14. Richmond, R.H. 1993. Coral reefs: Present problems and future concerns resulting from anthopogenic disturbance. *American Zoologist* 33:524–536.
15. Bell, P.R. 1991. Status of eutrophication in the Great Barrier Reef Lagoon. *Marine Pollution Bulletin* 23:89–93.
16. Hunter, C.L., and C.W. Evans. 1995. Coral reefs in Kaneohe Bay, Hawaii: Two centuries of Western influence and two decades of data. *Bulletin of Marine Science* 57:499.
17. Department of Alaska Fish and game 1918. *Alaska Fish and Game* 21(4), Special Issue.
18. Holway, M. 1991. Soiled shores. *Scientific American* 265: 102–106.
19. Robinson, A.R. 1973. Sediment, our greatest pollutant? In RW. Tank, ed., *Focus on Environmental Geology*, pp. 186–192. New York: Oxford University Press.
20. Yorke, T.H. 1975. Effects of sediment control on sediment transport in the northwest branch, Anacostia River basin, Montgomery Country, Maryland. *Journal of Research* 3:481–494.
21. Poole, W. 1996. Rivers run through them. *Land and People* 8:16–21.
22. Haikin, M. 2007. Nanotechnology takes on water pollution. *Business 2.0 Magazine*. Accessed May 30, 2008 @ money.cnn.com.
23. Natural Resources Defense Council. 2008. Mimicking nature to solve a water pollution problem. Accessed May 30, 2008 @ www.nrdc.org.
24. Carey, J. 1984 (February/'March). Is it safe to drink? *National Wildlife*, Special Report pp. 19–2l.
25. Pye, U.I., and R. Patrick. 1983. Groundwater contamination in the United States. *Science* 221:713–718.
26. Newmark, J. 2008, May. Plastic people of the universe. *Discover*.

Better Planet Special Issue, pp. 46–51.

27. Foxworthy, G. L. 1978. Nassau Country, Long Island, New York—Water problems in humid country. In G. D. Robinson and A. M. Spieker, eds., *Nature to Be Commanded*, pp. 55–68. U.S. Geological Survey Professional Paper 950. Washington, DC: U.S. Government Printing Office.
28. Van der Leeden, F., F.L. Troise, and D.K. Tood. 1990. *The Water Encyclopedia*, 2d ed. Chelsea, MI: Lewis Publishers.
29. U.S. Geologic Survey. 1997. Predicting the impact of relocating Boston's sewage outfall. *UCGC Fact Sheet* 185–97.
30. Jobling, S., M. Nolan, C.R. Tyler, G. Brighty, and J.P. Sumpter. 1998. Widespread sexual disturbance in wild fish. *Environmental Science and Technology* 32(17):2498–2506.
31. Environmental Protection Agency, Drinking Water Committee of the Science Advisory Board. 1995. *An SAB Report: Safe Drinking Water. Future Trends and Challenges*. Washington, DC: Environmental Protection Agency.
32. Jewell, W.J. 1994. Resource—recovery wastewater treatment. *American Scientist* 82:366–375.
33. Task Force on Water Reuse. 1989. *Water Reuse: Manual of Practice SM-3*. Alexandria. VA: Water Pollution Control Federation.
34. Kadlec, R.H., and R.L. Knight. 1996. *Treatment Wetlands*. New York: Lewis Publishers.
35. Breaux, A.M., and J.W. Day Jr. 1994. Policy considerations for wetland wastewater treatment in the coastal zone: A case study for Lousiana. *Coastal Management* 22:285–307.
36. Day, J.W., Jr., J.M. Rybczyk, L. Carboch, W.H. Conner, P. Delgado-Sanchez, R.T. Pratt, and W. Westphal. 1998. A review of recent studies of the ecology and economic aspects of the application of secondary treated municipal effluent wetlands in southern Louisiana. In L.P. Rozas et al., eds., Symposium on Recent Research in Coastal Louisiana, February 1998, Louisiana Sea Great College Program, pp. 1–12.
37. Breaux, A., S. Fuber, and J. Day 1995. Using natural coastal wetland systems: An economic benefit analyis. *Journal of Environmental Management* 44:285–291.
38. Barone, J. 2008, May. Better Water. *Discover*. Better Planet Special Issue, pp. 31--32.
39. Faustini, J.M., et al.2009. Assessing stream ecosystem condition in the United States. *EOS*, *Transactions, American Geophysical Union*, 36:309–310.
40. Hileman, B. 1995. Rewrite of Clean Water Act draws praise, fire. *Chemical & Engineering News* 73:8.
41. Mallin, M.A. 2000. Impacts of industrial animal production on rivers and estuaries. *American Scientist* 88(l):26–37.
42. Bowie, P. 2000. No act of God. *The Amichs Journal* 21(4): 16–21.

Chapter 20 Notes

1. Mann, M.E. and 8 others. 2009. Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science* 326:1256–1260.
2. Fagan, B.M. 2008.*The Great Warming: Climate Change and the Rise and Fall of Civilizations*. New York: Bloomsbury Press.
3. Le Roy Ladurie, E. (1971)
4. National Research Council. 2006. Surface temperature reconstructions for the last 2,000 years. Washington DC: National Academy Press.
5. Fagan, B 2004. *The Long Summer: How Climate Changed Civilization* NY: Basic Books.
6. Marsh, W.M., and Dozier, J. 1981. *Landscape*. New York: John Wiley & Sons.
7. Crowley, T.J. 2000. Causes of climate change over the past 1000 years. *Science* 289:270–277.
8. Hansen, J., et al. 2005. Efficiency of climate forcrngs. *Joumal of Geophysical Research* 110 (D18104):45P.
9. Callendar, C.S. The artifcial production of carbon dioxiod and its influence on tempeature. *Quarterly Journal of the Royal Meteorological Society* 84(1938):223–237; Can carbon dioxide influence climate? *Weather* 4(1949):310–14; On the Amount of Carbon Dioxide in the Atmosphere Talus 10(1958):243
10. NOAA. 2009. Paleo proxy data. In Introduction to Paleoclimatology. Accessed March 24, 2010. www.ncdc.noaa.gov.
11. Caillon, N., J.P. Severinghouse, et al, 2003. Timing of atmospheric CO_2 and Antarctic temperature changes across termination III. *Science* 299: 1728–1731.
12. Encyclopedia Britannica online. Accessed January2, 2009. http://www.britannica.com/EBchecked/topic-art/174962/69345/Carbon-dioxide-concentrations-in-Earths-atmosphere-plotted-over-the-past.
13. Hansen, J., et al. 2005. Efficiency of climate forcing. *Journal of Geophysical Research* 110 (D18104):45P.
14. Brook, E. 2008, Palaeoclimate – Windows on the greenhouse, *Nature*, 453(7193), 291-292, Doi 10.1038/453291a.
15. Dlugokencky, E.J., L.P. Steele, P.M. Lang, and K.A. Masarie. 1994. The growth rate and distribution of atmospheric methane. *Journal of Geophysical Research* 99(D8): 17021-17043.
16. Hansen, J., A. Lacis, and M. Prather 1989. Greenhouse effect of chlorofluorocarbons and other trace gases. *Journal of Geophysical Research* 94(D13): 16417-16421.
17. Rodhe, H. 1990. A comparison of the contribution of various gases to the greenhouse effect. *Science* 248:1217-1219.
18. Hansen, J., A. Lacis and M. Prather 1989. Greenhouse effect of chlorofluorocarbons and other trace gases. *Journal of Geophysical Research* 94(D13): 16417-16421.
19. IPCC. 2007. Climate Change 2007: The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report, IPCC. New York: Cambridge University Press, 989P.
20. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York: Oxford University Press.'
21. Bennett, K. 1990. Milankovitch Cycles and their effects on Species in ecological and evolutionary time. *Paleobiology* 16(1):11–12.

22. Foukal, P., C. Frohlich, H. Sprint, and T. M. L. Wigley. 2006. Variations in solar luminosity and their effect on the Earth's climate. *Nature* 443:151-166.
23. Soon, W. 2007. Implications of the secondary role of carbon dioxide and methane forcing in climate change: Past, present and future. *Physical Geography* 28(2): 97-125.
24. IPCC. 2007. Climate change 2007: The Physical science basis: Working Group I Contribution to the Fourth Assessment Report, IPCC. New York: Cambridge University Press, 989P.
25. Broker, W. 1997. Will our ride into the greenhouse future be a smouth one? *Geology Today* 7 no.5: 2-6.
26. Steager, R. 2006. The source of Europe's mild climate. *American Scientist* 94:334-341.
27. Hidore, J. J., Oliver, J.E., Snow M., and Snow, R. 2010. *Climatology*. Upper Saddle River, NJ: Prentice Hall.
28. Jet Propulsion Laboratory. El Niño–When the Pacific Ocean speaks, Earth listens. Accessed September 25, 2008 at wmv.jpl.nasa.gov.
29. Botkin, D.B. 1990. *Discordant Harmonies: A New Ecology for the 21st Century*. New York: Oxford University Press.
30. NOAA. 2009. Global climate change impacts in the United States. Washington, DC: Cambridge University Press. Editors: Thomas R. Karl, NOAA National Climatic Data Conter; Jerry M. Melillo, Marine Biological Laboratory, Thomas C. Peterson, NOAA National Climatic Data Center.
31. IPCC. 2007. Climate change 2007: Synthesis report. Valencia, Spain: IPCC.
32. Pelto, M.S. 1996. Recent Changes in Glacier and Alpine Runoff in the North Cascades, Washington. *Hydrological Processes* 10:1173-80.
33. Appenzeller, T. 2007. The Big Thaw. *National Geographic* 211(6):56-71.
34. Mote. P.W., and G. Kasen, 2007. The shrinking glaciers of Kilimanjaro: can global warming be blamed? *American Scientist* 95(4): 218-25.
35. Stroeve, J., M. Serreze, and S. Drobot. 2008. "Arctic Sea Ice Extent Plummets in 2007. EOS, Transactions." *American Geophysical Union* 89(2): 13–14.
36. Parkinson, C. L. 2008. "Recent Trend Reversals in Arctic Sea Ice Extent—Possible Connections to the North Atlantic Oscillation." *Polar Geography* 31(1):3-14.
37. Morrison, J., J. Wahr, R. Kwok, and Perelta Ferriz. 2006. "Recent trends in Arctic Ocean Mass Distribution Revealed by GRACE." *Geophysical Reserve Letters.* 34:L07602.
38. Botkin, D.B. 2007. Forcasting effects of global warming on biodiversity. *Bio Science* 57(3):227–236.
39. Charmantier, A., Robin H. McCleery, Lionel R. Cole, Chris Perrins, Loeske E. B. Kruuk, Ben C. Sheldon. 2008, "Adaptive Phenotypic Plasticity in Response to Climate Change in a Wild Bird Population." *Science* 320(5877): 800–803.
40. Grime, J. P., Jason D. Fridley, Andrew P. Askew, Ken Thompson, John G. Hodgson, and Chris R. Bennett. 2008. "Long-term Resistance to Simulated Climate Change in an Infertile Grassland." *PNAS* 105(29):10028 10032. Earth System Science Committee (1988). *Earth System Science: A Preview.* Boulder, Colorado: University Corporation for Atmospheric Research.
41. Rogers, D. J., and S. E. Randolph. 2000. "The Global Spread of Malaria in a Future, Warmer World." *Science* 289:1763–1766.
42. Sumilo, D., Asokliene, L., Bormane, A. Vasilenko, V., and Golovijova,I. 2007. "Climate Change Cannot Explain the Upsurge of Tick-Borne Encephalitis in the Baltics." *PLoS ONE* 2(6): e500 doi:10.1371/journa.pone.0000500.
43. Botkin, D.B., 2010. *Powering the Future: A Scientist's Guide to Energy independence.* (Pearson FT Press Science. May 2010.
44. Dunn, S. 2001. "Decarbonizing the Energy Economy." In *World Watch Institute State of the World 2001.* New York: Norton.
45. Rice, C. W. 2002. "Storing Carbon in Soil: Why and How." *Geotimes* 47(1):14–17.
46. Friedman, S. J. 2003. "Storing Carbon in Earth." *Geotimes* 48(3):16–20.
47. Bartlett, K. 2003. "Demonstrating Carbon Sequestration." *Geotimes* 48 (3):22–23. 48 on P66 http://www. juliantrubin.com/bigten/photosynthesisexperiments.html; and a variety of other sources.
48. http://www.IPCC.ch/pdf/presentations/himalanga-statement-20january2010.pdf

Chapter 21 Notes

1. National Park Service. 1984. *Air Resources Management Manual*.
2. U.S. Environmental Protection Agency. 2008. National air quality trends through 2007. www.epa.gov.
3. Araujo, J.A. and 10 others. 2008. Ambient particulate pollutants in the ultrafine range promote early atherosclerosis and systematic oxidative stress. *Circulation Research* 102: 589–596.
4. Godish, T. 1991. *Air Quality*, 2d ed. Chelsea, MI.: Lewis Publishers.
5. Seitz, F., and C. Plepys. 1995. Monitoring air quality in healthy people 2000. *Healthy People 2000: Statistical Notes no. 9*. Atlanta: Centers for Disease Control and Prevention, National Center for Health Statistics.
6. American Lung Association. 2009. *State of the Air 2009*. www. stateofftheair.org
7. Moore, C. 1995. Poisons in the air. *International Wildlife* 25:38–45.
8. Pope, C. A., III, D.V. Bates, and M.E. Raizenne. 1995. Health effects of particulate air pollution: Time for reassessment? *Environmental Health Perspectives* 103:472–480.
9. Travis, D.J., A.M. Carleton, and R.G. Lauritsen 2002. Contrails reduce daily temperature range. *Nature* 419:601.
10. U.S. Environmental Protection Agency. 2008. Acid Rain. www.epa.gov.
11. Canadian Department of the Environment. 1984. *The acid rain story*. Ottawa: Minister of Supply and Services.

12. Lippmann, M., and R.B. Schlesinger. 1979. *Chemical Contamination in the Human Environment*. New York: Oxford University Press.
13. Winkler, E.M. 1998 (September). The complexity of urban stone decay. *Geotimes*, pp. 25–29.
14. U.S. Environmental Protection Agency. 2009. Acid Rain Program SO_2 Allowances Fact Sheet. www.epa.gov.
15. U.S. Environmental Protection Agency 2006. National scale air toxics assessment for 1999. Estimated emissions. Concentrations and risks. Technical Fact Sheet. Accessed April 10, 2006 at www.epa.gov.
16. Tyson, P. 1990. Hazing the Arctic. *Earthwatch* 10:23–29.
17. NASA. 2008. NASA satellite measures pollution from East Asia to North America. www.nasa.gov.
18. Pittock, A.B., L.A. Frakes, D. Jenssen, J.A. Peterson, and J.W. Zillman, eds. 1978. *Climatic Change and Variability: A Southern Perspective*. New York: Cambridge University Press.
19. Blake, D.R., and F.S. Rowland. 1995. Urban leakage of liquefied petroleum gas and its impact on Mexico City air quality. *Science* 269:953.
20. Pountain, D. 1993 (May). Complexity on wheels. *Byte*, pp. 213–220.
21. Moore, C. 1995. Green revolution in the making. *Sierra* 80:50.
22. U.S. Environmental Protection Agency. 2008. Case Study 22. AEP and Centain Teed put environmental process by-products to beneficial uase in wallboard. www.epa.gov.
23. Kolstad, C. D. 2000. *Environmental Economics*. New York: Oxford University Press.
24. Crandall, R. W. 1983. *Controlling Industrial Pollution: The Economics and Politics of Clean Air*. Washington, DC: Brookings Institution.
25. Hall, J.V., A.M. Winer, M.T. Kleinman, F.W. Lurmann, V. Brajer, and S.D. Colome. 1992. Valuing the health benefits of clean air. *Science* 255:812–816.
26. Krupnick, A.J., and P.R. Portney. 1991. Controlling urban air pollution: A benefits-cost assessment. *Science* 252:522–528.
27. Lipfert, F.W., S.C. Morris, R.M. Friedman, and J.M. Lents. 1991. Air pollution benefit-cost assessment. *Science* 253:606.
28. Rowland, F.S. 1990. Stratospheric ozone depletion of chlorofluorocarbons. *AMBIO* 19:281–292.
29. Rowland F.S. 2007. Stratospheric ozone depletion by chlorofluorocarbons. Nobel Lecture for the encyclopedia of Earth. www.eoearth.org.
30. Smith, R.C., B.B. Prezelin, K.S. Baker, R.R. Bidigare, N.P. Boucher, T. Coley, D. Karentz, S. Macintyre, H.A. Matlick, D. Menzies, M. Ondrusek, Z. Wan, and K.J. Waters. 1992. Ozone depletion: Ultraviolet saturation and phytoplankton biology in Antarctic waters. *Science* 255:952–959.
31. NASA. 2009 Ozone Facts: History of the ozone hole. http://earth observatory.nasa.gov.
32. Hamill, P., and O.B. Toon. 1991. Polar stratospheric clouds and the ozone hole. *Physics Today* 44:34–42.
33. Stolarski, R.S. 1988. The Antarctic ozone hole. *Scientific American* 258:30–36.
34. Molina, M.J., and F.S. Rowland. 1974. Stratospheric sink for chlorofluoromethanes: Chlorine-atom catalyzed distribution of ozone. *Nature* 249:810–812.
35. Brouder, P. 1986 (June). Annals of chemistry in the face of doubt. *New Yorker*, pp. 20–87.
36. Khalil, M.A.K., and R.A. Rasmussen. 1989. The potential of soils as a sink of chlorofluorocarbons and other manmade chlorocarbons. *Geophysical Research Letters* 16:679–682.
37. Rowland, F.S. 1989. Chlorofluorocarbons and the depletion of stratospheric ozone. *American Scientist* 77:36–45.
38. Toon, O.B., and R.P. Turco. 1991. Polar stratospheric clouds and ozone depletion. *Scientific American* 264:68–74.
39. Worldwatch Institute 2008. Vital Signs 2007–2008. New York: W.W. Norton.
40. Webster, C.R., R.D. May, D.W. Toohey, L.M. Avallone, J.G. Anderson, P. Newman, L. Lait, M. Schoeberl, J.W. Elkins, and K.R. Chay. 1983. Chlorine chemistry on polar stratospheric cloud particles in the Arctic winter. *Science* 261:1130–1134.
41. Kerr, R.A. 1992. New assaults seen on Earth's ozone shield. *Science* 255:797–798.
42. Shea, C.P. 1989. Mending the Earth's shield. *World Watch* 2:28–34.
43. Kerr, J.B., and C.T. McElroy. 1993. Evidence for large upward trends of ultraviolet-B radiation linked to ozone depletion. *Science* 262:1032–1034.
44. U.S. Environmental Protection Agency. 2006. Ozone depletion. Accessed April 16, 2006. www.epa.gov.
45. Cutter Information Corp. 1996. Reports discuss present and future state of ozone layer. *Global Environmental Change Report* V, VIII, 21, no. 22, pp. 1–3.
46. Showstack, R. 1998. Ozone layer is on slow road to recovery, new science assessment indicates. *Eos* 79(27):317–318.
47. Spurgeon, D. 1998. Surprising success of the Montreal Protocol. *Nature* 389(6648):219.
48. Zimmerman, M.R. 1985. Pathology in Alaskan mummies. *American Scientist* 73:20–25.
49. Ehrlich, P.R., A.H. Ehrlich, and J.P. Holdren. 1970. *Ecoscience: Population, Resources, Environment.* San Francisco: Freeman.
50. Conlin, M. 2000 (June 5). Is your office killing you? *Business Week,* pp. 114–124.
51. U.S. Environmental Protection Agency. Basic information: Formaldehyde. Accessed April 28, 2008 at www.epa.gov
52. Anonymous. FEMA Hurries Hurricane Survivors Out of Toxic Trailers. Environment News Service (ENS). February 15, 2008.
53. U.S. Environmental Protection Agency. 1991. *Building Air Quality: A Guide for Building Owners and Facility Managers.* EPA/400/ 1–91/033, DHHS (NIOSH) Pub. No. 91–114. Washington, DC: Environmental Protection Agency.

54. Zummo, S.M., and M.H. Karol. 1996. Indoor air pollution: Acute adverse health effects and host susceptibility. *Environmental Health* 58:25–29.
55. Godish, T. 1997. *Air Quality,* 3d ed. Boca Raton, FL: Lewis Publishers.
56. O'Reilly, J.T., P. Hagan, R. Gots, and A. Hedge. 1998. *Keeping Buildings Healthy.* New York: Wiley.
57. Brenner, D.J. 1989. *Radon: Risk and Remedy.* New York: W. H. Freeman.
58. U.S. Environmental Protection Agency. 1992. *A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon,* 2d ed. ANR-464. Washington, DC: Environmental Protection Agency.
59. Henshaw, D.L., J.P. Eatough, and R.B. Richardson. 1990. Radon as a causative factor in induction of myeloid leukaemia and other cancers. *The Lancet* 335:1008–1012.
60. Pershagen, G., G. Akerblom, O. Axelson, B. Clavensjo, L. Damber, G. Desai, A. Enflo, F. Lagarde, H. Mellander, M. Svartengren, and G.A. Swedjemark. 1994. Residential radon exposure and lung cancer in Sweden. *New England Journal of Medicine* 330:159–164.
61. Nero, A.V., Jr. 1988. Controlling indoor air pollution. *Scientific American* 258:42–48.
62. Committee on Indoor Air Pollution. 1981. *Indoor Pollutants.* Washington, DC: National Academy Press.
63. Massachusetts Department of Public Health, Bureau of Environmental Health Assessments. 1995. *Symptom Prevalence Survey Related to Indoor Air Concerns at the Registry of Motor Vehicles Building, Ruggles Station.*
64. Horton, W.G.B. 1995. *NOVA: Can Buildings Make You Sick?* Video production. Boston: WGBH.
65. U.S. Environmental Protection Agency. 1986. *Radon Reduction Techniques for Detached Houses: Technical Guidance.* EPA 625/5–86–019. Research Triangle Park, NC: Air and Energy Engineering Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.
66. U.S. Environmental Protection Agency. Radon-resistance new construction (RRNC). Accessed April 22, 2006. www.epa.gov.

Chapter 22 Notes

1. The official Web site of the High Line and Friends of the High Line, http://www.thehighline.org/about/high-line-history.
2. UNEP, http://www.unep.org/web/2005/english/information_Material/facts.asp.
3. World Resources Institute, http://archive.wri.org/item_detail.cfm?id=2795&section=climate&pages=pubs_content_text&z=?
4. EPA. May 11, 2006. What is urban sprawl? http://www.epa.gov/maia/html/sprawl.html.
5. Butler, Rhett. 2003. *World's Largest Urban Areas [Ranked by Urban Area Population, The World Gazetteer*, http://www.mongabay.com citiesurban01.htm.
6. Neubauer, D. 2004 (September 24). Mixed blessings of the megacities. *Yale Global Online Magazine*, http://yalelobal.–yale.edu.
7. Haub, C., and D. Cornelius. 2000. *World Population Data Sheet*. Washington, DC: Population Reference Bureau.
8. Nossiter, Adam. 2008. Big plans are slow to bear fruit in New Orleans. *New York Times*, April 1, 2008.
9. Richard Fausset. 2009. Defying economy, New Orleans keeps rebuilding. *Los Angeles Times*, April 03, 2009. http://artices. latimes.com/2009/apr/03/nation/na–rebuilding–new–orleans3.
10. Leibbrand, K. 1970. *Transportation and Town Planning*. Translated by N. Seymer. Cambridge, MA.: MIT Press.
11. Mumford, L. 1972. The natural history of urbanization. In R.L. Smith, ed., *The Ecology of Man: An Ecosystem Approach*, pp. 140–152. New York: Haper & Row.
12. The material about Olmsted is primarily from Beveridge, C.E. 2001. *The Papers of Frederick Law Olmsted*, Vols. 1–6 and supplementary series vol. 1; 1997–2001. Baltimore: Johns Hopkins University Press; and Beveridge, C. 1998. *Frederick Law Olmsted: Designing the American Landscape*. Universe.
13. Detwyler, T.R., and M.G. Marcus, eds.1972. *Urbanization and the Environment: The Physical Geography of the City*. North Scituate, MA: Duxbury Press.
14. Butti, K., and J. Perlin. 1980. *A Golden Thread: 2500 Years of Solar Architecture and Technology*. New York: Cheshire.
15. McHarg, I.L. 1971. *Design with Nature*. Garden City, NY: Doubleday.
16. Ford, A.B., and O. Bialik. 1980. Air pollution and urban factors in relation to cancer mortality. *Archives of Environmental Health* 35:350–359.
17. Nadel, I.B., C.H. Oberlander, and L.R. Bohm. 1977. *Trees in the City*. New York: Pergamon.
18. Dreistadt, S.H., D.L. Dahlsten, and G.W. Frankie. 1990. Urban forests and insect ecology. *Bioscience* 40:192–198.
19. Leedly, D.L., and L.W. Adams. 1984. *A Guide to Urban Wildlife Management*. Columbia, MD: National Institute for Urban Wildlife.
20. Tylka, D. 1987. Critters in the city. *American Forests* 93:61–64.
21. Mannan, R.W., Robert J. Steidl, and Clint W. Boal. 2008. Identifying habitat sinks: A case study of Cooper's hawk in an urban environment. *Urban Ecosystems* II:141–148.
22. Department of Environmental Protection, New York. 2006. Peregrine falcons in New York City. http://www.nyc.gov/html/dep/–html/news/falcon.html.
23. Mannan, Steidl, and Boal, Identifying habitat sinks.
24. Tylka, Critters in the city.
25. Adams, L.W., and L.E. Dove. 1989. Wildlife reserves and corridors in the urban environment. Columbia, MD: National Institute for Urban Wildlife.
26. http://www.responsiblewildifemanagement.org/bubo–nic–plague.htm.

27. U.S. Environmental Protection Agency. 2006 (May 11). http://www.epa.gov/maia/html/sprawl.html.

Chapter 23 Notes

1. Sullivan, D.E. 2006. *Recycled cell phones—A treasure trove of valuable metals*. U.S. Geological Survey Fact Sheet 2006–3097.
2. Kropschot, S.J., and K.M. Johnson. 2006. U.S. Geological Survey Circular 1289. Menlo Park, CA.
3. Hudson, T.L., F.D. Fox, and G.S. Plumlee. 1999. *Metal Mining and the Environment*. Alexandria, VA: American Geological Institute.
4. McKelvey, V.E. 1973. Mineral resource estimates and public policy. In D.A. Brobst and W.P. Pratt, eds., *United States Mineral Resources*, pp. 9–19. U.S. Geological Survey Professional Paper 820.
5. U.S. Department of the Interior, Bureau of Mines. 1993. *Mineral Commodity Summaries*, 1993. I 28.149:993. Washington, DC: U.S. Department of the Interior.
6. McGreery, P. 1995. Going for the goals: Will states hit the wall? *Waste Age* 26:68–76.
7. Brown, L.R. 1999 (March/April). Crossing the threshold. *World Watch*, pp. 12–22.
8. Meyer, H.O.A. 1985. Genesis of diamond: A mantle saga. *American Mineralogist* 70:344–355.
9. Kesler, S.F. 1994. *Mineral Resources, Economics, and the Environment*. New York: Macmillan.
10. Awramik, S.A. 1981. The pre-Phanerozoic biosphere—three billion years of crises and opportunities. In M.H. Nitecki, ed., *Biotic Crises in Ecological and Evolutionary Time*, pp. 83–102. Spring Systematics Symposium. New York: Academic Press.
11. Margulis, L., and J.E. Lovelock. 1974. Biological modulation of the Earth's atmosphere. *Icarus* 21:471–489.
12. Lowenstam, H.A. 1981. Minerals formed by organisms. *Science* 211:1126–1130.
13. Brobst, D.A., W.P. Pratt, and V.E. McKelvey, 1973. *Summary of United States mineral resources*. U.S. Geological Survey Circular 682.
14. Jeffers, T.H. 1991 (June). Using microorganisms to recover metals. *Minerals Today*. Washington, DC: U.S. Department of Interior, Bureau of Mines, pp. 14–18.
15. Haynes, B.W. 1990 (May). Environmental technology research. *Minerals Today*. Washington, DC: U.S. Bureau of Mines, pp. 13–17.
16. Sullivan, P.M., M.H. Stanczyk, and M.J. Spendbue. 1973. *Resource Recovery from Raw Urban Refuse.* U.S. Bureau of Mines Report of Investigations 7760.
17. Davis, F.F. 1972 (May). Urban ore. *California Geology*, pp. 99–112.
18. U.S. Geological Survey. 2010. *Minerals Yearbook* 2007—*Recycling Metals*. Accessed April 3, 2010 at http://minerals.usgs.gov.
19. Galley, J.E. 1968. Economic and industrial potential of geologic basins and reservoir strata. In J.E. Galley, ed., *Subsurface Disposal in Geologic Basins: A Study of Reservoir Strata*, pp. 1–19. American Association of Petroleum Geologists Memoir 10. Tulsa, OK.: American Association of Petroleum Geologists.
20. Relis, P., and A. Dominski. 1987. *Beyond the Crisis: Integrated Waste Management*. Santa Barbara, CA: Community Environmental Council.
21. Allenby, B.R. 1999. *Industrial Ecology: Policy Framework and Implementation*. Upper Saddle River, NJ: Prentice-Hall.
22. Garner, G., and P. Sampat. 1999 (May). Making things last: Reinventing of material culture. *The Futurist*, pp. 24–28.
23. U.S. Environmental Protection Agency. *Municipal solid waste*. Accessed April 21, 2006 at www.epa.gov.
24. Relis, P., and H. Levenson. 1998. *Discarding Solid Waste as We Know It: Managing Materials in the 21st Century*. Santa Barbara, CA: Community Environmental Council.
25. Young, J.E. 1991. Reducing waste-saving materials. In L.R. Brown, ed., *State of the World*, 1991, pp. 39–55. New York: W.W. Norton.
26. Steuteville, R. 1995. The state of garbage in America: Part I. *BioCycle* 36:54.
27. Gardner, G. 1998 (January/February). Fertile ground or toxic legacy? *World Watch*, pp. 28–34.
28. Rathje, W.L., and C. Murphy. 1992. Five major myths about garbage, and why they're wrong. *Smithsonian* 23:113–122.
29. Rathje, W.L. 1991. Once and future landfills. *National Geographic* 179(5):116–134.
30. U.S. Environmental Protection Agency. 2002. *Solid waste management: A local challenge with global impacts*. Accessed May 26, 2010 at www.epa.gov.
31. Schneider, W.J. 1970. *Hydrologic implications of solid-waste disposal*. 135(22). U.S. Geological Survey Circular 601F. Washington, DC: U.S. Geological Survey.
32. Thomas, V.M., and T.G. Spiro. 1996. The U.S. dioxin inventory: Are there missing sources? *Environmental Science & Technology* 30:82A-85A.
33. Turk, L.J. 1970. Disposal of solid wastes—acceptable practice or geological nightmare? In *Environmental Geology,* pp. 1–42. Washington, DC: American Geological Institute Short Course, American Geological Institute.
34. Hughes, G.M. 1972. Hydrologic considerations in the siting and design of landfills. *Environmental Geology Notes*, no. 51. Urbana: Illinois State Geological Survey.
35. Bergstrom, R.E. 1968. Disposal of wastes: Scientific and administrative considerations. *Environmental Geology Notes*, no 20. Urbana: Illinois State Geological Survey.
36. Cartwright, K., and Sherman, F.B. 1969. Evaluating sanitary landfill sites in Illinois. *Environmental Geology Notes*, no. 27. Urbana: Illinois State Geological Survey.
37. Rahn, P.H. 1996. *Engineering Geology*, 2nd ed. Upper Saddle River, NJ: Prentice-Hall.

38. Bullard, R.D. 1990. *Dumping in Dixie: Race, Class and Environmental Quality*. Boulder, CO: Westview Press.
39. Sadd, J.L., J.T. Boer, M Foster, Jr., and L.D. Snyder 1997. Addressing environmental justice: Demographics of hazardous waste in Los Angeles County. *Geology Today* 7(8):18–19.
40. Walker, W.H. 1974 Monitoring toxic chemical pollution from land disposal sites in humid regions. *Ground Water* 12:213–218.
41. Watts, R.J. 1998. *Hazardous Wastes*. New York: John Wiley & Sons.
42. Wilkes, A.S. 1980. *Everybody's Problem: Hazardous Waste*. SW-826. Washington, DC: U.S. Environmental Protection Agency, Office of Water and Waste Management.
43. Harder, B. 2005 (November 8). Toxic e-waste is cashed in poor nations. *National Geographic News*.
44. Elliot, J. 1980. Lessons from Love Canal. *Journal of the American Medical Association* 240:2033–2034, 2040.
45. Whittell, G. 2000 (November 29). Poison in paradise. *(London) Times* 2, p. 4.
46. U.S. Environmental Protection Agency. 2010. Summary of the Comprehensive Environmental Response, Compensation, and Liability (Superfund). Accessed March 19, 2010 at www.epa.gov.
47. Bedient, P.B., H.S. Rifai, and C J. Newell. 1994. *Ground Water Contamination*. Englewood Cliffs, NJ: Prentice-Hall.
48. Huddleston, R.L. 1979. Solid-waste disposal: Land farming. *Chemical Engineering* 86:119–124.
49. McKenzie, G.D., and W.A. Pettyjohn. 1975. Subsurface waste management. In G.D. McKenzie and R.O. Utgard, eds., *Man and His Physical Environment: Readings in Environmental Geology*, 2nd ed., pp. 150–156. Minneapolis, MN: Burgess Publishing.
50. National Research Council, Committee on Geological Sciences 1972. *The Earth and Human Affairs*. San Francisco: Canfield Press.
51. Cox, C. 1985. The Buried Threat: Getting Away from Land Disposal of Hazardous Waste. No. 115–5. California Senate Office of Research.
52. Council on Environmental Quality. 1970. Ocean Dumping: A National Policy: A Report to the President. Washington, DC: U.S. Government Printing Office.
53. Lenssen, N. 1989 (July–August). The ocean blues. *World Watch*, pp. 26–35.
54. Woods Hole Oceanographic Institute, 2010. Plastic particles permeate the Atlantic. *Oceanus* Sept. 2, 2010 at www.whoi.edu
55. U.S. Environmental Protection Agency. 2000. Forward pollution protection: The future look of environmental protection. Accessed August 12, 2000, at http://www.epa.gov/p2/p2case.htm#num4.
56. Wellmar, F.W., and M. Kosinowoski. 2003. Sustainable development and the use of non renewable sources. *Geotimes* 48(12):14–17.

Chapter 24 Notes

1. NOAA Website http://response.restoration.noaa.gov/dwh.php?entry_id=809, accessed June 27, 2010.
2. NOAA Website http://response.restoration.noaa.gov/dwh.php?entry_id=809, accessed June 27, 2010.
3. NOAA.2010. Deepwater Horizon incident, Gulf of Mexico. at http://response.restoration.noaa.gov.
4. Jusserand, J. 1897. *English Wayfaring Life in the Middle Ages* (XIVth Century). London: T. Fisher Unwin.
5. Cohen, B.S. 1970. The Constitution, the public trust doctrine and the environment. *Utah Law Review* 388.
6. From http://www.cr.nps.gov/history/hisnps/NPSHistory/briefhistory.htm.
7. Bureau of Land Management facts, on the BLM Website.
8. Steiner, F. 1983. Regional planning: Historic and contemporary examples. *Landscape Planning* 10:297–315.
9. Section 26 of the TVA Act, http://www.tva.gov/
10. From http://www.npr.org/programs/atc/features/2003/aug/water/part1.html. See also http://www.library.unt.edu/gpo/powell/publications.htm.
11. Forman, D. 2004. *Rewilding North America: A vision of conservation for the 21st century*. Washington, D.C.: Island Press.
12. From http://www.eco.freedom.org/el/20031001/joyce.shtml.
13. Yannacone, V.J., Jr., B.S. Cohen, and S.G. Davison. 1972. Environmental rights and remedies. *Lawyers Co-operative Pub*., pp. 39–46.
14. Bacow, L.S., and M. Wheeler. 1984. *Environmental Dispute Resolution*. New York: Plenum Press.
15. Renner, M. 2002. Breaking the link between resources and repression. In *Worldwatch Institute State of the World 2002*. New York: Norton.
16. Rockström, J., et al., 2009. A safe operating space for humanity. *Nature* 461: 472–475.