Water Resources

13

Water Conflicts in the Middle East: A Preview of the Future?

CORE CASE STUDY

Many countries in the Middle East face water shortages and rising tensions over water sources they must share. Most water in this dry region comes from three river basins: the Nile, the Jordan, and the Tigris–Euphrates (Figure 13-1).

Africa's Nile River flows through seven countries, each of which draws on it for irrigation and drinking water and flushes mostly untreated sewage and other effluents into it. Three countries—Ethiopia, Sudan, and Egypt—use most of the water that flows in the Nile. Egypt, where it rarely rains, gets more than 97% of its freshwater from the river and is last in line to tap this precious source. To meet the water and food needs of their rapidly growing populations, Ethiopia and Sudan plan to divert more water from the river. Such upstream diversions would reduce the amount of water available to Egypt, which cannot exist without irrigation water from the Nile.

Egypt has several choices. It could go to war with Sudan and Ethiopia for more water, cut its rapid population growth, or reduce irrigation water waste. Other options are to import more grain to reduce the need for irrigation water, work out water-sharing agreements with other countries, or suffer the harsh human and economic consequences of *hydrological poverty*.

The Jordan basin is by far the most water-short region, with fierce competition for its water among Jordan, Syria, Palestine (Gaza and the West Bank), and Israel. Syria, which is projected to increase its population by 70% between 2008 and 2050, plans to build dams and withdraw more water from the Jordan River, decreasing the downstream water supply for Jordan and Israel. If Syria goes through with its plans, Israel warns that it may destroy the largest dam. In contrast, Israel has cooperated with Jordan and Palestine over their shared water resources.

Turkey, located at the headwaters of the Tigris and Euphrates Rivers (Figure 13-1), controls water flowing downstream through Syria and Iraq and into the Persian Gulf. Turkey is building 24 dams along the upper Tigris and Euphrates to generate electricity and irrigate a large area of land.

If completed, these dams will reduce the flow of water downstream to Syria and Iraq by as much as 35% in normal years and by much more in dry years. Syria also plans to build a large dam on the Euphrates to divert water arriving from Turkey. This will leave little water for Iraq and could lead to a water war between Iraq and Syria.

Resolving these water distribution problems will require negotiating agreements to share water supplies, slowing population growth, cutting water waste, raising water prices to help improve irrigation efficiency, and increasing grain imports to reduce irrigation water needs.

Two or more countries share some 263 of the world's water basins, but countries in only 158 of the basins have water-sharing agreements. This explains why conflicts among nations over shared water resources are likely to increase as populations grow, demand for water increases, and supplies decrease in many parts of the world.

To many analysts, emerging water shortages in many parts of the world—along with the related problems of biodiversity loss and climate change—are the three most serious environmental problems the world faces during this century.

This chapter discusses the world's water problems and ways to use this irreplaceable resource more sustainably. About two-thirds of the water used by the world's people is wasted. A key solution to the world's water supply problems is to sharply reduce such waste.

Figure 13-1 Many countries in the Middle East, which has one of the world's highest population growth rates, face water shortages and conflicts over access to water because they share water from three major river basins.

Key Questions and Concepts

13-1 Will we have enough usable water?

CONCEPT 13-1A We are using available freshwater unsustainably by wasting it, polluting it, and charging too little for this irreplaceable natural resource.

CONCEPT 13-1B One of every six people does not have sufficient access to clean water, and this situation will almost certainly get worse.

13-2 Is extracting groundwater the answer?

CONCEPT 13-2 Groundwater that is used to supply cities and grow food is being pumped from aquifers in some areas faster than it is renewed by precipitation.

13-3 Is building more dams the answer?

CONCEPT 13-3 Building dam and reservoir systems has greatly increased water supplies in some areas, but it has disrupted ecosystems and displaced people.

13-4 Is transferring water from one place to another the answer?

CONCEPT 13-4 Transferring water from one place to another has greatly increased water supplies in some areas, but it has also disrupted ecosystems.

13-5 Is converting salty seawater to freshwater the answer?

CONCEPT 13-5 We can convert salty ocean water to freshwater, but the cost is high, and the resulting salty brine must be disposed of without harming aquatic or terrestrial ecosystems.

13-6 How can we use water more sustainably?

CONCEPT 13-6 We can use water more sustainably by cutting water waste, raising water prices, slowing population growth, and protecting aquifers, forests, and other ecosystems that store and release water.

13-7 How can we reduce the threat of flooding?

CONCEPT 13-7 We can lessen the threat of flooding by protecting more wetlands and natural vegetation in watersheds and by not building in areas subject to frequent flooding.

Note: Supplements 2 (p. S4), 3 (p. S10), 4 (p. S20), 5 (p. S31) and 13 (p. S78) can be used with this chapter.

Our liquid planet glows like a soft blue sapphire
in the hard-edged darkness of space.
There is nothing else like it in the solar system.
It is because of water.

JOHN TODD

13-1 Will We Have Enough Usable Water?

CONCEPT 13-1A We are using available freshwater unsustainably by wasting it, polluting it, and charging too little for this irreplaceable natural resource.

CONCEPT 13-1B One of every six people does not have sufficient access to clean water, and this situation will almost certainly get worse.

Freshwater Is an Irreplaceable Resource That We Are Managing Poorly

We live on a water planet, with a precious layer of water—most of it saltwater—covering about 71% of the earth's surface (Figure 8-2, p. 163). Look in the mirror. What you see is about 60% water, most of it inside your cells.

Water is an amazing substance with unique properties that affect life on earth (Science Focus, p. 67). You could survive for several weeks without food but for only a few days without water. And it takes huge amounts of water to supply you with food, provide

Links: CORE CASE STUDY refers to the Core Case Study. SUSTAINABILITY refers to the book's sustainability theme. CONCEPT LINK indicates links to key concepts in earlier chapters.

you with shelter, and meet your other daily needs and wants. Water also plays a key role in sculpting the earth's surface, moderating climate, and removing and diluting wastes and pollutants.

Despite its importance, water is one of our most poorly managed resources. We waste it and pollute it. We also charge too little for making it available. This encourages still greater waste and pollution of this resource, for which we have no substitute (**Concept 13-1A**).

Access to water is a *global health issue* because lack of water that is safe for drinking and sanitation is the world's single largest cause of illness. In 2007, the World Health Organization (WHO) estimated that each year more than 1.6 million people—90% of them children under age five—die from largely preventable waterborne diseases such as diarrhea, typhoid fever, and hepatitis.

Water is an *economic issue* because it is vital for reducing poverty and producing food and energy. It is a *women's and children's issue* in developing countries because poor women and girls often are responsible for finding and carrying daily supplies of water (Figure 13-2). And water is a *national and global security issue* because of increasing tensions within and between nations over access to limited but shared water resources in the Middle East (**Core Case Study**) and other areas of the world.

CORE CASE STUDY

Water is an *environmental issue* because excessive withdrawal of water from rivers and aquifers and pollution of water result in lower water tables, lower river flows, shrinking lakes, losses of wetlands, declining water quality, declining fish populations, species extinctions, and degradation of ecosystem services provided by aquatic systems. Virtually all of these environmental indicators related to water availability and quality are worsening in some regions.

Most of the Earth's Freshwater Is Not Available to Us

Only a tiny fraction of the planet's abundant water supply—*about 0.024%*—is readily available to us as liquid freshwater in accessible groundwater deposits and in lakes, rivers, and streams. The rest is in the salty oceans, frozen in polar ice caps and glaciers, or deep underground and inaccessible.

Fortunately, the world's freshwater supply is continually collected, purified, recycled, and distributed in the earth's *hydrologic cycle*—the movement of water in the seas, in the air, and on land, which is driven by solar energy and gravity (Figure 3-17, p. 66). This irreplaceable water recycling and purification system works well, unless we overload it with slowly degradable and nondegradable wastes or withdraw water from underground and surface water supplies faster than it is replenished. We also interfere with this cycle when we destroy wetlands and cut down forests that store and slowly release water, or alter the cycle's rate and distribution patterns as a result of climate change caused by global warming. In parts of the world, we are doing all of these things (**Concept 8-3**, p. 171, and **Concept 8-5**, p. 179), mostly because we have placed little or no value on the earth's natural ecological services (Figure 1-3, p. 8, and Science Focus, p. 218).

CONCEPT LINKS

On a global basis we have plenty of freshwater. But differences in average annual precipitation and economic resources divide the world's continents, countries, and people into water *haves* and *have-nots.* For example, Canada, with only 0.5% of the world's population, has 20% of the world's liquid freshwater, while China, with 20% of the world's people, has only 7% of the supply. Asia with 60% of the world's population has only 30% of the supply.

We Get Freshwater from Groundwater and Surface Water

Some precipitation infiltrates the ground and percolates downward through spaces in soil, gravel, and rock until

A. Ishokon-UNEP/Peter Arnold, Inc.

Figure 13-2 Girl carrying water from a well across dried out and cracked earth during a severe drought in India.

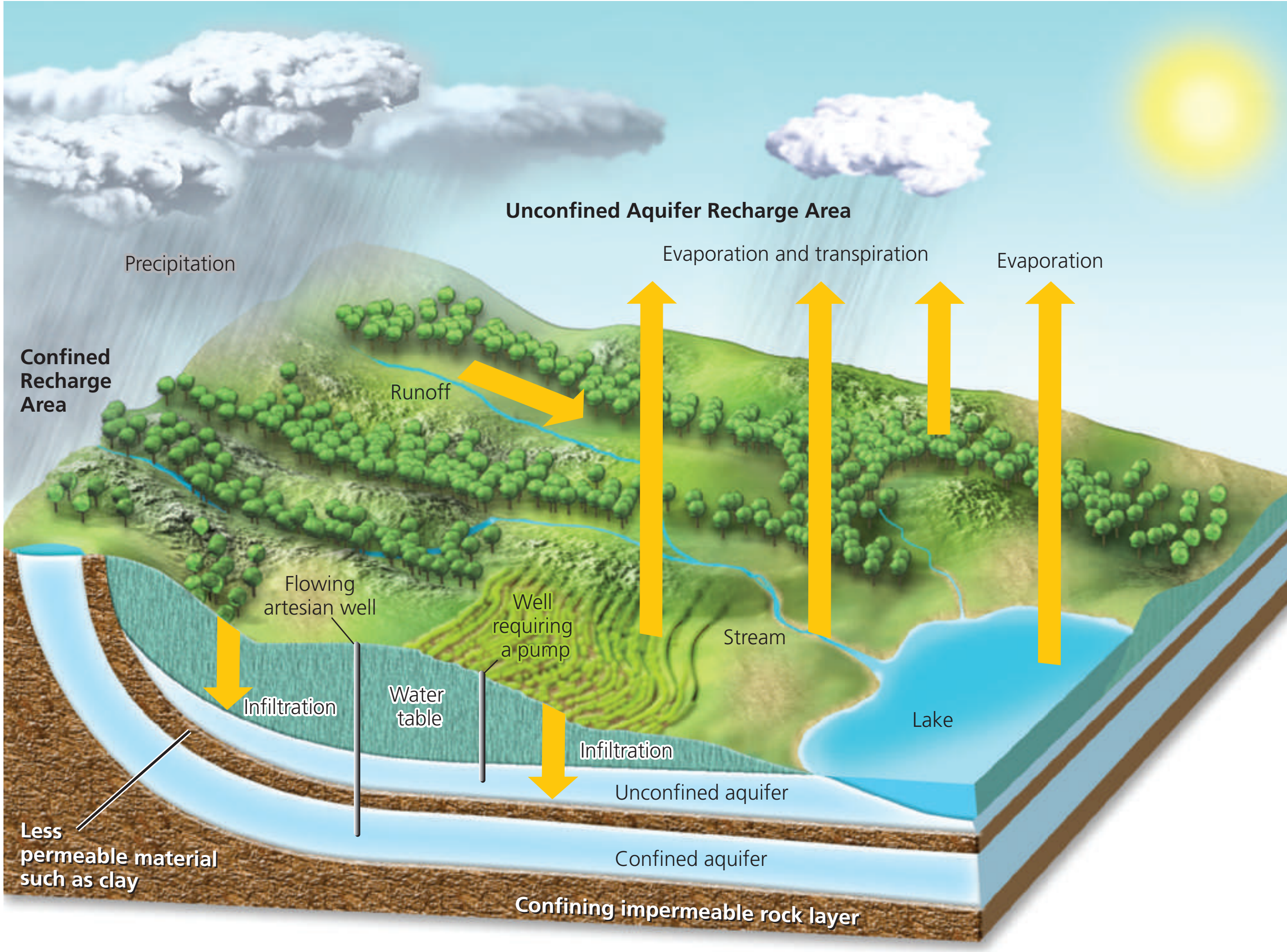


Figure 13-3 Natural capital: groundwater system. An *unconfined aquifer* is an aquifer with a permeable water table. A *confined aquifer* is bounded above and below by less permeable beds of rock, and its water is confined under pressure. Some aquifers are replenished by precipitation; others are not.

an impenetrable layer of rock stops it (Figure 13-3). The water in these spaces is called **groundwater**—one of our most important sources of freshwater and a key component of the earth's natural capital.

The spaces in soil and rock close to the earth's surface hold little moisture. Below a certain depth, in the **zone of saturation,** these spaces are completely filled with water. The top of this groundwater zone is the **water table.** It falls in dry weather, or when we remove groundwater faster than nature can replenish it, and it rises in wet weather.

Deeper down are geological layers called **aquifers:** underground caverns and porous layers of sand, gravel, or bedrock through which groundwater flows. Groundwater normally moves from points of high elevation and pressure to points of lower elevation and pressure. Some caverns have rivers of groundwater flowing through them. But the porous layers of sand, gravel, or bedrock in most aquifers are like large elongated sponges through which groundwater seeps—typically moving only a meter or so (about 3 feet) per year and rarely more than 0.3 meter (1 foot) per day. Watertight layers of rock or clay below such aquifers keep the water from escaping deeper into the earth.

Most aquifers are replenished naturally by precipitation that percolates downward through soil and rock, a process called *natural recharge.* Others are recharged from the side by *lateral recharge* from nearby rivers and streams. Most aquifers recharge extremely slowly. Because so much of the urban landscape has been built on or paved over, water can no longer penetrate the ground to recharge aquifers in some urban areas.

Nonrenewable aquifers get very little, if any, recharge. They are found deep underground and were formed tens of thousands of years ago. Withdrawing water from these aquifers amounts to *mining* a nonrenewable resource. Such withdrawals will deplete these ancient deposits of liquid natural capital, and they represent an unsustainable use of this resource (**Concept 1-1B**, p. 6).

CONCEPT LINK

One of our most important resources is **surface water,** the freshwater from precipitation and snowmelt that flows across the earth's land surface and into rivers, streams, lakes, wetlands, estuaries, and ultimately to the oceans. Precipitation that does not infiltrate the ground or return to the atmosphere by evaporation is called **surface runoff.** Surface water replenished by runoff is classified as a renewable but finite resource. The land from which surface water drains into a particular river, lake, wetland, or other body of water is called its **watershed** or **drainage basin.**

There is a *hydrological connection* between surface water and groundwater because eventually most groundwater flows into rivers, lakes, estuaries, and wetlands. Thus, if we disrupt the hydrologic cycle by removing groundwater faster than it is replenished, nearby streams, lakes, and wetlands could dry up, resulting in degradation of aquatic biodiversity and various ecological services (see *The Habitable Planet,* Video 8, at **www.learner.org/resources/series209.html**).

We Use a Large and Growing Portion of the World's Reliable Runoff

According to hydrologists (scientists who study water supplies), two-thirds of the annual surface runoff in rivers and streams is lost by seasonal floods and is not available for human use. The remaining one-third is **reliable surface runoff:** the amount of surface runoff that we can generally count on as a source of freshwater from year to year.

During the last century, the human population tripled, global water withdrawal increased sevenfold, and per capita withdrawal quadrupled. As a result, we now withdraw about 34% of the world's reliable runoff. Because of increased population growth alone, global withdrawal rates of surface water could reach more than 70% of the reliable runoff by 2025, and 90% if per capita withdrawal of water continues increasing at the current rate. This is a global average. Withdrawal rates already severely strain the reliable runoff in some areas. For example, in the arid American Southwest, up to 70% of the reliable runoff is withdrawn for human purposes. In other words, many areas are using their water resources unsustainably as our ecological footprints spread across the earth (Figure 1-10, p. 15; **Concept 1-3**, p. 12; and Figure 3 in Supplement 4, pp. S24–S25). And because of climate change, caused mostly by the burning of fossil fuels and clearing of forests, once reliable runoff in many areas may become unreliable.

CONCEPT LINK

Worldwide, we use 70% of the water we withdraw each year from rivers, lakes, and aquifers to irrigate cropland. Industry uses another 20% of the water withdrawn each year, and cities and residences use the remaining 10%.

Affluent lifestyles require large amounts of water, and much of it is used inefficiently. According to environmental consultant Fred Pearce, author of *When the Rivers Run Dry,* it takes about 450,000 liters (120,000 gallons) or 2,400 bathtubs full of water to produce a small car. It takes 140 liters (37 gallons) to produce a cup of coffee, and 25 bathtubs full of water to produce a typical T-shirt.

■ **CASE STUDY**

Freshwater Resources in the United States

The United States has more than enough renewable freshwater; but it is unevenly distributed, and much of it is contaminated by agricultural and industrial practices. The eastern states usually have ample precipitation, whereas many western and southwestern states have little (Figure 13-4, top). Many people think of Seattle, Washington, as the rainiest city in the United States. But, in order, the three rainiest cities in the lower 48 states over the past 30 years were Mobile, Alabama; Pensacola, Florida; and New Orleans, Louisiana.

In the East, most water is used for energy production, power plant cooling, and manufacturing. In various parts of the eastern United States, the most serious water problems are flooding and occasional urban

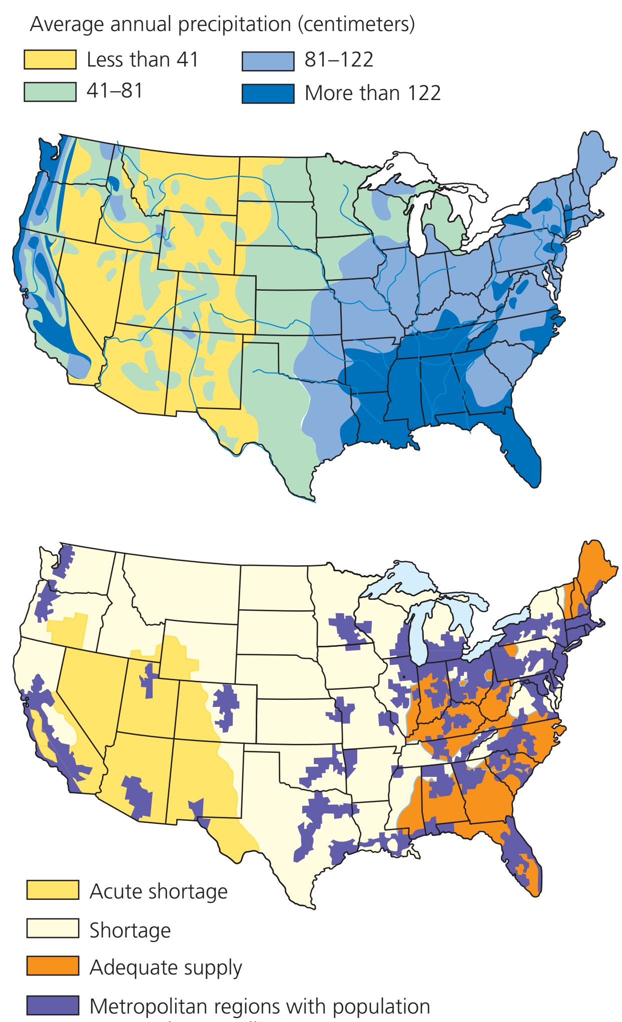


Figure 13-4 Average annual precipitation and major rivers (top) and water-deficit regions in the continental United States and their proximity to metropolitan areas having populations greater than 1 million (bottom). **Question:** Why do you think some areas with moderate precipitation still suffer from water shortages? (Data from U.S. Water Resources Council and U.S. Geological Survey)

shortages as a result of pollution. Another occasional problem is **drought:** a prolonged period in which precipitation is at least 70% lower and evaporation is higher than normal in an area that is normally not dry.

In the arid and semiarid areas of the western half of the United States (Figure 13-4, bottom), irrigation counts for 85% of water use, much of it unnecessarily wasted. The major water problem is a shortage of runoff caused by low precipitation (Figure 13-4, top), high evaporation, and recurring severe drought.

Almost half the water used in the United States comes from groundwater sources, and the rest comes from rivers, lakes, and reservoirs. Water tables in many water-short areas, especially in the arid and semiarid western half of the lower 48 states, are dropping quickly as farmers and rapidly growing urban areas (Figure 13-4, bottom) deplete many aquifers faster than they can be recharged. Excessive withdrawal of groundwater from an aquifer near a river or stream can decrease or deplete these sources of surface water. When the water table drops below the level of the bottom of a stream, its water drains into the aquifer (see *The Habitable Planet,* Video 8, at **www.learner.org/resources/series209.html**).

In 2007, the U.S. Geological Survey projected that at least 36 U.S. states are likely to face water shortages by 2013 because of a combination of drought, rising temperatures, population growth, urban sprawl, and excessive use and waste of water. In 2003, the U.S. Department of the Interior mapped out *water hotspots* in 17 western states (Figure 13-5). In these areas, competition for scarce water to support growing urban areas, irrigation, recreation, and wildlife could trigger intense political and legal conflicts between states and between rural and urban areas within states during the next 20 years.

This is already happening, in fact. In 2007, the U.S. Supreme Court heard a case in which the state of Montana accused the state of Wyoming of taking more than its fair share of water from two tributaries of the Yellowstone River that supply water for wells and farms in both states. Predicted long-term drought and global warming will increase the number and intensity of such disputes in the United States and other parts of the world in coming years.

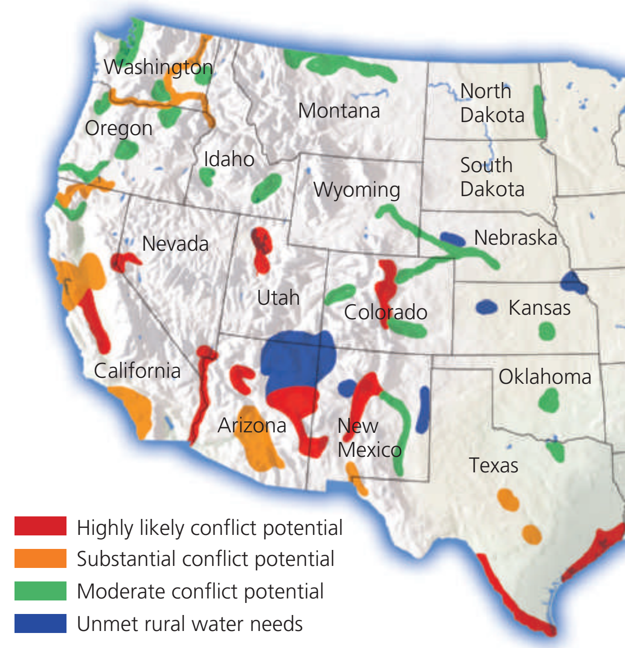


Figure 13-5 Water *hotspots* in 17 western states that, by 2025, could face intense conflicts over scarce water needed for urban growth, irrigation, recreation, and wildlife. Some analysts suggest that this is a map of places not to live during the next 25 years. **Question:** If you live in one of these hotspot areas, have you noticed any signs of conflict over water supplies? (Data from U.S. Department of the Interior)

Water Shortages Will Grow

The main factors causing water scarcity are a dry climate, drought, too many people using a normally reliable supply of water, and wasteful use of water.

Figure 13-6 shows the current degree of stress faced by the world's major river systems, based on a comparison of the amount of available surface water with the amount used per person. More than 30 countries—most of them in the Middle East (**Core Case Study**) CORE CASE STUDY and Africa—now face water scarcity. By 2050, some 60 countries, many of them in Asia, are likely to be suffering from water stress. In 2006, the Chinese government reported that two-thirds of Chinese cities faced water shortages. Rapid urbanization and economic growth are expected to put further strains on China's already short water resources (**Concept 13-1B**).

> **THINKING ABOUT**
> **Water and the Middle East** CORE CASE STUDY
> How might scarcity of water in the Middle East (**Core Case Study**) affect nations that are dependent on oil from the Middle East? How could this impact your lifestyle?

Because only 5% of Egypt is inhabitable, almost all of the country's 75 million people live along the Nile River (Figure 13-1, **Core Case Study**) CORE CASE STUDY or the Mediterranean Sea in cities such as Cairo—one of the world's most densely populated cities. Egypt's already severe water supply problem will likely get worse as the country's population is expected to increase to 118 million by 2050.

Poor people bear the brunt of water shortages. In 2005, the United Nations reported that 1.1 billion people—one of every six—lacked regular access to enough clean water for drinking, cooking, and washing, and 2.6 billion people did not have access to even basic sanitation. This already serious situation will almost certainly get worse. In 2007, the United Nations estimated that by 2025, *at least 3 billion of the world's projected 7.9 billion people will lack access to safe water* (**Concept 13-1B**). Most of these individuals suffering from hydrological poverty will be located in arid and semi-

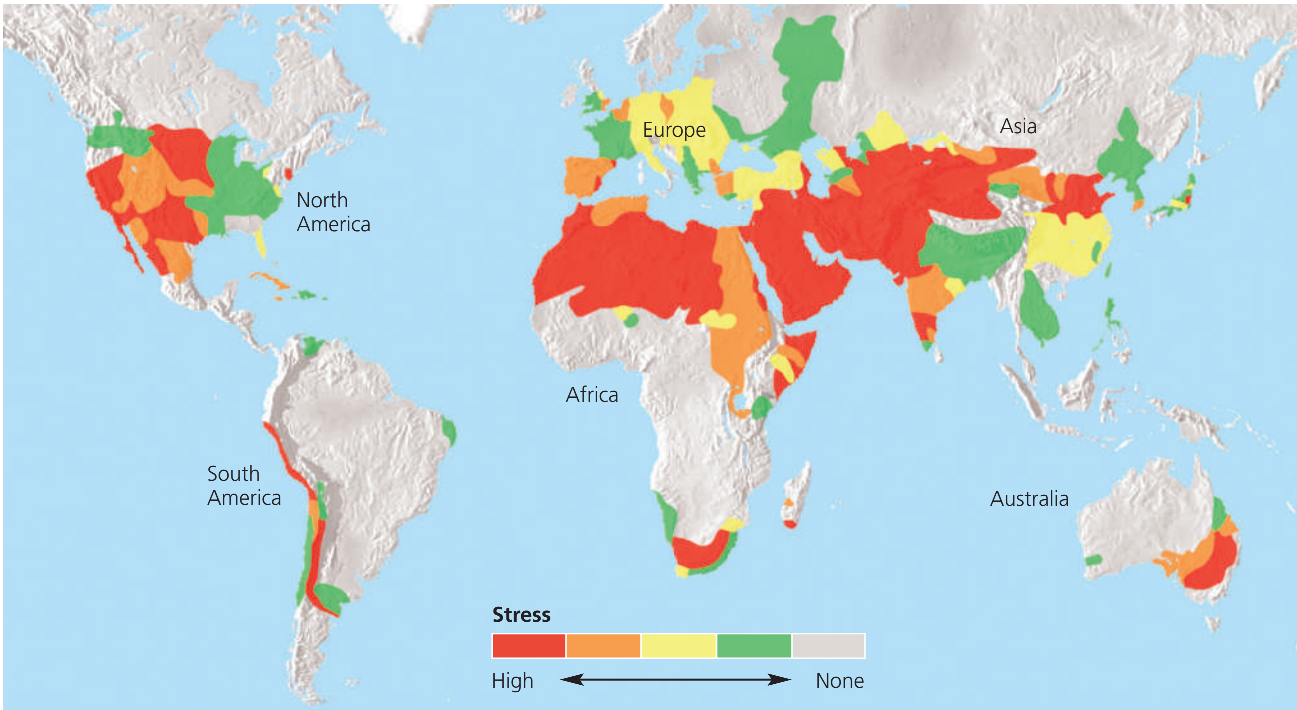


Figure 13-6 **Natural capital degradation**: stress on the world's major river basins, based on a comparison of the amount of water available with the amount used by humans (**Concept 13-1B**). **Questions:** If you live in a water-stressed area, what signs of stress have you noticed? In what ways, if any, has it affected your life? (Data from World Commission on Water Use in the 21st century)

arid regions with rapidly-growing populations. Many of these countries are on the growing list of failing states (Figure 17, p. S19, Supplement 3). The likely results: a flood of refugees from arid and semiarid regions searching for water, land, and food, and intense conflicts within and between countries—especially in the Middle East (**Core Case Study**) and Asia—over dwindling shared water resources. CORE CASE STUDY

Long-Term Severe Drought Is Increasing

Drought is usually caused by an extended period of below-normal rainfall. But it can also result from diminished groundwater due to falling water tables or other factors, such as climate change, that reduce the normally available water supply.

Severe drought has a number of harmful environmental effects. It dries out soils (Figure 13-2), reduces stream flows, decreases tree growth and biomass, lowers net primary productivity (Figure 3-16, p. 64), reduces crop yields, and causes a shift in some biomes toward relatively dry conditions such as those found in savannas and deserts.

Between 1979 and 2008, the total area of the earth experiencing severe or extreme drought more than tripled in what some observers call "The Big Dry." Currently, about 30% of the earth's land area—roughly equal to the size of Asia—experiences severe drought. In 2007, climate researcher David Rind and his colleagues at the NASA Goddard Institute for Space Studies, projected that by 2059, as much as 45% of the earth's land surface could experience extreme drought, mostly as a result of climate change caused by global warming.

Since 1999, except for a couple of wet years, much of the United States, especially the arid and already water-short Southwest (Figure 13-5), has experienced severe drought. The prolonged drought, coupled with greatly increased population and development in the U.S. Southwest, has led to drops in crop productivity and increasing squabbles over water supplies between farmers and rapidly growing populations of urban dwellers.

This drought is likely to continue. After looking at 19 global climate models used in a 2007 report from the U.N. Intergovernmental Panel on Climate Change (IPCC), climate researcher Richard Seager and his colleagues at the Lamont-Doherty Earth Observatory of Columbia University predicted that the southwestern United States and parts of northern Mexico will have long periods of extreme drought throughout the rest of this century.

In Water-Short Areas Farmers and Cities Compete for Water Resources

In water-short areas, tempers are flaring as farmers and cities compete for available water from rivers and aquifers. Farmers are losing this battle, and thus have decreased access to water resources in many parts of the world at a time when they are trying to feed 82 million more people each year.

THINKING ABOUT
Access to Water

Between farmers and city dwellers, which group should have greater access to water in water-short areas? Explain. Can you think of a compromise for resolving this dilemma?

Some water-short countries are reducing their irrigation water needs by importing grain to free up more of their water for industrial and urban development. Thus, water shortages are leading to increasing competition among countries in the world's grain markets, where financially strong countries have an advantage.

Adding to the intensity of this global competition for water and grain is the growing use of crops such as soybeans, sugarcane, oil palms, and corn to produce biofuels. A 2007 National Academy of Science study warned that increased corn production in the United States to produce ethanol will decrease water supplies and encourage aquifer depletion in some areas and increase pollution of streams and aquifers from use of pesticides and fertilizers. Bottom line: *farmers, cities, and car owners are increasingly competing for access to the world's grain and water supplies, which in turn can degrade some of the natural capital that provides these resources.*

Who Should Own and Manage Freshwater Resources?

Most people believe that everyone should have access to clean water. But who will pay for making this water available?

Most water resources are owned by governments and managed as publicly owned resources for their citizens. An increasing number of governments, while retaining ownership of these public resources, are hiring private companies to manage them. But some are selling their water resources to private companies.

Two large French companies—Veolia and Suez—realize that water scarcity is rapidly becoming one of world's most urgent environmental problems and that there is a lot of money to be made in owning and managing water resources. Their long-range strategy is to buy or manage as much of the world's privately and publicly owned water suppliers as possible, especially in Europe, North America, and China. For example, Veolia with 70,000 employees provides water for 108 million people in 57 countries, including 17 Chinese cities.

Currently, 85% of Americans get their water from publicly owned utilities. This may change. Within 10 years, these two European-based water companies aim to control 70% of the water supply in the United States by buying up American water companies and entering into agreements with most cities to manage their water supplies.

Some argue that private companies have the money and expertise to manage these resources better and more efficiently than government bureaucracies can. Experience with this public–private partnership approach has yielded mixed results. Some private water management companies have done a good job.

For example, in 2002 Veolia was hired to manage the water and wastewater system in the Chinese city of Pudong. Since then, the company has laid more than 1,400 kilometers (900 miles) of pipe, hooked up more than 300,000 new structures to the rapidly growing system, built water-treatment and sewage treatment plants, and hired 7,000 local workers. It also established a 24-hour customer call-in help center (a rarity in China) and a control room to monitor the status of every water connection in Pudong.

Some government officials want to go even further and sell public water resources to private companies. For example, in Cochabamba, Bolivia's third largest city, 60% of the water was being lost through leaky pipes. With no money to fix the pipes, the Bolivian government sold the city's water system to a subsidiary of Bechtel Corporation, an American owned global engineering and construction company. Within 6 months, the company sharply increased water rates and began seizing and selling the houses of people who did not pay their water bills. A general strike ensued in this city of about 500,000 people, and violent street clashes between protesters and government troops led to 10,000 people being injured and 7 deaths. Bechtel executives fled the city and the Bolivian government tore up the contract with Bechtel.

Today, the city's water management system is in shambles and most of the leaks persist because of insufficient funds. Bechtel filed a $50 million suit against Bolivia in the World Bank's trade court for not honoring the contract, but decided to drop the suit in 2005 after being subjected to 4 years of international protests by citizen groups.

A similar problem occurred when a subsidiary of Bechtel signed a 30-year contract in 2000 to run the water and sanitation services for Guayaquil, Ecuador's largest city. In 2007, residents of the city were demanding damages from the company for contract violations, including broken pipelines, exorbitant water rates, malfunctioning sewage systems, unsafe tap water, repeated water cutoffs, failure to extend services to low-income neighborhoods, and public health problems from a lack of wastewater treatment. Citizens are calling for a return to local, public control of water resources and sanitation.

Many people oppose full privatization of water resources because they believe that water is a public resource too important to be left solely in private hands. Also, once a city's water systems have been taken over by a foreign-based corporation, efforts to return the systems to public control can be quite costly for taxpayers and can lead to severe economic penalties under the rules of the World Trade Organization (WTO).

Some analysts point to two other potential problems in a fully privatized water system. *First,* because private companies make money by delivering water, they have an incentive to sell as much water as they can rather than to conserve it. *Second,* because they have too little money to pay water bills, the poor will continue to be left out. There are no easy answers for managing the water that everyone needs.

HOW WOULD YOU VOTE?

Should private companies own or manage most of the world's water resources? Cast your vote online at **academic .cengage.com/biology/miller**.

The most common ways to increase the supply of freshwater in a particular area are to withdraw groundwater, to build dams and reservoirs to store runoff in rivers for release as needed, to transport surface water from one area to another, and to use water more efficiently. The rest of this chapter evaluates these options.

13-2 Is Extracting Groundwater the Answer?

CONCEPT 13-2 Groundwater that is used to supply cities and grow food is being pumped from aquifers in some areas faster than it is renewed by precipitation.

Water Tables Fall When Groundwater Is Withdrawn Faster Than It Is Replenished

Most aquifers are renewable sources unless their water becomes contaminated or is removed faster than it is replenished by rainfall, as is occurring in many parts of the world. Aquifers provide drinking water for nearly half of the world's people. In the United States, aquifers supply almost all of the drinking water in rural areas, one-fifth of that in urban areas, and 37% of irrigation water. Relying more on groundwater has advantages and disadvantages (Figure 13-7).

Water tables are falling in many areas of the world because the rate of pumping water from aquifers (mostly to irrigate crops) exceeds the rate of natural recharge from rainfall and snowmelt (**Concept 13-2**). The world's three largest grain producers—India, China, and the United States—and several other countries such as Saudi Arabia, Iran, Yemen, Israel, Mexico, and Pakistan are overpumping many of their aquifers.

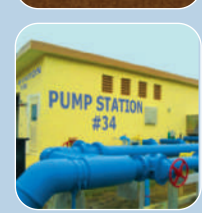
Currently, more than half a billion people are being fed by grain produced through the unsustainable use of groundwater. This number is expected to grow until the water runs out or until governments put caps on aquifer withdrawal rates, stop providing subsidies that encourage overpumping and water waste, and raise water prices.

The widespread drilling of inexpensive tubewells by small farmers, especially in India and China, has accelerated aquifer overpumping. As water in aquifers is removed faster than it is renewed, water tables fall. Then farmers drill deeper wells, buy larger pumps, and use more energy to pump water to the surface, eventually depleting aquifers or making it too costly to pump the remaining water. In China and India, the increasing demand for electricity to run the pumps is met mostly by building more coal-fired power plants, which add greenhouse gases and other pollutants to the atmosphere.

TRADE-OFFS

Withdrawing Groundwater

Advantages	Disadvantages
Useful for drinking and irrigation	Aquifer depletion from overpumping
Available year-round	Sinking of land (subsidence) from overpumping
Exists almost everywhere	Aquifers polluted for decades or centuries
Renewable if not overpumped or contaminated	Saltwater intrusion into drinking water supplies near coastal areas
No evaporation losses	Reduced water flows into surface waters
Cheaper to extract than most surface waters	Increased cost and contamination from deeper wells

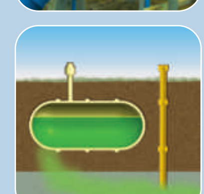
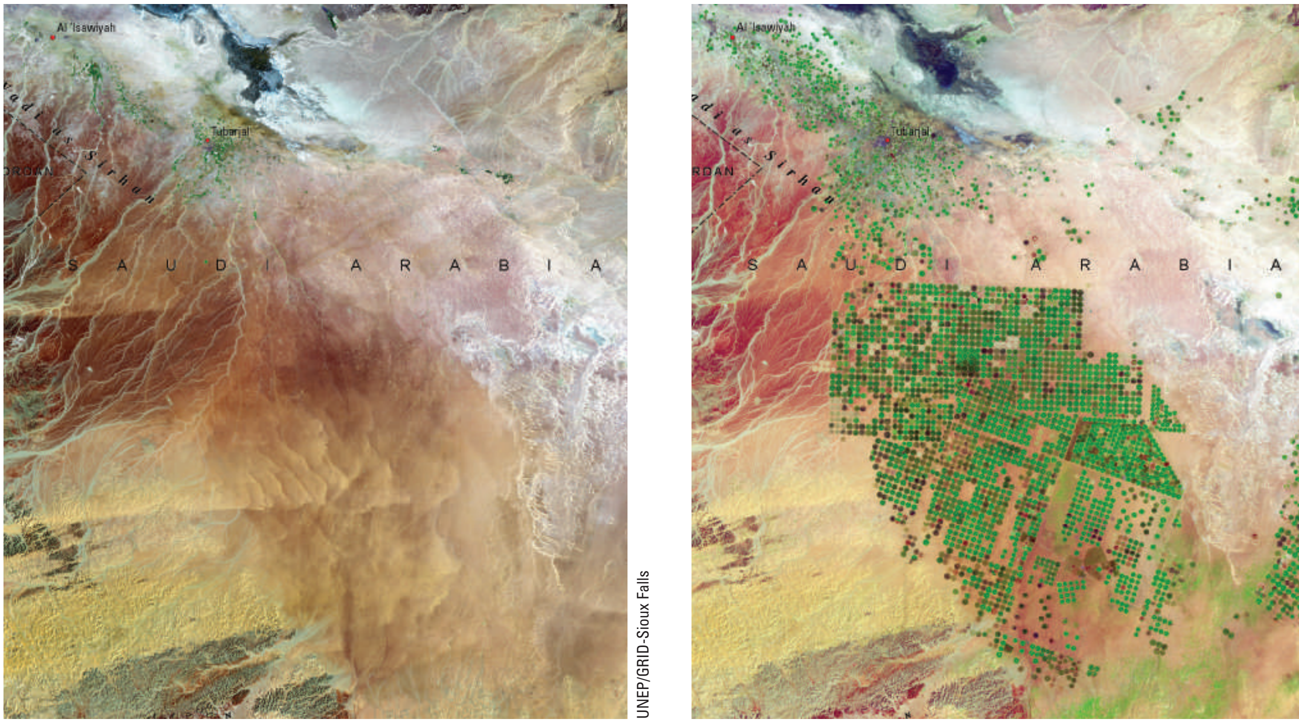


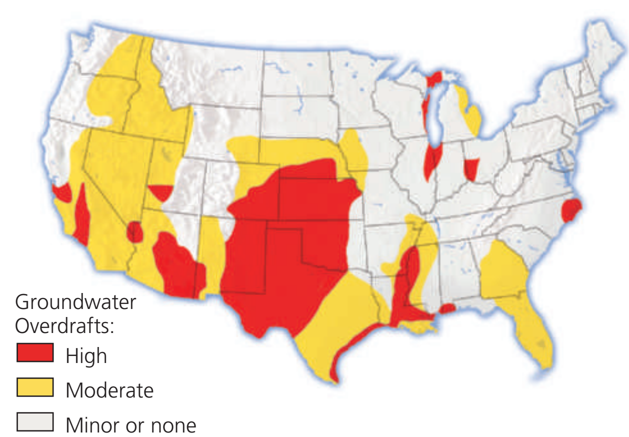
Figure 13-7 Advantages and disadvantages of withdrawing groundwater. **Question:** Which two advantages and which two disadvantages do you think are the most important? Why?



1986 **2004**

Figure 13-8 **Natural capital degradation:** development of irrigation by pumping groundwater from an ancient and nonrenewable aquifer in a vast desert region of Saudi Arabia between 1986 (left) and 2004 (right). Irrigated areas appear as green dots (each representing a circular spray system), and brown dots show areas where wells have gone dry and the land has returned to desert. Hydrologists estimate that because of aquifer depletion, most irrigated agriculture in Saudi Arabia may disappear within 10–20 years.

Arid Saudi Arabia is as water-poor as it is oil-rich. It gets about 70% of its drinking water at a high cost from the world's largest system for removing salt from seawater, located on its eastern coast. The rest of the country's water is pumped from deep aquifers—most as nonrenewable as the country's oil—and used to grow irrigated crops on desert land (Figure 13-8) and to fill large numbers of fountains and swimming pools from which precious water evaporates into the hot, dry desert air. Hydrologists estimate that because of aquifer depletion, most irrigated agriculture in Saudi Arabia may disappear within 1 to 2 decades.



CENGAGENOW™ **Active Figure 13-9** **Natural capital degradation:** areas of greatest aquifer depletion from groundwater overdraft in the continental United States, including the vast, central Ogallala aquifer. Aquifer depletion is also high in Hawaii and Puerto Rico (not shown on map). *See an animation based on this figure at* CengageNOW™. **Question:** If you live in the United States, how is your lifestyle affected directly or indirectly by water withdrawn from the essentially nonrenewable Ogallala aquifer? (Data from U.S. Water Resources Council and U.S. Geological Survey)

■ **CASE STUDY**

Aquifer Depletion in the United States

In the United States, groundwater is being withdrawn, on average, four times faster than it is replenished, according to the U.S. Geological Survey (**Concept 13-2**). Figure 13-9 shows the areas of greatest depletion. One of the most serious overdrafts is in the lower half of the Ogallala, the world's largest known aquifer, which lies under eight Midwestern states from South Dakota to Texas (Figure 13-10). Serious groundwater depletion is also taking place in California's Central Valley, which supplies half of the country's fruit and vegetables (the long red area in the California portion of Figure 13-9).

The gigantic Ogallala aquifer supplies about one-third of all the groundwater used in the United States and has helped to turn the Great Plains into one of

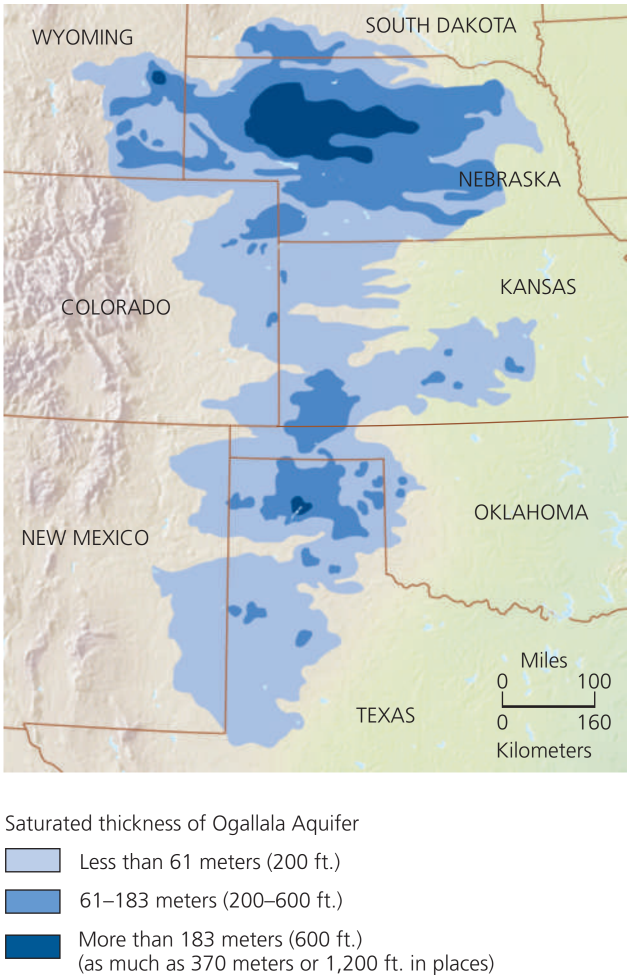


Figure 13-10 **Natural capital degradation:** The Ogallala is the world's largest known aquifer. If the water in this aquifer were above ground, it could cover all of the lower 48 states with 0.5 meter (1.5 feet) of water. Water withdrawn from this aquifer is used to grow crops, raise cattle, and provide cities and industries with water. As a result, this aquifer, which is renewed very slowly, is being depleted, especially at its thin southern end in parts of Texas, New Mexico, Oklahoma, and Kansas. (Data from U.S. Geological Survey)

world's most productive irrigated agricultural regions. The problem is that the Ogallala is essentially a one-time deposit of liquid natural capital with a very slow rate of recharge.

The northernmost states (Wyoming, Nebraska, South Dakota, and parts of Colorado) still have ample water supplies from the aquifer. However, in parts of the southern states, where the aquifer is thinner, the water is being depleted rapidly—especially in the Texas–Oklahoma High Plains. In some of these areas water is being pumped out at a rate that is 10–40 times higher than the natural recharge rate. This has lowered the water table more than 30 meters (100 feet). The resulting higher pumping costs make it too expensive to irrigate crops in some areas. As a result, the amount of irrigated farmland in Texas has decreased by about 11% in recent years, as farmers abandon agriculture or return to lower yield dryland farming.

Government subsidies designed to increase crop production and to encourage farmers to grow water-thirsty crops have only accelerated depletion of the Ogallala. They include crop-disaster payments and tax breaks in the form of groundwater depletion allowances (with larger breaks for heavier groundwater use).

Depletion of the Ogallala threatens biodiversity. In some places, the Ogallala flows onto the land and creates wetlands, which are vital habitats for many species, especially birds. When the water tables fall, many of these aquatic oases of biodiversity will disappear, along with the ecosystem services they provide.

THINKING ABOUT
The Ogallala

What are three things you would do to promote more sustainable use of the Ogallala aquifer?

Groundwater Overpumping Has Other Harmful Effects

Overpumping of aquifers not only limits future food production, but also increases the gap between the rich and poor in some areas. As water tables drop, farmers must drill deeper wells, buy larger pumps, and use more electricity to run the pumps. Poor farmers cannot afford to do this and end up losing their land and working for richer farmers or migrating to cities already crowded with poor people struggling to survive.

Withdrawing large amounts of water sometimes causes the sand and rock in aquifers to collapse, which causes the land above the aquifer to *subside* or sink, a phenomenon known as *land subsidence.* Once an aquifer becomes compressed from subsidence, recharge is impossible. Land subsidence can damage roadways, water and sewer lines, and building foundations. Areas in the United States suffering from this problem include California's San Joaquin Valley, Baton Rouge in Louisiana, the Phoenix area in Arizona, and the Houston–Galveston area in Texas.

Mexico City, built on an old lakebed, has one of the world's worse subsidence problems because of increasing groundwater overdrafts due to rapid population growth and urbanization. Some parts of the city have sunk as much as 10 meters (33 feet). Parts of Beijing in China and Bangkok in Thailand are also sinking.

Sinkholes, which can appear suddenly and unexpectedly, are another kind of land subsidence. They are large craters that form when the roof of an underground cavern collapses after being drained of the groundwater that supports it. Sinkholes can appear suddenly and can swallow homes, businesses, roads, cars, and trees.

Groundwater overdrafts near coastal areas, where many of the world's largest cities and industrial areas are found, can cause contamination of groundwater supplies by pulling saltwater into freshwater aquifers

SCIENCE FOCUS

Are Deep Aquifers the Answer?

With global water shortages looming, scientists are evaluating *deep aquifers* as future water sources. Preliminary results suggest that some of these aquifers hold enough water to support billions of people for centuries. And the water quality in these aquifers may be much higher than that of most rivers and lakes.

The first problem is to locate such aquifers and determine whether they contain freshwater or saline water. One way to do this is to drill a borehole and measure the electrical resistance of layers of geological material at different depths. An aquifer containing freshwater has a higher electrical resistance than more saline aquifers. Measurements of the natural radioactive emissions of gamma rays (Figure 2-7, top, p. 41) emitted by rocks at different levels can also help locate aquifers. In addition, scientists send vibrations into the earth and use a seismograph to evaluate the water content of various geological layers.

A series of boreholes are used to estimate properties such as the size, depth, and flow rate of an aquifer. Such data can be mapped and evaluated by using mathematical models. The radioisotope carbon-14 can be used to determine the age of the water.

Once an aquifer is located, deep wells must be drilled to extract water samples, which are analyzed for salt content, oxygen levels, and presence of other chemicals. Because most of these aquifers are huge, samples must be withdrawn from different areas of such aquifers.

There are two major concerns about tapping these nonrenewable deposits of water. *First,* little is known about the geological and ecological impacts of pumping water from deep aquifers. *Second,* some deep aquifers flow beneath several different countries, and no international water treaties govern rights to such water. Thus, conflicts could arise over who has the right to tap these aquifers.

Critical Thinking

What are some other possible problems that could arise from tapping deep aquifers?

SOLUTIONS

Groundwater Depletion

Prevention	Control
Waste less water	Raise price of water to discourage waste
Subsidize water conservation	Tax water pumped from wells near surface waters
Limit number of wells	Set and enforce minimum stream flow levels
Do not grow water-intensive crops in dry areas	Divert surface water in wet years to recharge aquifers

Figure 13-11 Ways to prevent or slow groundwater depletion by using water more sustainably. **Question:** Which two of these solutions do you think are the most important? Why?

thus making the groundwater undrinkable and unusable for irrigation. This problem is especially serious in coastal areas of the U.S. states of Florida, California, South Carolina, Georgia, New Jersey, and Texas, as well as in coastal areas of Turkey, Manila in the Philippines, and Bangkok in Thailand. Rising sea levels from global warming will increase saltwater intrusion and decrease the amount of groundwater available in heavily populated coastal areas.

Figure 13-11 lists ways to prevent or to slow the problem of groundwater depletion by using this largely renewable resource more sustainably. **GREEN CAREER:** Hydrogeologist

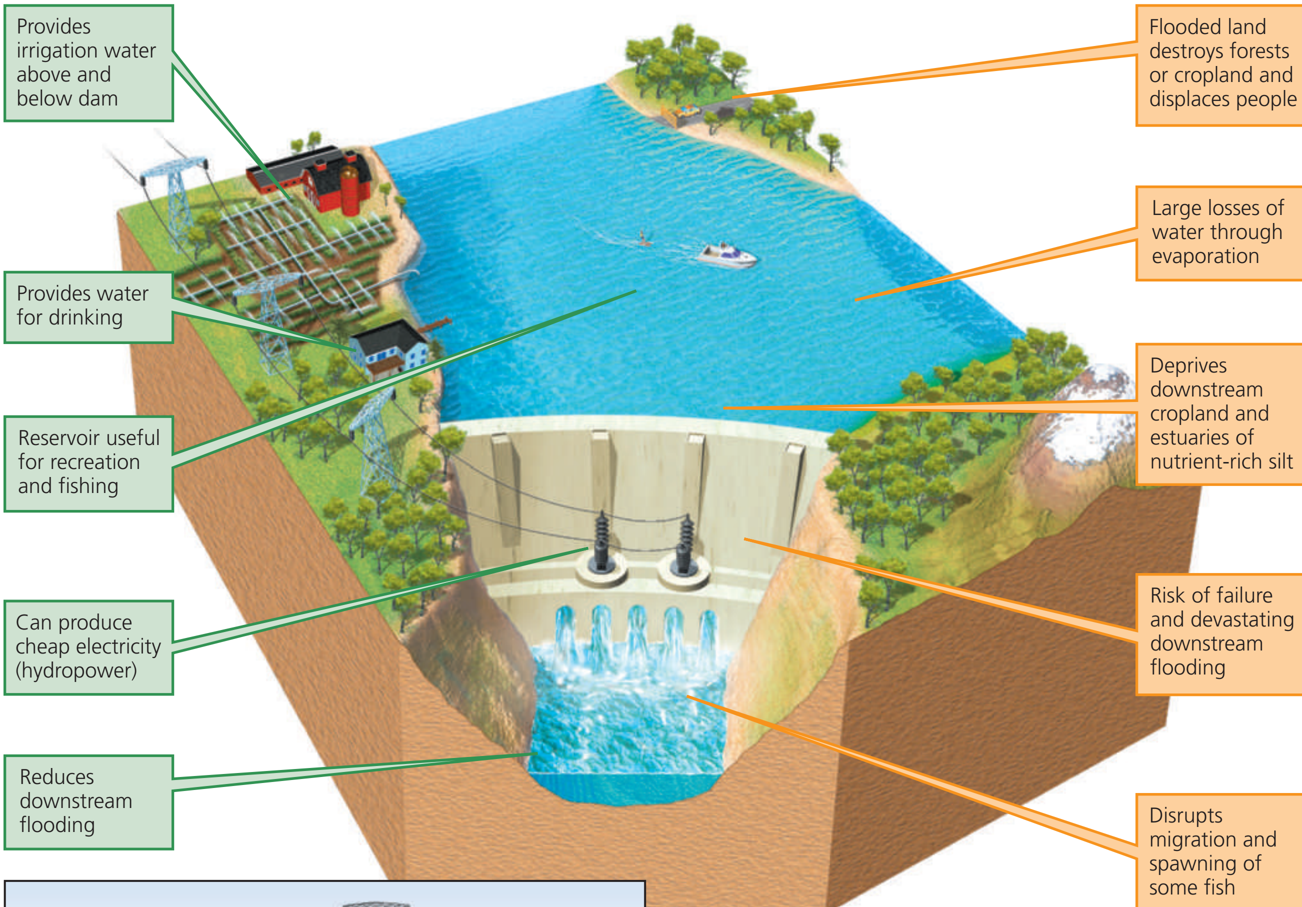
Scientists are also evaluating the use of deep aquifers as a source of freshwater (Science Focus, above).

13-3 Is Building More Dams the Answer?

▶ **CONCEPT 13-3 Building dam and reservoir systems has greatly increased water supplies in some areas, but it has disrupted ecosystems and displaced people.**

Large Dams and Reservoirs Have Advantages and Disadvantages

A **dam** is a structure built across a river to control the river's water flow. After a river is dammed, the river's flow creates an artificial lake, or **reservoir,** behind the dam. The main goals of a dam and reservoir system are to capture and store runoff and release it as needed to control floods, generate electricity (hydroelectricity), and supply water for irrigation and for towns and cit-



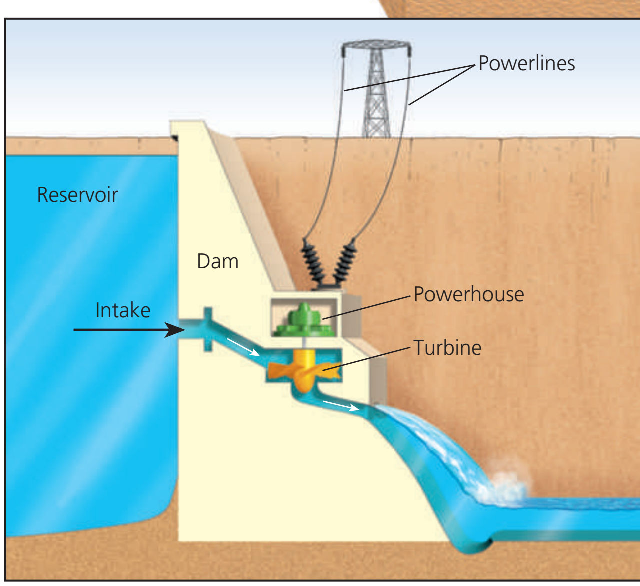
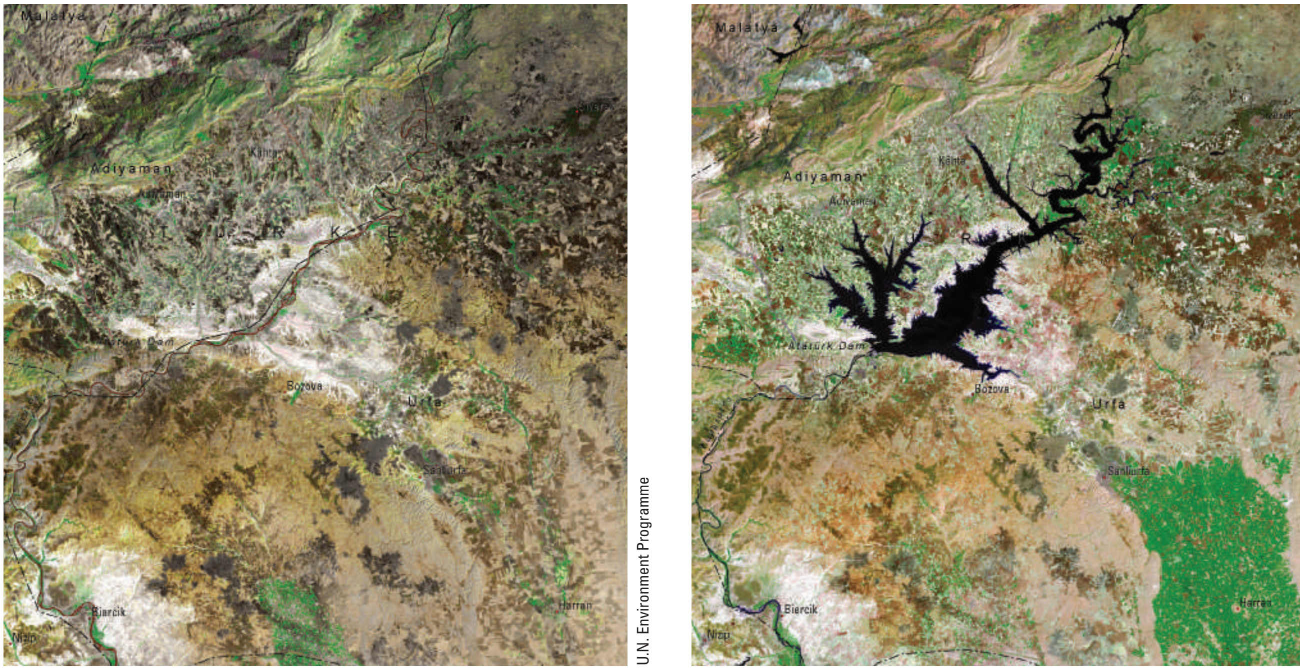


Figure 13-12 **Trade-offs:** advantages (green) and disadvantages (orange) of large dams and reservoirs (**Concept 13-3**). The world's 45,000 large dams (higher than 15 meters or 49 feet) capture and store about 14% of the world's runoff, provide water for almost half of all irrigated cropland, and supply more than half the electricity used by 65 countries. The United States has more than 70,000 large and small dams, capable of capturing and storing half of the country's entire river flow. **Question:** Which single advantage and which single disadvantage do you think are the most important? Why?

ies. Reservoirs also provide recreational activities such as swimming, fishing, and boating. Today, there are about 800,000 dams worldwide, 45,000 of them large dams—at least 15 meters (49 feet) high. Large dams and reservoirs have both benefits and drawbacks (Figure 13-12).

Large dams (22,000 of them in China) have increased the annual reliable runoff available for human use by nearly one-third. As a result, reservoirs now hold 3 to 6 times more water than flows in the world's natural rivers. These dams and reservoirs have helped to reduce flooding and grow crops in arid areas (Figure 13-13, p. 326). One-fourth of the world's dams produce about 20% of the world's electricity.

Large dams and reservoirs also have disadvantages. Worldwide, this engineering approach to river management has displaced 40–80 million people from their homes. It has flooded an area of mostly productive land roughly equal to the area of the U.S. state of California, and it has impaired some of the important ecological services rivers provide (Figure 11-16, p. 270, and **Concept 13-3**). And according to the 2007 WWF study, about one-fifth of the world's freshwater fish and plant species are either extinct or endangered primarily



U.N. Environment Programme

U.N. Environment Programme

1976 **1999**

Figure 13-13 In 1976, a rural area of eastern Turkey was too dry for growing crops, as illustrated by the brown areas and the small number of crop fields shown in the satellite photo (left). In 1990, the Atatürk Dam was constructed on the Euphrates River (Figure 13-1). It is the largest of 22 dams built on the Euphrates and Tigris rivers in the 1980s and 1990s to provide irrigation water and hydroelectricity to arid southeastern Turkey. The satellite photo on the right shows the same area in 1999. The large areas of green show irrigated crop fields, especially around the town of Harran at the bottom right. The project has increased food production and provided electricity. However, Syria and Iraq are concerned that water diverted by this and other proposed dams on the Euphrates will leave too little water to meet each country's needs.

because dams and water withdrawals have destroyed many free-flowing rivers.

Because of evaporation and seepage into porous rock beds, the reservoirs behind some dams lose large amounts of water. Reservoirs also eventually fill up with sediment, mud, and silt, usually within 50 years, which makes them useless for storing water or producing electricity. About 85% of dam and reservoir systems in the United States will be 50 years old by 2020.

Some Rivers Are Running Dry and Some Lakes Are Shrinking

A series of dams on a river and withdrawals of river water for agricultural and urban uses, especially in arid areas, can disrupt the hydrologic cycle by reducing downstream flow to a trickle and preventing river water from reaching the sea. According to a 2007 study by the World Wildlife Fund (WWF), only 21 of the planet's 177 longest rivers run freely from their sources to the sea (Figure 8-17, p. 176) because of dams, excessive water withdrawals, and in some areas, prolonged severe drought. Projected climate change will worsen this situation in many areas because the earth's climate and hydrological cycles are intertwined.

Examples of major rivers running dry part of the year include the Colorado (Case Study, at right) and the Rio Grande in the southwestern United States, the Yangtze and Yellow in China, the Ganges in India, the Indus in Pakistan, the Danube in Europe, and Africa's Nile River–Lake Victoria (Chapter 11 Core Case Study, p. 249). Many smaller rivers have totally disappeared.

THINKING ABOUT

Dams and Egypt

CORE CASE STUDY

Upstream dams and diversions of water from the Nile River by Ethiopia and Sudan will reduce the water available to Egypt, which cannot exist without such water. Which one or more of the options discussed in the **Core Case Study** do you think Egypt should pursue? Explain.

Some of the world's lakes and inland seas are shrinking and, in some cases, disappearing because of excessive diversion of water from rivers that feed them and overpumping of adjacent aquifers. An example is Lake Chad in central Africa. Because of greatly increased use of river water for irrigation, the lake has shrunk by 96% since the 1960s and may soon disappear completely.

Large numbers of lakes have disappeared in China. One reason is that since 1985, China's Yellow River, which flows through five provinces before emptying into the Yellow Sea, has often failed to reach the sea. As a result, China's Qinhai province has lost more than 2,000 of its 4,077 lakes since 1985. The following two case studies illustrate the benefits and harmful effects of damming rivers (**Concept 13-3**).

HOW WOULD YOU VOTE?

Do the advantages of large dams outweigh their disadvantages? Cast your vote online at **academic.cengage.com /biology/miller**.

CASE STUDY

The Colorado River Basin—An Overtapped Resource

The Colorado River, the major river of the arid southwestern United States, flows 2,300 kilometers (1,400 miles) through seven states and eventually to the Gulf of California (Figure 13-14). During the past 50 years, this once free-flowing river, which gets its water mostly from snowmelt from the Rocky Mountains, has been tamed by a gigantic plumbing system consisting of 14 major dams and reservoirs (Figure 13-15) and canals that supply water to farmers, ranchers, and cities.

This system lies in a mostly desert area within the rain shadow (Figure 7-7, p. 145) of California's mountain ranges. It provides water and electricity for more than 25 million people in seven states. The river's water is used to produce about 15% of the nation's crops and livestock. It also supports a multibillion-dollar recreation industry of whitewater rafting, boating, fishing, camping, and hiking.

The river supplies water to some of the nation's driest and hottest cities. Take away this tamed river and Las Vegas, Nevada, would be a mostly uninhabited desert area; San Diego and Los Angeles, California, could not support their present populations; and California's Imperial Valley, which grows a major portion of the nation's vegetables, would consist mostly of cactus and mesquite plants.

Lake Mead behind Hoover Dam (Figure 13-14) supplies about 90% of water for the desert city of Las Vegas, Nevada—one of the country's fastest growing urban areas. In 2008, U.S. researchers Tim Barnett and David Pierce estimated that there is a 50% chance that by 2021, Lake Mead will run dry because of greater water demands and decreased flow of the Colorado River due to increased drought and evaporation of water.

There are four major problems associated with use of this river's water. *First,* the Colorado River basin includes some of the driest lands in the United States and Mexico (Figure 13-4). *Second,* for its size, the river has only a modest flow of water. *Third,* legal pacts signed in 1922 and 1944 allocated more water for human use in the United States and Mexico than the river can

Figure 13-14 The *Colorado River basin.* The area drained by this basin is equal to more than one-twelfth of the land area of the lower 48 states. Two large reservoirs—Lake Mead behind the Hoover Dam and Lake Powell behind the Glen Canyon Dam—store about 80% of the water in this basin.

Jim Wark/Peter Arnold, Inc.

Figure 13-15 Aerial view of Glen Canyon dam built across the Colorado River in 1963 and its reservoir called Lake Powell, the second largest reservoir in the United States.

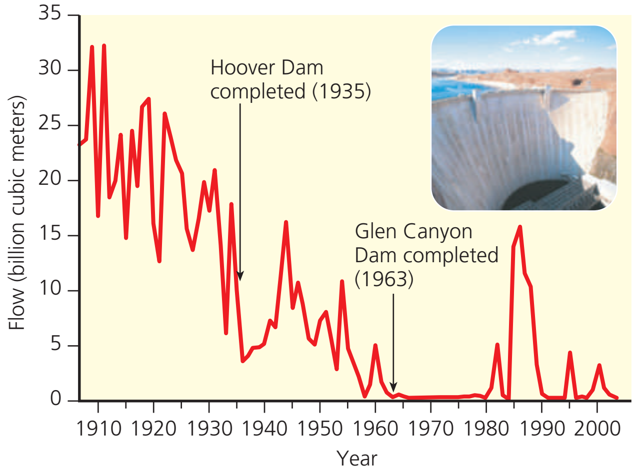


Figure 13-16 The flow of the Colorado River measured at its mouth has dropped sharply since 1905 as a result of multiple dams, water withdrawals for agriculture and urban areas, and prolonged drought (Data from U.S. Geological Survey).

supply—even in rare years without a drought. The pacts allocated no water for environmental purposes.

Fourth, since 1905, the amount of water flowing to the mouth of the Colorado River has dropped dramatically (Figure 13-16). Since 1960, the river has rarely made it to the Gulf of California because of the many dams, the increased water withdrawals, and a prolonged drought in the American Southwest, which is projected to last throughout this century. This threatens the survival of species that spawn in the river and species that live in its estuary near the coast.

The water available from the Colorado is likely to decrease even more because of climate change caused by global warming. According to projections, as the climate continues to warm, mountain snows that feed the river will melt faster and earlier and evaporate in greater amounts.

If some of the Southwest's largest reservoirs empty out during this century, the region could experience an economic and ecological catastrophe with political and legal battles over who will get how much of the region's greatly diminished water supply. Agricultural production would drop sharply and many people in the region's booming desert cities, such as Phoenix, Arizona, and Las Vegas, Nevada, likely would have to migrate to other areas. Withdrawing more groundwater is not a solution because water tables beneath much of the area served by the Colorado River have been dropping, sometimes drastically, due to overpumping (Figure 13-9).

Traditionally, about 80% of the water withdrawn from the Colorado has been used to irrigate crops and raise cattle. The U.S. government paid for the dams and reservoirs and has supplied many farmers and ranchers with water at low prices. These government subsidies have led to inefficient use of irrigation water on thirsty crops such as rice, cotton, and alfalfa in this water-short area.

In addition, as the flow of the Colorado River slows in large reservoirs behind dams it drops much of its load of suspended silt. This deprives the river's coastal delta of much needed sediment and causes flooding and loss of ecologically important coastal wetlands. The amount of silt being deposited on the bottoms of the Lake Powell and Lake Mead reservoirs is roughly 20,000 dump truck loads every day. Sometime during this century, these reservoirs will probably be too full of silt to store enough water for generating hydroelectric power or controlling floods.

Some researchers argue that the seven states using the Colorado River should enact and enforce strict water conservation measures and sharply increase the price of water from the river. They also suggest measures to slow population growth and urban development, stop subsidizing agriculture in this region, shift water-thirsty crops to less arid areas, and stop building golf courses and growing green lawns in desert areas. People living in or moving to areas served by the river would have to realize that they are living in a desert and must adapt to their environment by drastically reducing their water usage.

These problems illustrate the challenges faced by governments and people living in arid and semiarid regions with shared river systems, as population growth and economic development place increasing demands on limited or decreasing supplies of surface water. Without major changes in water policies and management to drastically increase the efficiency of water use, the future for large numbers of people in such areas may dry up.

THINKING ABOUT
The Colorado River

What are three measures you would take to deal with the problems of the Colorado River system? How would you implement them politically?

■ CASE STUDY
China's Three Gorges Dam

China's Three Gorges Dam, built across the Yangtze River, is the world's largest hydroelectric dam and reservoir. Two kilometers (1.2 miles) long, the dam was built at a cost of at least $25 billion. Like all dams, it has created benefits and harmful effects (Figure 13-12).

When its giant reservoir fills, the dam will be able to produce an amount of electricity equal to that of 22 large coal-burning or nuclear power plants, enough electricity to provide power for a city 10 times as large as the U.S. city of Los Angeles, California. This will help to reduce China's dependence on coal and its emissions of the greenhouse gas CO_2.

The dam will also help to hold back the Yangtze River's floodwaters, which have killed more than 500,000 people during the past 100 years—including 4,000 people in 1998. The estimated cost of damage caused by the 1998 flood alone equals the cost of the entire dam project. In addition, the dam will enable large cargo-carrying ships to travel deep into China's interior, greatly reducing transportation costs, and increasing trade in a relatively poor region of China.

When filled, the 600-kilometer-long (370-mile-long) reservoir behind the dam will cover an area almost equal in length to the distance between the U.S. cities of San Francisco and Los Angeles, California. This enormous reservoir will flood one of China's most beautiful areas, including 1,350 cities and villages and thousands of archeological and cultural sites. It will displace about 5.4 million people.

Some scientists contend that the slower flow of water in the reservoir will continually release huge amounts of sediment that will shorten the projected life of the reservoir and limit the flood-prevention capacity of the dam. In addition, productive farming regions below the dam will no longer receive annual deposits of nutrient-rich sediment.

Because the dam is built over a seismic fault, some geologists worry that it might collapse and cause a major flood that would kill millions of people. Engineers claim that the dam can withstand the maximum projected earthquake. Yet, some 80 small cracks have already been discovered in the dam.

Another problem is that plant and animal matter rotting underwater in the gigantic reservoir will release methane gas—which is a much more potent greenhouse gas than CO_2—into the atmosphere. The hydroelectric power generated by the dam will allow the Chinese to avoid some additional CO_2 emissions by not having to build as many new coal-burning power plants. But the reservoir's methane emissions will offset these savings in CO_2 emissions.

Opponents of the dam also claim that it will convert the Yangtze River to the world's largest sewer, because most cities and factories along the river dump their untreated sewage and other wastes directly into it. Opponents estimate that the hidden long-term harmful environmental and social costs of the dam project will be close to $75 billion—three times the direct cost of the project. Critics claim that it would have been cheaper, less disruptive, and safer to build a series of smaller dams.

THINKING ABOUT
The Three Gorges Dam

Do you think that the benefits of the Three Gorges Dam will outweigh its harmful effects? Explain.

13-4 Is Transferring Water from One Place to Another the Answer?

CONCEPT 13-4 Transferring water from one place to another has greatly increased water supplies in some areas, but it has also disrupted ecosystems.

California Transfers Massive Amounts of Water from Water-Rich Areas to Water-Poor Areas

Tunnels, aqueducts, and underground pipes can transfer stream runoff collected by dams and reservoirs from water-rich areas to water-poor areas, but they also create environmental problems (**Concept 13-4**).

One of the world's largest water transfer projects is the *California Water Project* (Figure 13-17, p. 330). It uses a maze of giant dams, pumps, and aqueducts to transport water from water-rich northern California to water-poor southern California's heavily populated agricultural regions and cities. This project supplies massive amounts of water to areas that, without such water transfers, would be mostly desert.

For decades, northern and southern Californians have feuded over how the state's water should be allocated under this project. Southern Californians want more water from the north to grow more crops and to support Los Angeles, San Diego, and other growing urban areas. Agriculture consumes three-fourths of the water withdrawn in California, much of it used inefficiently for water-thirsty crops such as rice and alfalfa growing in desert-like conditions.

Northern Californians counter that sending more water south degrades the Sacramento River, threatens fisheries, and reduces the river's power to flush pollutants out of San Francisco Bay. They also argue that much of the water sent south is wasted. They point to studies showing that making irrigation just 10% more efficient would provide enough water for domestic and industrial uses in southern California. But low water prices, mostly because government subsidies make it uneconomical for farmers to invest in improving irrigation efficiency.

According to a 2002 study by a group of scientists and engineers, projected global warming will sharply reduce water availability in California (especially

Figure 13-17 The California Water Project and the Central Arizona Project. These projects involve large-scale water transfers from one watershed to another. Arrows show the general direction of water flow.

southern California) and other water-short states in the western United States, even in the best-case scenario. Some analysts project that sometime during this century, many people living in arid southern California cities, as well as farmers in this area, may have to move elsewhere because of a shortage of water.

Pumping more groundwater is not the answer, because groundwater is already being withdrawn faster than it is replenished in much of central and southern California (Figure 13-9). According to many analysts, it would be quicker and cheaper to reduce water waste by improving irrigation efficiency, not growing water-thirsty crops in arid areas, and raising the historically low price of water to encourage water conservation.

■ **CASE STUDY**

The Aral Sea Disaster

The shrinking of the Aral Sea (Figure 13-18) is the result of a large-scale water transfer project in an area of the former Soviet Union with the driest climate in central Asia. Since 1960, enormous amounts of irrigation water have been diverted from the inland Aral Sea and its two feeder rivers to create one of the world's largest irrigated areas, mostly for raising cotton and rice. The irrigation canal, the world's longest, stretches more than 1,300 kilometers (800 miles).

This large-scale water diversion project, coupled with droughts and high evaporation rates due to the area's hot and dry climate, has caused a regional ecological and economic disaster. Since 1961, the sea's salinity has risen sevenfold and the average level of its water has dropped by 22 meters (72 feet). It has lost 89% of its volume of water and has split into two major parts (Figure 13-18, right). Water withdrawal for agriculture has reduced the two rivers feeding the sea to mere trickles.

About 85% of the area's wetlands have been eliminated and roughly half the local bird and mammal species have disappeared. In addition, a huge area of former lake bottom has been converted to a human-made desert covered with glistening white salt. The sea's increased salt concentration—three times saltier than ocean water—caused the presumed extinction of 26 of the area's 32 native fish species. This has devastated the area's fishing industry, which once provided work for more than 60,000 people. Fishing villages and boats once located on the sea's coastline now sit abandoned in the middle of a salt desert (Figure 13-19).

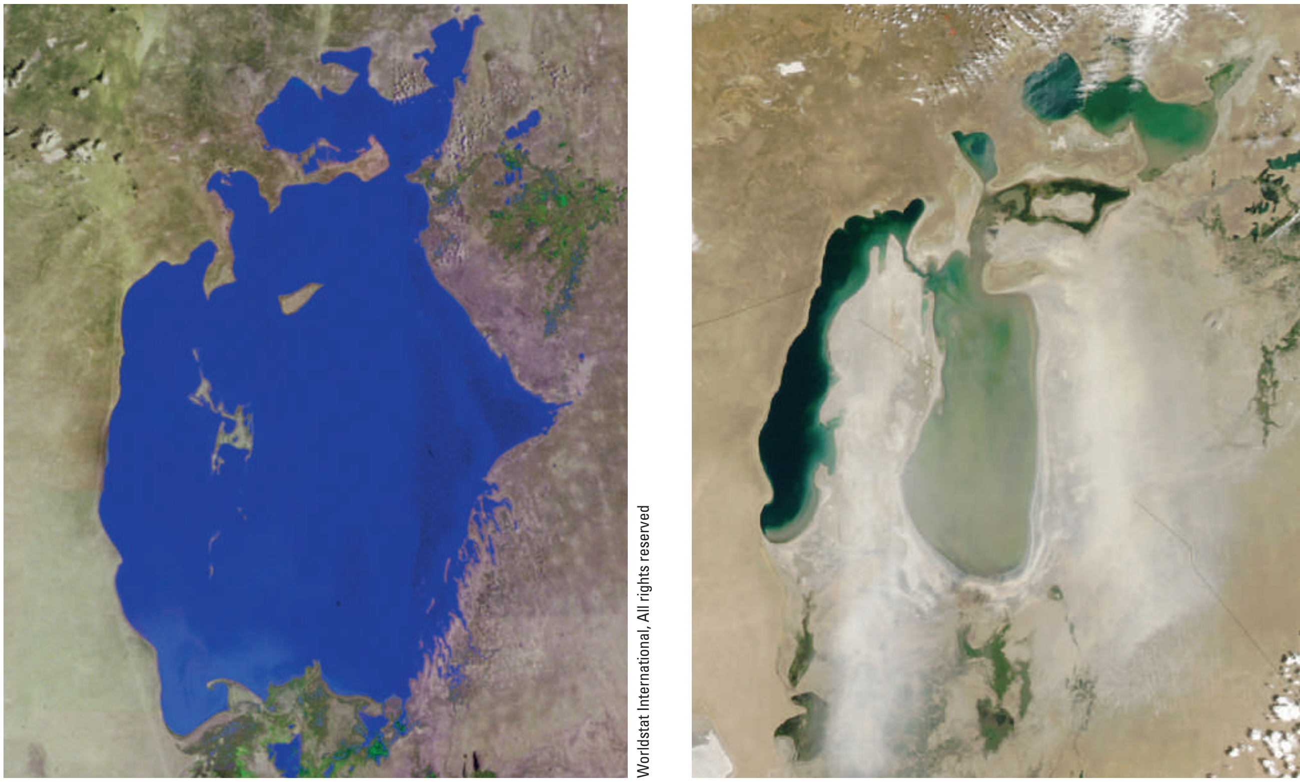
Winds pick up the sand and salty dust and blow it onto fields as far as 500 kilometers (310 miles) away. As the salt spreads, it pollutes water and kills wildlife, crops, and other vegetation. Aral Sea dust settling on glaciers in the Himalayas is causing them to melt at a faster than normal rate—a prime example of unexpected connections and unintended consequences.

Shrinkage of the Aral Sea has also altered the area's climate. The once-huge sea acted as a thermal buffer that moderated the heat of summer and the extreme cold of winter. Now there is less rain, summers are hotter and drier, winters are colder, and the growing season is shorter. The combination of such climate change and severe salinization has reduced crop yields by 20–50% on almost one-third of the area's cropland.

To raise yields, farmers have used more herbicides, insecticides, and fertilizers, which have percolated downward and accumulated to dangerous levels in the groundwater—the source of most of the region's drinking water. Many of the 45 million people living in the Aral Sea's watershed have experienced increasing health problems—including anemia, respiratory illnesses, liver and kidney disease, eye problems, and various cancers—from a combination of toxic dust, salt, and contaminated water.

To make matters worse, Soviet scientists who were engaged in top-secret biological warfare studies buried hundreds of metric tons of deadly anthrax bacterial spores and other deadly toxins on an island in the Aral Sea. As the lakeshores receded, this island grew and joined the mainland in 2001. There is concern that any surviving disease organisms could reach people via fleas or infected rodents or by their removal and use by terrorists.

Since 1999, the United Nations and the World Bank have spent about $600 million to purify the area's drinking water and upgrade irrigation and drainage systems. This has improved irrigation efficiency and flushed salts from croplands. A dike completed in 2005 has raised the average level of the small Aral by 3 meters (10 feet) and decreased its salinity, allowing substantial fishing of several species. Some artificial wet-



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NASA image courtesy of Jeff Schmaltz, MODIS Rapid Response Team, NASA-Goddard Space Flight Center

1976 **2006**

Figure 13-18 **Natural capital degradation:** the *Aral Sea* was once the world's fourth largest freshwater lake. Since 1960, it has been shrinking and getting saltier because most of the water from the rivers that replenish it has been diverted to grow cotton and food crops (**Concept 13-4**). These satellite photos show the sea in 1976 and in 2006. It has split into two major parts, little Aral on the left and big Aral on the right. As the lake shrank, it left behind a salty desert, economic ruin, increasing health problems, and severe ecological disruption. **Question:** What do you think should be done to help prevent further shrinkage of the Aral Sea?

lands and lakes have been constructed to help restore aquatic vegetation, wildlife, and fisheries.

The five countries surrounding the lake and its two feeder rivers have worked to improve irrigation efficiency and to partially replace water-thirsty crops with others requiring less irrigation water. As a result, the total annual volume of water in the Aral Sea basin has been stabilized. Nevertheless, experts expect the largest portion of the Aral Sea to continue shrinking.

China Plans a Massive Transfer of Water

The Chinese government has begun a massive engineering project to transfer water from three of its southern river basins to its populous and parched northern provinces. This $62.5 billion South–North Water Transfer Project will use a series of canals, dams, reservoirs, and pumping stations to supply water to the north for irrigation and drinking.

One route, which is more than 1,000 kilometers (620 miles) long, will transfer about 2% of the flow of the Yangtze River to the north; it began supplying water to Beijing in 2008. Work on a second, equally long route is proceeding, while construction of a third,

Paul Howell/UNEP/Peter Arnold, Inc.

Figure 13-19 Ship stranded in desert formed by shrinkage of the Aral Sea.

more complex route linking watersheds in western China and Tibet is not expected to start for at least another decade. If everything goes as planned, by 2050, the system will transfer ten times more water than is transferred from northern to southern California (Figure 13-17). It will provide water for almost half a billion people in northern China.

Critics of this huge project are worried that high levels of pollution in the three rivers from which water will be extracted and transported will contaminate northern water supplies. They are also concerned that the large-scale removal of water could damage southern ecosystems, especially the fragile watersheds in Tibet.

But many Chinese scientists believe that the potential economic, health, and environmental benefits of the project outweigh its risks. They point out that increasing desertification (Figure 12-13, p. 289) in northern China is eroding biodiversity and reducing supplies of drinking water for at least 96 million Chinese, because pollutants are becoming concentrated in small bodies of water. In addition, northern China needs much more water to support its large population, intensive agriculture, and rapid industrialization. The additional water will also help to reduce overpumping of aquifers. The central government has required northern cities receiving the water to implement water conservation measures to keep the additional water from being squandered.

However, Chinese and U.S. climate models predict that northern China will become increasingly wet as average temperatures rise from projected global warming. This shift could begin within a decade and render the water transfer project, especially the third route, unnecessary.

13-5 Is Converting Salty Seawater to Freshwater the Answer?

CONCEPT 13-5 We can convert salty ocean water to freshwater, but the cost is high, and the resulting salty brine must be disposed of without harming aquatic or terrestrial ecosystems.

Removing Salt from Seawater Seems Promising but Is Costly

Desalination involves removing dissolved salts from ocean water or from brackish (slightly salty) water in aquifers or lakes for domestic use. It is another way to increase supplies of freshwater (**Concept 13-5**).

One method for desalinating water is *distillation*—heating saltwater until it evaporates (leaving behind salts in solid form) and condenses as freshwater. Another method is *reverse osmosis* (or *microfiltration*), which uses high pressure to force saltwater through a membrane filter with pores small enough to remove the salt.

According to a 2004 report by the U.S. National Academy of Sciences, about 15,000 desalination plants operate in more than 125 countries, especially in the arid nations of the Middle East, North Africa, the Caribbean, and the Mediterranean. They meet less than 0.3% of the world's demand for freshwater.

Saudi Arabia has the world's largest number of desalination plants, and the United States has the world's second-largest desalination capacity. By 2008, water-short Israel was getting almost half of its water from desalination. And China plans to build enough desalination plants to provide 16–25% of the water used in its coastal areas by 2010.

There are three major problems with the widespread use of desalination. One is the high cost and energy footprint. It takes a lot of energy to desalinate water, with distillation requiring about ten times as much energy as reverse osmosis requires. A second problem is that pumping large volumes of seawater through pipes and using chemicals to sterilize the water and keep down algal growth kills many marine organisms.

A third problem is that desalination produces large quantities of briny wastewater that contain lots of salt and other minerals. Dumping this concentrated brine into nearby coastal ocean waters increases the salinity of the ocean water, which threatens food resources and aquatic life in the vicinity. Disposing of it on land could contaminate groundwater and surface water.

Using desalinated water produced by reverse osmosis to irrigate crops could reduce soil salinization (Figure 12-14, p. 289). However, Israeli scientist U. Yermiyahu and his colleagues reported in 2007 that desalinization removes ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and sulfate (SO_4^{2-}) that are essential to plant growth. Thus, these ions must be added to desalinated irrigation water, which raises its already high cost, or the desalinated water must be blended with conventional irrigation water.

Bottom line: Currently, significant desalination is practical only for water-short, wealthy countries and

SCIENCE FOCUS

The Search for Improved Desalination Technology

Scientists are working to develop new membranes for reverse osmosis that can separate water from salt more efficiently and under less pressure and thus use less energy. Such technologies might bring down the cost of using desalination to produce drinking water but not to the point where they are cheap enough to irrigate conventional crops.

This may change if scientists can figure out how to use solar energy or other means to desalinate seawater cheaply and how to safely dispose of the resulting salty wastewater. Another possibility is the development of molecular size nanofilters to desalinate water at an affordable cost.

A consortium of companies is proposing to build ships that would carry desalination equipment. The ships would operate offshore, transferring the water to shore through seabed pipelines or in food grade shuttle tankers. The ships would have lower fuel costs than do land-based desalination plants. They would also not be affected by onshore power failures, because they would generate their own power by using clean-burning biodiesel oil in gas turbine engines. In addition, they would be able to move away from the paths of storms and draw water from depths below where most marine organisms are found. And the resulting brine could be returned to the ocean and diluted far away from coastal waters. California officials are evaluating this approach.

Two Australian companies, Energetech and H2AU, have joined forces to build an experimental desalination plant that uses the power generated by ocean waves—an indirect form of solar energy—to drive reverse-osmosis desalination. This approach eliminates air pollution created from burning fossil fuels to produce electricity, and it conserves energy. Thus, costs should be much lower than for other desalination methods. The plant will be located offshore where the resulting brine can be mixed with ocean water without affecting near-shore ecosystems.

In 2005, General Electric, one of the world's largest companies, began focusing on finding better ways to desalinate water. Because about 40% of the world is going to be short of freshwater in the next 10–20 years, GE sees desalination as one of the world's major growth businesses. **GREEN CAREER:** Desalination engineer

Before building a desalination plant, scientists urge reducing water needs by enacting strict water conservation regulations, fixing leaks in urban water supply systems, educating customers about water conservation, and cleaning up and reusing urban waste water. All of these solutions are much cheaper than desalination.

Critical Thinking

Use the second law of thermodynamics (p. 43) to explain why desalinated water is so costly.

cities that can afford its high cost (**Concept 13-5**). But scientists and engineers are working to develop better and more affordable desalination technologies (Science Focus, above).

RESEARCH FRONTIER

Developing better and more affordable desalination technologies. See **academic.cengage.com/biology/miller**.

13-6 How Can We Use Water More Sustainably?

CONCEPT 13-6 We can use water more sustainably by cutting water waste, raising water prices, slowing population growth, and protecting aquifers, forests, and other ecosystems that store and release water.

Reducing Water Waste Has Many Benefits

Mohamed El-Ashry of the World Resources Institute estimates that *65–70% of the water people use throughout the world is wasted through evaporation, leaks, and other losses*. The United States, the world's largest user of water, does slightly better but still loses about half of the water it withdraws. El-Ashry believes it is economically and technically feasible to reduce such water losses to 15%, thereby meeting most of the world's water needs for the foreseeable future (**Concept 13-6**).

Improving water use efficiency would decrease the burden on wastewater plants and reduce the need for expensive dams and water transfer projects that destroy wildlife habitats and displace people. It would also slow depletion of groundwater aquifers and save both energy and money.

According to water resource experts, the main cause of water waste is *its low cost to users. Underpricing* is mostly the result of government subsidies that provide irrigation water, electricity, and diesel fuel used by farmers to pump water from rivers and aquifers at below-market prices.

Because these subsidies keep water prices low, users have little or no financial incentive to invest in water-saving technologies. According to water resource expert Sandra Postel, "By heavily subsidizing water, governments give out the false message that it is abundant and can afford to be wasted—even as rivers are drying up, aquifers are being depleted, fisheries are collapsing, and species are going extinct."

But farmers, industries, and others benefiting from government water subsidies argue that the subsidies promote settlement and farming of arid, unproductive land; stimulate local economies; and help keep the prices of food, manufactured goods, and electricity low.

THINKING ABOUT
Government Water Subsidies

Should governments provide subsidies to farmers and cities to help keep the price of water artificially low? Explain.

Most water resource experts believe that when water scarcity afflicts many areas in this century, governments will have to make the unpopular decision to raise water prices. China did so in 2002 because it faced water shortages in most of its major cities, with rivers running dry, lakes disappearing, and water tables falling in key agricultural areas.

Higher water prices encourage water conservation but make it difficult for low-income farmers and city dwellers to buy enough water to meet their needs. When South Africa raised water prices, it dealt with this problem by establishing *lifeline* rates that give each household a set amount of free or low-priced water to meet basic needs. When users exceed this amount, they pay higher prices as their water use increases—*a user-pays approach.*

The second major cause of water waste is *a lack of government subsidies for improving the efficiency of water use.* A basic rule of economics is that you get more of what you reward. Withdrawing subsidies that encourage water waste and providing subsidies for efficient water use would sharply reduce water waste and help reduce water shortages. Two goals of such subsidies should be to greatly improve the efficiency of irrigation, which accounts for 70% of the world's water use, and to use inexpensive means to collect rainwater and pipe it to where it is needed.

HOW WOULD YOU VOTE? ✓

Should water prices be raised sharply to help reduce water waste? Cast your vote online at **academic.cengage.com/biology/miller**.

We Can Cut Water Waste in Irrigation

About 60% of the irrigation water applied throughout the world does not reach the targeted crops. Most irrigation systems obtain water from a groundwater well or a surface water source. The water then flows by gravity through unlined ditches in crop fields so the crops can absorb it (Figure 13-20, left). This *flood irrigation* method delivers far more water than is needed for crop growth and typically loses 40% of the water through evaporation, seepage, and runoff. This wasteful method is used on 97% of China's irrigated land.

More efficient and environmentally sound irrigation technologies can greatly reduce water demands and water waste on farms by delivering water more precisely to crops—a more crop per drop strategy. For example, the *center-pivot, low-pressure sprinkler* (Figure 13-20, right) uses pumps to spray water on a crop. This results in a series of circular irrigated areas as shown by the green dots in Figure 13-8, right. Typically, it allows 80% of the water to reach crops. *Low-energy, precision application (LEPA) sprinklers,* another form of center-pivot irrigation, put 90–95% of the water where crops need it.

Drip or *trickle irrigation,* also called *microirrigation* (Figure 13-20, center), is the most efficient way to deliver small amounts of water precisely to crops. It consists of a network of perforated plastic tubing installed at or below the ground level. Small pinholes in the tubing deliver drops of water at a slow and steady rate, close to the roots of individual plants.

Current drip irrigation systems are costly but they drastically reduce water waste; 90–95% of the water input reaches the crops, and crop yields are 20–90% more than those of conventional gravity flow systems. By using less water, they also reduce the amount of salt that irrigation water leaves in the soil.

Drip irrigation is used on just over 1% of the world's irrigated crop fields and 4% of those in the United States. This percentage rises to 90% in Cyprus, 66% in Israel, and 13% in California. If water were priced closer to the value of the ecological services it provides and if government subsidies that encourage water waste were reduced or eliminated, drip irrigation would quickly be used to irrigate most of the world's crops.

Good news. The capital cost of a new type of drip irrigation system developed by the nonprofit International Development Enterprises (IDE) is one-tenth as much per hectare as that of conventional drip systems. Increased use of this inexpensive system designed for poor farmers will raise crop yields in water-short areas and help to lift poor families out of poverty. According to the United Nations, reducing current global withdrawal of water for irrigation by just 10% would save enough water to grow crops and meet the estimated additional water demands of cities and industries through 2025.

RESEARCH FRONTIER

Developing more efficient and affordable irrigation systems. See **academic.cengage.com/biology/miller**.

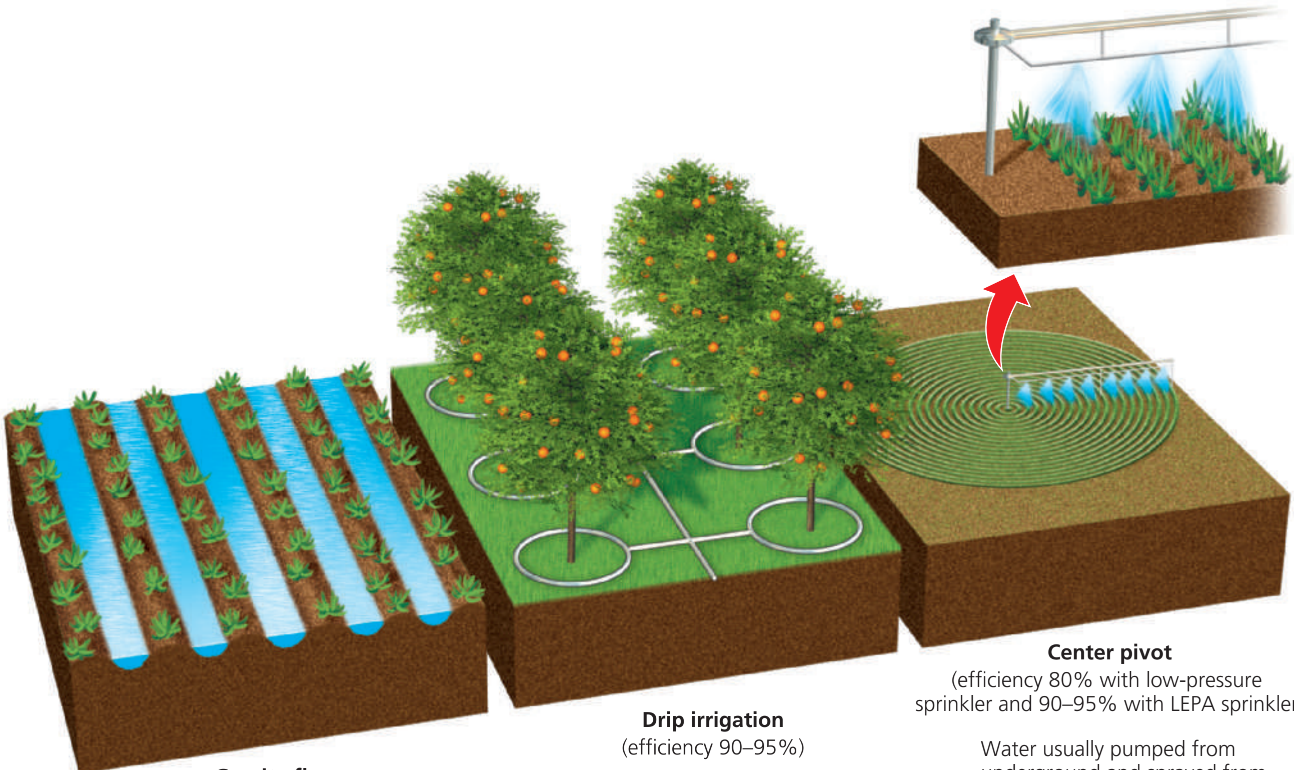


Figure 13-20 Major *irrigation systems.* Because of high initial costs, center-pivot irrigation and drip irrigation are not widely used. The development of new, low-cost, drip-irrigation systems may change this situation.

Figure 13-21 lists other ways to reduce water waste in crop irrigation. Since 1950, Israel has used many of these techniques to slash irrigation water waste by 84% while irrigating 44% more land. Israel now treats and reuses 30% of its municipal sewage water for crop production and plans to increase this to 80% by 2025. The government also gradually eliminated most water subsidies to raise Israel's price of irrigation water to one of the highest in the world. Israelis also import most of their wheat and meat and concentrate on growing fruits, vegetables, and flowers that need less water. For decades, wastewater from sewage treatment plants in many parts of the world has been used to water parks and golf courses and to irrigate flowers and other nonfood crops.

SOLUTIONS

Reducing Irrigation Water Waste

- Line canals bringing water to irrigation ditches
- Irrigate at night to reduce evaporation
- Monitor soil moisture to add water only when necessary
- Grow several crops on each plot of land (polyculture)
- Encourage organic farming
- Avoid growing water-thirsty crops in dry areas
- Irrigate with treated urban wastewater
- Import water-intensive crops and meat

Figure 13-21 Methods for reducing water waste in irrigation. **Question:** Which two of these solutions do you think are the most important? Why?

Developing Countries Use Low-Tech Methods for Irrigation

Many of the world's poor farmers use small-scale and low-cost traditional irrigation technologies. For example, millions of farmers in countries such as Bangladesh use human-powered treadle pumps to pump groundwater close to the earth's surface through irrigation ditches (see Photo 6 in the Detailed Contents). These wooden devices are cheap (about $25), easy to build from local materials, and operate on leg power. Other farmers in some developing countries use buckets, small tanks with holes, or cheap plastic tubing systems for drip irrigation.

Rainwater harvesting is another simple and inexpensive way to provide water for drinking and for growing crops throughout most of the world. It involves running pipes from rooftops and digging channels to catch rainwater that would otherwise run off the land. It is stored in shallow aquifers, ponds, and water tanks for use during dry spells. This is especially useful in developing countries, such as India, where much of the rain comes in a short monsoon season. In south Australia, over 40% of households use rainwater stored in tanks as their main source of drinking water. And half a million households and buildings in Germany harvest rainwater.

Other strategies used by poor farmers to increase the amount of crop per drop of rainfall include polyculture farming and agroforestry to create canopy cover over crops and to reduce water losses by evaporation. Farmers also plant deep-rooted perennial crop varieties (Science Focus, Figure 12-C, p. 309), control weeds, and mulch fields to retain more moisture.

In foggy mountainous areas, fog-catcher nets, developed by scientists in Chile, are used to harvest water. These upright volleyball-style plastic nets are placed on hilltops to intercept and remove water droplets from passing fog and clouds. The water is channeled into a storage tank or into gutters and then to a network of pipes that transfer it to wherever it is used.

We Can Cut Water Waste in Industry and Homes

Producers of chemicals, paper, oil, coal, primary metals, and processed food use almost 90% of the water used by industry in the United States. Some of these industries recapture, purify, and recycle water to reduce their water use and water treatment costs. For example, more than 95% of the water used to make steel is recycled. However, most industrial processes could be redesigned to use much less water. Raising water prices would spur such research. Figure 13-22 lists ways to use water more efficiently in industries, homes, and businesses (**Concept 13-6**).

Flushing toilets with water (most of it clean enough to drink) is the single largest use of domestic water in the United States. Since 1992, U.S. government standards have required that new toilets use no more than 6.1 liters (1.6 gallons) of water per flush. Architect and designer William McDonough has designed a toilet with a bowl so smooth that nothing sticks to it, including bacteria. Only a light mist is needed to flush it. Low-flow showerheads can cut shower water flow in half and save about 19,000 liters (5,000 gallons) per person each year.

According to U.N. studies, 40–60% of the water supplied in nearly all of the world's major cities in developing countries is lost mostly through leakage of water mains, pipes, pumps, and valves. Water experts say that fixing these leaks should be a high government priority that would cost less than building dams or importing water. Even in advanced industrialized countries such as the United States these losses average 10–30%. However, leakage losses have been reduced to about 3% in Copenhagen, Denmark, and to 5% in Fukuoka, Japan.

It does not require a government program to detect and fix leaks. To detect a silent toilet water leak, add a few drops of food coloring to the toilet tank and wait 5 minutes. If the color shows up in the bowl, you have a leak. Be sure to fix leaking faucets. A faucet dripping

SOLUTIONS

Reducing Water Waste

- Redesign manufacturing processes to use less water
- Recycle water in industry
- Landscape yards with plants that require little water
- Use drip irrigation
- Fix water leaks
- Use water meters
- Raise water prices
- Use waterless composting toilets
- Require water conservation in water-short cities
- Use water-saving toilets, showerheads, and front-loading clothes washers
- Collect and reuse household water to irrigate lawns and nonedible plants
- Purify and reuse water for houses, apartments, and office buildings

Figure 13-22 Methods of reducing water waste in industries, homes, and businesses (**Concept 13-6**). **Question:** Which three of these solutions do you think are the most important? Why?

once per second wastes up to 8,200 liters (3,000 gallons) of water a year.

Many homeowners and businesses in water-short areas are using drip irrigation and copying nature by replacing green lawns with plants that need little water. This water-thrifty landscaping, called *xeriscaping* (pronounced "ZEER-i-scaping"), reduces water use by 30–85% and sharply reduces needs for labor, fertilizer, and fuel. It is also an example of reconciliation ecology (p. 244), so it helps preserve biodiversity, and it reduces polluted runoff, air pollution, and yard wastes.

About 50–75% of the slightly dirtied water from bathtubs, showers, sinks, dishwashers, and clothes washers in a typical house could be stored in a holding tank and then reused as *gray water* to irrigate lawns and nonedible plants, to flush toilets, and to wash cars. Israel reuses 70% of its wastewater (sewage water) to irrigate nonfood crops. In Singapore, all sewage water is treated at reclamation plants for reuse by industry. Such measures mimic the way nature purifies water by recycling it, and thus they follow one of the four **scientific principles of sustainability** (see back cover).

Underpricing is also a major cause of excessive water use and waste in homes and industries (**Concept 13-6**). Many water utility and irrigation authorities charge a flat fee for water use and some charge less for the largest users of water. About one-fifth of all U.S. public water systems do not have water meters and charge a single low rate for almost unlimited use of high-quality water. Also, many apartment dwellers have little incentive to conserve water because water use charges are included in their rent. When the U.S. city of Boulder, Colorado, introduced water meters, water use per person dropped by 40%.

In Brazil, an electronic device called a water manager allows customers to obtain water on a pay-as-you-go basis. Water users buy a smart card (like a long-distance phone card) that contains a certain number of water credits. When they punch in the card's code on their water manager device, the water company automatically supplies them with a specified amount of water. Brazilian officials say this approach saves water and electrical power and typically reduces household water bills by 40%. **GREEN CAREER:** Water conservation specialist

We Can Use Less Water to Remove Wastes

Currently, we use large amounts of freshwater good enough to drink to flush away industrial, animal, and household wastes. According to the FAO, if current trends continue, within 40 years we will need the world's entire reliable flow of river water just to dilute and transport the wastes we produce. We could save much of this water by using systems that mimic the way nature deals with wastes.

For example, sewage treatment plants remove valuable plant nutrients and dump most of them into rivers, lakes, and oceans. This overloads aquatic systems with plant nutrients that could be recycled to the soil. We could mimic nature and return the nutrient-rich sludge produced by conventional waste treatment plants to the soil as a fertilizer, instead of using freshwater to transport it. Banning the discharge of industrial toxic chemicals into sewage treatment plants would help to make this feasible.

Another way to recycle waste is to rely more on waterless composting toilets that convert human fecal matter to a small amount of dry and odorless soil-like humus material that can be removed from a composting chamber every year or so and returned to the soil as fertilizer. One of the authors (Miller) successfully used a composting toilet for 15 years.

We Need to Use Water More Sustainably

More sustainable use of water is based on the commonsense principle stated in an old Inca proverb: "The frog does not drink up the pond in which it lives." Figure 13-23 lists strategies that scientists have suggested for using water more sustainably (**Concept 13-6**).

SOLUTIONS

Sustainable Water Use

- Waste less water and subsidize water conservation
- Do not deplete aquifers
- Preserve water quality
- Protect forests, wetlands, mountain glaciers, watersheds, and other natural systems that store and release water
- Get agreements among regions and countries sharing surface water resources
- Raise water prices
- Slow population growth

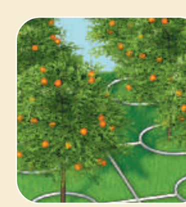


Figure 13-23 Methods for achieving more sustainable use of the earth's water resources (**Concept 13-6**). **Question:** Which two of these solutions do you think are the most important? Why?

Each of us can help to bring about such a *blue revolution* by using less water and cutting our water waste to reduce our water footprints (Figure 13-24). As with other problems, the solution starts with thinking globally and acting locally.

WHAT CAN YOU DO?

Water Use and Waste

- Use water-saving toilets, showerheads, and faucet aerators
- Shower instead of taking baths, and take short showers
- Repair water leaks
- Turn off sink faucets while brushing teeth, shaving, or washing
- Wash only full loads of clothes or use the lowest possible water-level setting for smaller loads
- Use recycled (gray) water for watering lawns and houseplants and for washing cars
- Wash a car from a bucket of soapy water, and use the hose for rinsing only
- If you use a commercial car wash, try to find one that recycles its water
- Replace your lawn with native plants that need little if any watering
- Water lawns and yards only in the early morning or evening
- Use drip irrigation and mulch for gardens and flowerbeds

Figure 13-24 **Individuals matter:** ways in which you can reduce your use and waste of water. Visit www.h2ouse.org for an array of tips from the EPA and the California Urban Water Conservation Council on how to save water, no matter where you live. **Questions:** Which four of these actions do you think are the most important? Why? Which of these things do you plan to do?

13-7 How Can We Reduce the Threat of Flooding?

▶ **CONCEPT 13-7 We can lessen the threat of flooding by protecting more wetlands and natural vegetation in watersheds and by not building in areas subject to frequent flooding.**

Some Areas Get Too Much Water from Flooding

Some areas have too little water, but others sometimes have too much because of natural flooding by streams, caused mostly by heavy rain or rapidly melting snow. A flood happens when water in a stream overflows its normal channel and spills into the adjacent area, called a **floodplain.** Floodplains, which usually include highly productive wetlands, help to provide natural flood and erosion control, maintain high water quality, and recharge groundwater.

People settle on floodplains because of their many advantages, including fertile soil, ample water for irrigation, availability of nearby rivers for transportation and recreation, and flat land suitable for crops, buildings, highways, and railroads. To reduce the threat of flooding for people who live on floodplains, rivers have been narrowed and straightened (channelized), lined with protective levees and walls, and dammed to create reservoirs that store and release water as needed (Figures 13-12 and 13-15). However, in the long run, such measures can lead to greatly increased flood damage when prolonged rains overwhelm them.

Floods provide several benefits. They have created the world's most productive farmland by depositing nutrient-rich silt on floodplains. They also recharge groundwater and help refill wetlands, thereby supporting biodiversity and ecological services.

But floods kill thousands of people each year and cause tens of billions of dollars in property damage. Indeed, floods annually affect more people than the combined numbers affected by drought, tropical cyclones, famine, earthquakes, tsunamis, and volcanic eruptions. Floods usually are considered natural disasters, but since the 1960s, human activities have contributed to a sharp rise in flood deaths and damages.

One such human activity is *removal of water-absorbing vegetation,* especially on hillsides (Figure 13-25). Farm fields, pastures, pavement, or buildings usually replace such vegetation and absorb far less rainwater, or none at all. In 1998, for example, severe flooding in

China's Yangtze River watershed, home to 400 million people, killed at least 15 million people and caused massive economic losses. Scientists identified the causes as heavy rainfall, rapid snowmelt, and deforestation that had removed 85% of the watershed's tree cover. They also estimated the value of flood control, which the forested hills would have provided, to be three times the economic value of the lumber obtained by cutting the trees down. Chinese officials banned tree cutting in the watershed and accelerated tree replanting with the long-term goal of restoring some of the area's natural flood-control ecological services.

Removing protective mangrove forests (Figure 8-8, p. 168) in coastal areas can also allow for increased flooding from storms and tsunamis. Many such forests have been cleared to make way for shrimp farms.

Draining and building on wetlands, which naturally absorb floodwaters, is the second major human activity that increases the severity of flooding. When Hurricane Katrina struck the Gulf Coast of the United States in August 2005 and flooded the city of New Orleans (Figure 8-18, p. 177) and surrounding areas, the damage was intensified because of the degradation or removal of coastal wetlands that had historically helped to buffer the land from storm surges. Bottom line: Hurricane Katrina was a natural tragedy but its destructive effects were intensified because human activities had removed and degraded an important form of protective natural capital (Case Study, p. 177). Some scientists argue that, in order to help prevent future devastation of the Gulf Coast, a major priority should be to restore its coastal wetlands.

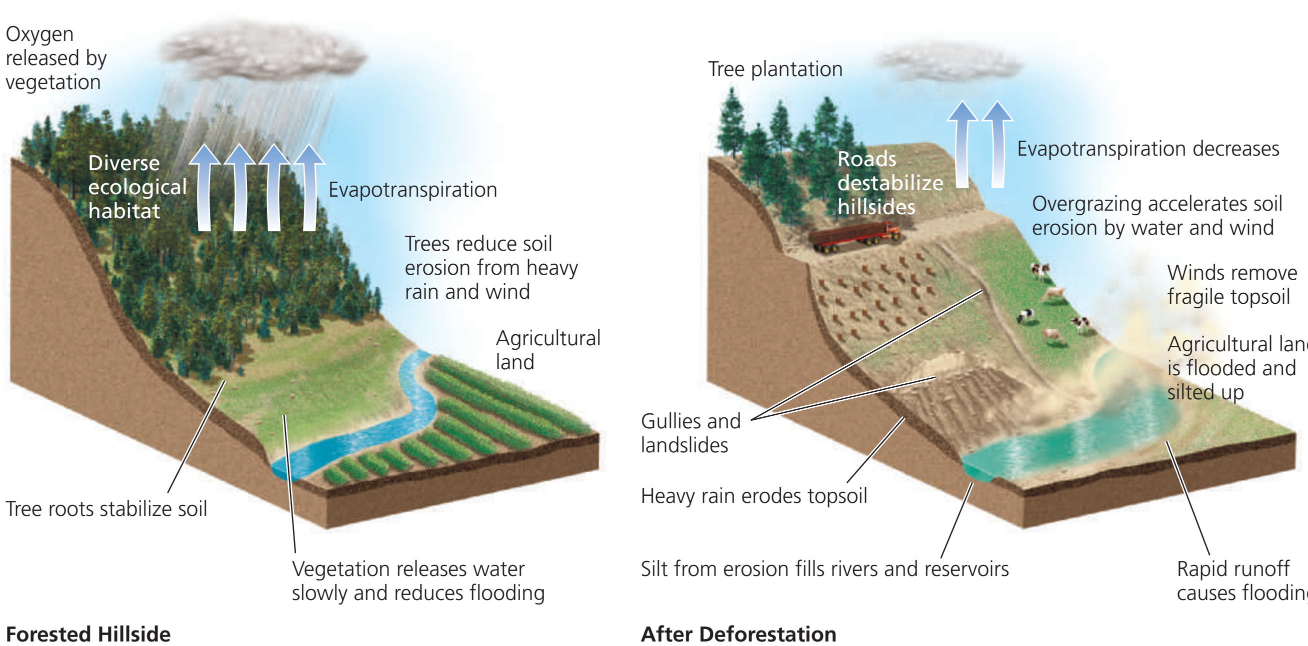
Obviously, people who choose to live on floodplains increase their own risk of damage from flooding. Choosing to live elsewhere would thus lower this threat, but many of the poor are forced to live in such risky areas (Case Study, below).

Another human-related factor that will increase flooding is global warming caused mostly by people burning fossil fuels and clearing forests. Reports in 2007 by the Organization for Economic Cooperation and Development (OECD) and the IPCC projected that, by the 2070s, as many as 150 million people living in many of the world's largest coastal cities—an amount equal to half of the current U.S. population—are likely to be at risk from flooding as a result of rising sea levels caused by climate change.

■ **CASE STUDY**

Living Dangerously on Floodplains in Bangladesh

Bangladesh is one of the world's most densely populated countries. In 2008, its 147 million people were packed into an area roughly the size of the U.S. state of Wisconsin. And the country's population is projected to increase to 215 million by 2050. Bangladesh is a very flat country, only slightly above sea level, and it is one of the world's poorest countries.



CENGAGENOW™ **Active Figure 13-25** **Natural capital degradation:** hillside before and after deforestation. Once a hillside has been deforested for timber, fuelwood, livestock grazing, or unsustainable farming, water from precipitation rushes down the denuded slopes, erodes precious topsoil, and can increase flooding and pollution in local streams. Such deforestation can also increase landslides and mudflows. A 3,000-year-old Chinese proverb says, "To protect your rivers, protect your mountains." *See an animation based on this figure at* CengageNOW. **Question:** How might a drought in this area make these effects even worse?

The people of Bangladesh depend on moderate annual flooding during the summer monsoon season, which helps them to grow rice and maintain soil fertility in the delta basin. The annual floods deposit eroded Himalayan soil on the country's crop fields. People have adapted to this moderate flooding. Most of their houses have flat thatch roofs on which families can take refuge with their belongings in case of flooding. The roofs can also be detached from the walls, if necessary, and floated like rafts. After the waters have subsided, a roof can be reattached to the walls of its house. But great floods can overwhelm such cultural adaptations.

In the past, great floods occurred every 50 years or so. But since the 1970s, they have come roughly every 4 years. Bangladesh's flooding problems begin in the Himalayan watershed, where rapid population growth, deforestation, overgrazing, and unsustainable farming on steep and easily erodible slopes have increased flows of water during monsoon season. Monsoon rains now run more quickly off the denuded Himalayan foothills, carrying vital topsoil with them (Figure 13-25).

This increased runoff of soil, combined with heavier-than-normal monsoon rains, has increased the severity of flooding along Himalayan rivers and downstream in Bangladesh. In 1998, a disastrous flood covered two-thirds of Bangladesh's land area for 9 months, drowned at least 2,000 people, and left 30 million people homeless. It also destroyed more than one-fourth of the country's crops, which caused thousands of people to die of starvation. In 2002, another flood left 5 million people homeless and flooded large areas of rice fields. Another major flood occurred in 2004.

Living on Bangladesh's coastal floodplain at sea level means coping with storm surges, cyclones, and tsunamis. In 1970, as many as 1 million people drowned as a result of one tropical cyclone. Another cyclone in 2003 killed more than a million people and left tens of millions homeless. And another in 2007 killed at least 3,200 people, left millions homeless, destroyed crop lands, and killed at least 1.25 million livestock.

In their struggle to survive, the poor in Bangladesh have cleared many of the country's coastal mangrove forests for fuelwood, farming, and aquaculture ponds for raising shrimp. The result: more severe flooding, because these coastal wetlands that had sheltered Bangladesh's low-lying coastal areas from storm surges, cyclones, and tsunamis were now gone. Damages and deaths from cyclones in areas of Bangladesh still protected by mangrove forests have been much lower than in areas where the forests have been cleared.

A rise in sea level and an increase in storm intensity, mostly because of climate change caused by global warming, will be a major threat in coming years to millions of Bangladeshis who live along its largely flat delta, bound by the Bay of Bengal. In 2007, the IPCC projected that rises in the world's sea level during this century, mostly from the expansion of water as it warms, could permanently flood as much as 11% of Bangladesh's land area. This would create millions of refugees with no place to go in this already densely populated country.

THINKING ABOUT
Bangladesh

What are three important measures that could be taken to help reduce the threat of flooding in Bangladesh?

We Can Reduce Flood Risks

Figure 13-26 lists some ways to reduce flooding risks (**Concept 11-7**). To improve flood control, we can rely less on engineering devices such as dams and levees and more on nature's systems, such as wetlands and natural vegetation in watersheds.

CONCEPT LINK

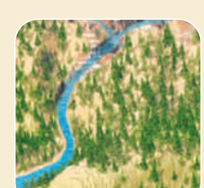
Channelizing streams reduces upstream flooding. But it also eliminates aquatic habitats, reduces groundwater discharge, and results in a faster flow, which can increase downstream flooding and sediment deposition. And channelization encourages human settlement in floodplains, which increases the risk of damages and deaths from major floods.

SOLUTIONS

Reducing Flood Damage

Prevention

- Preserve forests on watersheds
- Preserve and restore wetlands in floodplains
- Tax development on floodplains
- Use floodplains primarily for recharging aquifers, sustainable agriculture and forestry



Control

- Straighten and deepen streams (channelization)
- Build levees or floodwalls along streams
- Build dams

Figure 13-26 Methods for reducing the harmful effects of flooding (**Concept 13-7**). **Question:** Which two of these solutions do you think are the most important? Why?

Similarly, levees or floodwalls along the sides of streams contain and speed up stream flow, but they increase the water's capacity for doing damage downstream. And they do not protect against unusually high and powerful floodwaters, such as those that occurred in 1993 when two-thirds of the levees built along the Mississippi River in the United States were damaged or destroyed. Dams can reduce the threat of flooding by storing water in a reservoir and releasing it gradually, but they also have a number of disadvantages (Figure 13-12).

Perhaps one of the most important ways to reduce flooding is to *preserve existing wetlands* and *restore degraded wetlands* to take advantage of the natural flood control they provide in floodplains. This helps to protect biodiversity and to restore degraded ecological services provided by these aquatic ecosystems.

On a personal level, we can use the precautionary approach and *think carefully about where we choose to live.* Many poor people live in flood-prone areas because they have nowhere else to go. Most people, however, can choose not to live in areas especially subject to flooding or to water shortages.

REVISITING Water Conflicts in the Middle East and Sustainability

CORE CASE STUDY

SUSTAINABILITY

The **Core Case Study** that opens this chapter discussed the problems and tensions of Middle Eastern countries trying to share limited water resources. Israel has become the world's most water-efficient nation and has led the world in developing technologies and a water pricing system that help the country to use its limited water supplies more sustainably. Other water-short nations would benefit from following its example in saving water.

Generally the water resource strategies of the 20th century worked against natural ecological cycles and processes. Large dams, river diversions, levees, and other big engineering schemes have helped to provide much of the world with electricity, food, drinking water, and flood control. But they have also degraded the aquatic natural capital needed for long-term economic and ecological sustainability by seriously disrupting rivers, streams, wetlands, aquifers, and other aquatic systems.

The four **scientific principles of sustainability** (see back cover) can guide us in using water more sustainably during this century. Scientists hope to use solar energy to desalinate water and increase supplies, and solar energy is already used to purify water for drinking in some areas. Recycling more water will help us to reduce water waste. Preserving biodiversity by avoiding disruption of aquatic systems and their bordering terrestrial systems is a key factor in maintaining water supplies and water quality. And controlling human population growth is fundamental to using water resources more sustainably while maintaining water quality.

This *blue revolution,* built mostly around cutting water waste, will provide innumerable economic and ecological benefits. There is no time to lose in implementing it.

The benefits of working with nature's water cycle, rather than further disrupting it, are too compelling to ignore.

SANDRA POSTEL

REVIEW

1. Review the Key Questions and Concepts for this Chapter on p. 314. Describe water conflicts in the Middle East and possible solutions to these problems.

2. What percentage of the earth's freshwater is available to us? Define **groundwater, zone of saturation, water table,** and **aquifer.** Define **surface water, surface runoff,** and **watershed (drainage basin).** Distinguish between surface runoff and **reliable surface runoff.** What percentage of the world's reliable runoff are we using and what percentage are we likely to be using by 2025?

3. How is most of the world's water used? Describe the availability and use of freshwater resources in the United States. How many people in the world lack regular access to safe drinking water, and how many do not have access to basic sanitation? What is **drought** and what are its causes and harmful effects? Discuss the question of who should own and manage freshwater resources.

4. What are the advantages and disadvantages of withdrawing groundwater? Describe the problem of groundwater depletion in the world and in the United States, especially

over the Ogallala aquifer. Describe ways to prevent or slow groundwater depletion.

5. What is a **dam?** What is a **reservoir?** What are the advantages and disadvantages of large dams and reservoirs? What ecological services do rivers provide? Describe some problems associated with the use of the Colorado River basin. What are the advantages and disadvantages of China's Three Gorges Dam?

6. Describe the California Water Project and the controversy over this water transfer project. Describe the Aral Sea disaster. Describe China's South–North Water Transfer Project.

7. Define **desalination** and distinguish between distillation and reverse osmosis as methods for desalinating water. What are the limitations of desalination and how might they be overcome?

8. What percentage of the world's water is unnecessarily wasted and what are two causes of such waste? Describe four irrigation methods and describe ways to reduce water waste in irrigation in developed and developing countries. List ways to reduce water waste in industry and homes. List ways to use water more sustainably. Describe ways in which you can reduce your use and waste of water.

9. What is a **floodplain** and why do people like to live on floodplains? What are the benefits and drawbacks of floods? List three human activities that increase the risk of flooding. Describe the increased risk that many people in Bangladesh face. How can we reduce the risks of flooding?

10. Describe relationships between water conflicts in the Middle East (**Core Case Study**) and the four **scientific principles of sustainability**. CORE CASE STUDY SUSTAINABILITY

Note: Key Terms are in **bold** type.

CRITICAL THINKING

1. List three ways in which you could apply **Concept 13-6** to make your lifestyle more environmentally sustainable.

2. What do you believe are the three most important priorities for dealing with water shortages in parts of the Middle East as discussed in the **Core Case Study** that opens this chapter? Explain your choices. CORE CASE STUDY

3. List three ways in which human activities are affecting the water cycle. How might these effects impact your lifestyle? How might your lifestyle be contributing to these effects?

4. What role does population growth play in water supply problems? Relate this to water supply problems in the Middle East (**Core Case Study**) and in the U.S. city of Las Vegas, Nevada. CORE CASE STUDY

5. How do human activities increase the harmful effects of prolonged drought? Which of these activities are historical, and which are ongoing? Suggest ways to alter some of these activities in order to make them less harmful.

6. Explain why you are for or against **(a)** raising the price of water while providing lower rates for the poor and lower middle class, and **(b)** providing government subsidies to farmers for improving irrigation efficiency.

7. Calculate how many liters and gallons of water are wasted in 1 month by a toilet that leaks 2 drops of water per second. (1 liter of water equals about 3,500 drops and 1 liter equals 0.265 gallon.)

8. How do human activities increase the harmful effects of flooding? Describe an example from the news of how people are trying to change any of these activities to reduce their harmful effects. What are some ways in which other activities can be similarly altered?

9. Congratulations! You are in charge of the world. What are three actions you would take to provide sustainable supplies of water for the world's population?

10. List two questions that you would like to have answered as a result of reading this chapter.

Note: See Supplement 13 (p. S78) for a list of Projects related to this chapter.

ECOLOGICAL FOOTPRINT ANALYSIS

In 2005, the population of the U.S. state of Florida consumed 24.5 billion liters (6.5 billion gallons) of fresh water daily. It is projected that in 2025, the daily consumption will increase to 32.1 billion liters (8.5 billion gallons) per day. Between 2005 and 2025 the population of Florida is projected to increase from 17.5 million to 25.9 million.

1. Based on total fresh water use,
   a. Calculate the per capita consumption of water per *day* in Florida in 2005 and the projected per capita consumption per day for 2025.
   b. Calculate the per capita consumption of water per *year* in Florida in 2005 and the projected per capita consumption per year for 2025.

2. In 2005, how did the Florida's *average water footprint* (consumption per person per year), based only on water used within the state, compare with the average U.S. water footprint of approximately 249,000 liters (66,000 gallons) per person per year and the global average water footprint of 123,770 liters (32,800 gallons) per person per year?

LEARNING ONLINE

Log on to the Student Companion Site for this book at **academic.cengage.com/biology/miller**, and choose Chapter 13 for many study aids and ideas for further reading and research. These include flash cards, practice quizzing, Weblinks, information on Green Careers, and InfoTrac® College Edition articles.

AP* Review Questions for Chapter 13

1. Approximately what percentage of the water on the earth is saltwater?
(A) 97%
(B) 93%
(C) 75%
(D) 60%
(E) 45%

2. The Aral Sea is an area of severe
(A) invasive species intrusion.
(B) flooding.
(C) desertification.
(D) evapotranspiration.
(E) surface runoff.

3. One way to conserve water in agriculture is to employ
(A) dams.
(B) water diversion.
(C) center-pivot irrigation.
(D) adiabatic cooling techniques.
(E) drip irrigation.

4. The Ogallala aquifer is
(A) extremely small with concerns of endangered species.
(B) the largest aquifer in the world and considered non-renewable.
(C) located in China.
(D) undergoing severe salinization.
(E) increasing by about 2 feet per year.

5. The Colorado River project is
(A) extremely eutrophic.
(B) an untapped natural resource.
(C) a government-subsidized water utility.
(D) a large-scale water diversion project.
(E) a confined aquifer.

Use the following to answer questions 6–9.

(A) Aquifer
(B) Surface water
(C) Groundwater
(D) Water table
(E) Transpiration

6. The freshwater from precipitation and snowmelt

7. Evaporation from the leaves of plants into the atmosphere

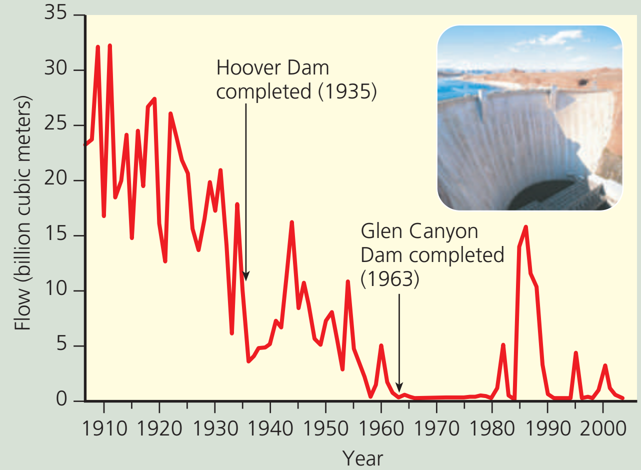
8. Underground caverns and porous layers of sand, gravel, or bedrock through which groundwater flows

9. Upper surface of the zone of saturation

10. A forested hillside will help eliminate
(A) overgrazing.
(B) droughts.
(C) pesticide use.
(D) flooding.
(E) unsustainable farming.

11. One method of desalination is
(A) reverse osmosis.
(B) aquifer depletion.
(C) waterlogging.
(D) acid nitrification.
(E) cellulose framing.

Use the graph below to answer questions 12–14.



12. According to the graph, the flow of the Colorado River has
(A) dropped continually since 1910.
(B) gone up and down but continues to trend downward.
(C) stayed steady over the last 10 years.
(D) dropped steadily from 1935 until 1945.
(E) slowly increased in the last 10 years.

13. What can be inferred about the climate from 1960 to 1980?
(A) There was excessive rainfall.
(B) Rainfall led to variation in flow.
(C) Flow steadily increased.
(D) There was a drought.
(E) Flow was higher than in 1985.

14. What best explains the general downward trend in Colorado River flow from 1910 until 1970?
(A) Damming of the Colorado River
(B) Excessive rainfall
(C) Excessive drought
(D) Farmers utilizing drip irrigation
(E) Utilization of an underground aquifer