CHAPTER 13

Water Resources

> Through the cycling of water, across space and time, we are linked to all life. . . . Water's gift is life. No water, no life.
>
> **SANDRA POSTEL**

Key Questions

13.1 Will we have enough usable water?

13.2 Is groundwater a sustainable resource?

13.3 How can we increase freshwater supplies?

13.4 Can water transfers expand water supplies?

13.5 How can we use freshwater more sustainably?

13.6 How can we reduce the threat of flooding?

Glen Canyon Dam and Lake Mead on the Colorado River, Arizona USA

Pytyczech/Dreamstime.com

The Colorado River Story

FIGURE 13.1 The *Colorado River basin:* The area drained by this river system is more than one-twelfth of the land area of the lower 48 states. This map shows 6 of the river's 14 dams. The photo shows the Hoover Dam and Reservoir of Nevada and Arizona.

The Colorado River, the major river of the arid southwestern United States, flows 2,300 kilometers (1,400 miles) through seven states to the Gulf of California (Figure 13.1, map). Most of its water comes from snowmelt in the Rocky Mountains. During the past 100 years, this once free-flowing river has been tamed by a gigantic plumbing system consisting of 14 major dams and reservoirs (Figure 13.1, photo) and canals that carry water to farmers, ranchers, industries, and cities.

This system of dams and reservoirs provides electricity from its hydroelectric plants to roughly 40 million people in seven states—about one of every eight people in the United States. It supplies irrigation water that is used to produce about 15% of the nation's crops and livestock. It also provides 90% of the drinking water for Las Vegas, Nevada, and large amounts of the water used in Phoenix, Arizona, and San Diego and Los Angeles, California. Take away the Colorado River's dam-and-reservoir system, and these cities would become largely uninhabitable desert areas. In California's Imperial Valley, vast fields of vegetables would eventually give way to cactus and mesquite plants.

So much water is withdrawn from this river to grow crops and support cities in a desert-like climate that very little of it reaches the sea. To make matters worse, since 1999, the system has experienced severe **drought,** a prolonged period, usually a season or more, in which precipitation is lower than normal and evaporation is higher than normal. As a result, in 2015 Lake Mead (chapter-opening photo) sank to a record low water level.

This overuse of the Colorado River illustrates the challenges faced by governments and people living in arid and semiarid regions with shared river systems. There are many of these arid, water-short areas scattered around the globe. In such areas, population growth and economic growth are putting increasing demands on limited or decreasing supplies of surface water.

To many analysts, emerging shortages of water for drinking and irrigation in several parts of the world represent one of the major environmental challenges of this century.

13.1 WILL WE HAVE ENOUGH USABLE WATER?

CONCEPT 13.1A We are using available freshwater unsustainably by extracting it faster than nature can replace it, and by wasting, polluting, and underpricing this irreplaceable natural resource.

CONCEPT 13.1B Freshwater supplies are not evenly distributed, and 1 of every 10 people on the planet does not have adequate access to clean water.

Freshwater Is an Irreplaceable Resource That We Are Managing Poorly

We live on a planet that is unique in our solar system because of a precious layer of water—most of it saltwater—covering about 71% of its surface. Look in the mirror. What you see is about 60% water, most of it inside your cells.

Water is an amazing chemical with unique properties that help to keep us and other species alive (see Science Focus 3.2, p. 64). You could survive for several weeks without food, but for only a few days without **freshwater,** or water that contains very low levels of dissolved salts. We have no substitute for this vital form of natural capital (**Concept 13.1A**).

It takes huge amounts of water to supply food and most of the other things that we use to meet our daily needs and wants. Water also plays a key role in determining the earth's climates and in removing and diluting some of the pollutants and wastes that we produce. And over eons, it has sculpted the planet's surface, creating valleys, canyons, and other land features.

Freshwater is one of the earth's most important forms of natural capital, but despite its importance, it is also one of our most poorly managed resources. We use it inefficiently and pollute it, and we do not value it highly enough. As a result, it is available at too low a cost to billions of consumers, and this encourages waste and pollution of this resource, for which we have no substitute **(Concept 13.1A).**

Access to freshwater is a *global health issue*. The World Health Organization (WHO) has estimated that each day, an average of more than 4,100 people die from waterborne infectious diseases because they do not have access to safe drinking water.

Access to freshwater is also an *economic issue* because water is vital for producing food and energy and for reducing poverty. According to the WHO, just 52% of the world's people have water piped to their homes. The rest have to find and carry it from distant sources or wells. This daily task usually falls to women and children (Figure 13.2).

Shiv Ji Joshi/National Geographic Creative

FIGURE 13.2 Each day these women carry water to their village in a dry area of India.

Water is also a *national and global security issue* because of increasing tensions within and between some nations over access to limited freshwater resources that they share.

Finally, water is an *environmental issue* because excessive withdrawal of freshwater from rivers and aquifers has resulted in falling water tables, dwindling river flows (**Core Case Study**), shrinking lakes, and disappearing wetlands. This, in combination with water pollution in many areas of the world, has degraded water quality, reduced fish populations, hastened the extinction of some aquatic species, and degraded aquatic ecosystem services (see Figures 8.4, p. 170, 8.12, p. 177, and 8.14, p. 179).

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

Only *0.024%* of the planet's enormous water supply is readily available to us as liquid freshwater stored in accessible underground deposits and in lakes, rivers, and streams. The rest is in the salty oceans (about 96.5% of the earth's volume of liquid water), in frozen polar ice caps and glaciers (1.7%), and underground.

Fortunately, the world's freshwater supply is continually recycled, purified, and distributed in the earth's *hydrologic cycle* (see Figure 3.19, p. 63). However, this vital ecosystem service begins to fail when we overload it with water pollutants or withdraw freshwater from underground and surface water supplies faster than natural processes replenish it.

In addition, research indicates that atmospheric warming is altering the water cycle by evaporating more water into the atmosphere. As a result, wet places will get wetter with more frequent and heavier flooding and dry places will get drier with more intense drought.

We have paid little attention to our effects on the water cycle mostly because we have thought of the earth's freshwater as a free and infinite resource. As a result, we have placed little or no economic value on the irreplaceable ecosystem services that water provides (**Concept 13.1A**), a serious violation of the full-cost pricing **principle of sustainability** (see Inside Back Cover). On a global basis, we have plenty of freshwater, but it is not distributed evenly (**Concept 13.1B**). Differences in average annual precipitation and economic resources divide the world's countries and people into water *haves* and *have-nots*. For example, Canada, with only 0.5% of the world's population, has 20% of its liquid freshwater, while China, with 19% of the world's people, has only 6.5% of the supply.

Groundwater and Surface Water Are Critical Resources

Some precipitation soaks into the ground and sinks downward through spaces in soil, gravel, and rock until an impenetrable layer of rock or clay stops it. The freshwater in these underground spaces is called **groundwater**—a key component of the earth's natural capital (Figure 13.3).

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

Deeper down are geological layers called **aquifers,** caverns and porous layers of sand, gravel or rock through which groundwater flows. Some aquifers contain caverns with rivers of groundwater flowing through them. However, most aquifers are like large, elongated sponges where groundwater seeps through porous layers of sand, gravel, or rock—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 freshwater from escaping deeper into the earth.

We use pumps to bring this groundwater to the surface for irrigating crops and supplying households and industries. Most aquifers are replenished, or *recharged*, naturally by precipitation that sinks downward through exposed soil and rock. Others are recharged from the side from nearby lakes, rivers, and streams (Figure 13.3).

According to the U.S. Geological Survey (USGS), groundwater makes up 95% of all freshwater available to us and other forms of life. However, most aquifers recharge slowly. Because so much of the earth's urban area landscapes have been built on or paved over, freshwater can no longer penetrate the ground to recharge aquifers below such areas. And in dry areas of the world, there is little precipitation available to recharge aquifers.

Some aquifers, called *deep aquifers*, were filled with water by glaciers that melted thousands of years ago. For this reason, they are also called *fossil aquifers*. Most of them, because of geological factors, cannot be recharged or will require many thousands of years to recharge. Many are located under coastal seabeds and were formed long ago when sea levels were lower and these areas were part of the land mass. Deep aquifers are nonrenewable, at least on the human timescale.

Another crucial resource is **surface water,** the freshwater from rain and melted snow that flows or is stored in lakes, reservoirs, wetlands, streams, and rivers. Precipitation that does not soak into the ground or return to the atmosphere by evaporation is called **surface runoff.** The land from which surface runoff drains into a particular stream, lake, wetland, or other body of water is called its **watershed,** or **drainage basin.** The drainage basin for the Colorado River is shown in yellow and green on the map in Figure 13.1 (**Core Case Study**).

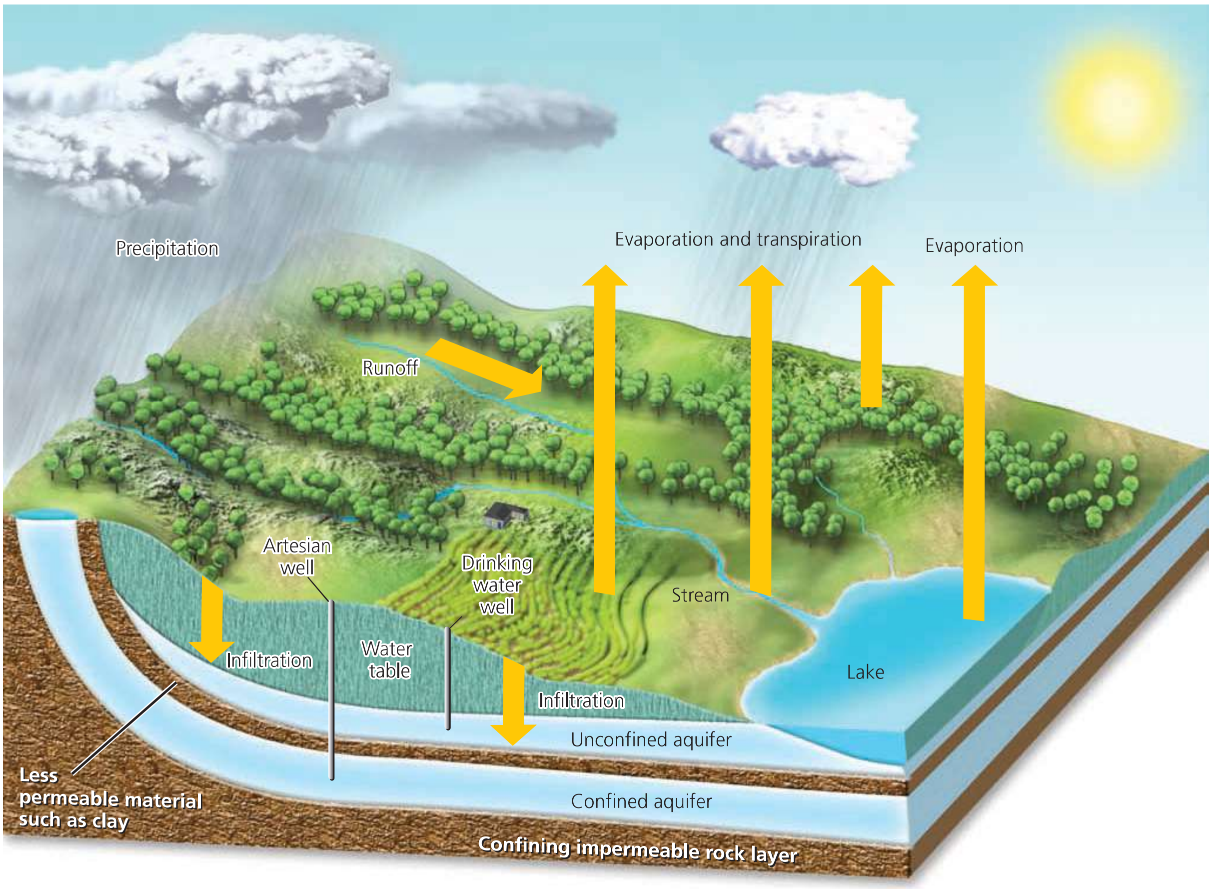


FIGURE 13.3 Natural capital: Much of the water that falls in precipitation seeps into the ground to become groundwater, stored in aquifers.

CONSIDER THIS . . .

CONNECTIONS Groundwater and Surface Water

There is usually a connection between surface water and groundwater because much groundwater flows into rivers, lakes, estuaries, and wetlands. Thus, if we remove groundwater in a particular location faster than it is replenished, nearby streams, lakes, and wetlands can dry up. This process degrades aquatic biodiversity and other ecosystem services.

We Are Using Increasing Amounts of the World's Reliable Runoff

According to *hydrologists*, scientists who study water and its properties and movement, two-thirds of the annual surface runoff of freshwater into rivers and streams is lost in seasonal floods and is not available for human use. The remaining one-third is **reliable surface runoff,** which we can generally count on as a source of freshwater from year to year. **GREEN CAREER: Hydrologist**

During the last century, the human population tripled, global water withdrawals increased sevenfold, and per capita withdrawals quadrupled. As a result, we now withdraw an estimated 34% of the world's reliable runoff. This is a global average. In the arid American Southwest, up to 70% of the reliable runoff is withdrawn for human purposes, mostly for irrigation (**Core Case Study**). Some water experts project that because of population growth, rising rates of water use per person, longer dry periods in some areas, and unnecessary water waste, we are likely to be withdrawing up to 90% of the world's reliable freshwater runoff by 2025.

Worldwide, we use 70% of the freshwater we withdraw each year from rivers, lakes, and aquifers to irrigate cropland and raise livestock. In arid regions, up to 90% of the regional water supply is used for food production. Industry uses roughly another 20% of the water withdrawn globally each year, and cities and residences use the remaining 10%. Our **water footprint** is a rough measure of the volume of freshwater that we use or pollute, directly and indirectly, to stay alive and to support our lifestyles. (See the Case Study that follows for information on U.S. water use.)

FIGURE 13.4 Producing and delivering a single one of each of the products listed here requires the equivalent of nearly one and usually many bathtubs full of freshwater, called *virtual water*. *Note:* 1 bathtub = 151 liters (40 gallons).

(Compiled by the authors using data from UN Food and Agriculture Organization, UNESCO-IHE Institute for Water Education, World Water Council, and Water Footprint Network.)

Bathtub: Baloncici/Shutterstock.com. Coffee: Aleksandra Nadeina/Shutterstock.com. Bread: Alexander Kalina/Shutterstock.com. Hamburger: Joe Belanger/Shutterstock.com. T-shirt: grmarc/Shutterstock.com. Jeans: Eyes wide/Shutterstock.com. Car: L Barnwell/Shutterstock.com. House: Rafal Olechowski/Shutterstock.com

Freshwater that is not directly consumed but is used to produce food and other products is called **virtual water.** It makes up a large part of our water footprints, especially in more-developed countries. Producing and delivering a typical quarter-pound hamburger, for example, takes about 2,400 liters (630 gallons or about 16 bathtubs) of freshwater—most of which is used to grow grain to feed cattle.

Figure 13.4 shows one way to measure the amounts of virtual water used for producing and delivering products. These values can vary depending on how much of the supply chain is included, but they give us a rough estimate of the size of our water footprints.

Because of global trade, the virtual water used to produce and transport products such as coffee and wheat (also called *embedded water*) is often withdrawn as groundwater or surface water in another part of the world. Thus, water can be imported in the form of products, often from countries that are short of water.

The three largest water footprints in the world belong to India, the United States, and China, in that order. Each of these is at least twice the size of any other country's footprint outside of the top three. Large exporters of virtual water—mostly in the form of wheat, corn, soybeans, and other foods—are the European Union, the United States, Canada, Brazil, India, and Australia. Indeed, Brazil's supply of freshwater per person is more than 8 times the U.S. supply per person, 14 times China's supply, and 29 times India's supply. Brazil is becoming one of the world's largest exporters of virtual water. However, prolonged severe droughts in parts of Australia, the United States, and the European Union are stressing the abilities of these countries to meet the growing global demand for their food exports.

CASE STUDY

Freshwater Resources in the United States

According to the USGS, the major uses of groundwater and surface freshwater in the United States are the cooling of electric power plants, irrigation, public water supplies, industry, and livestock production (Figure 13.5, left).

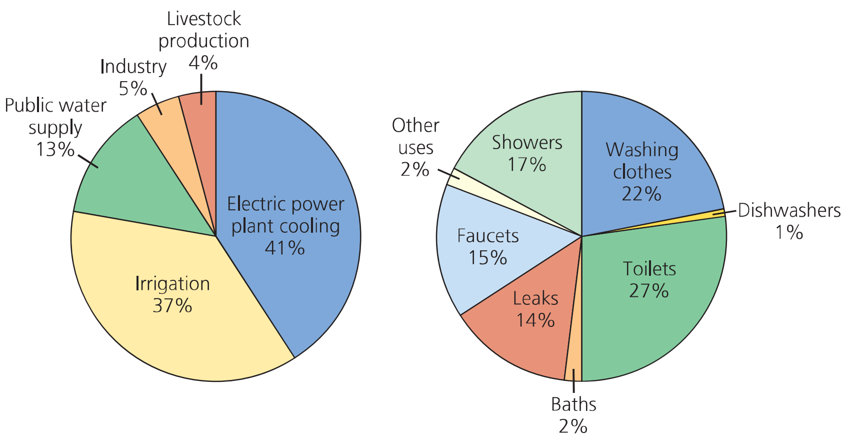


FIGURE 13.5 Comparison of primary uses of water in the United States (left) and uses of water in a typical U.S. household (right). ***Data analysis:*** Which three categories, added together (right), are smaller than the amount of water lost in leaks?

(Compiled by the authors using data from U.S. Geological Survey, World Resources Institute, and American Water Works Association.)

Every day, the average American directly uses between 300 and 377 liters (80 to 100 gallons) of freshwater—enough water to fill at least two typical bathtubs full of water. (A typical bathtub can contain about 151 liters or 40 gallons of water.) Household water is used mostly for flushing toilets, washing clothes, taking showers, and running faucets, or is lost through leaking pipes, faucets, and other fixtures (Figure 13.5, right).

The United States has more than enough renewable freshwater to meet its needs. However, 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 13.6).

In the eastern United States, most water is used for manufacturing and for cooling power plants (with most of the water heated and returned to its source). In many parts of this area, the most serious water problems are flooding, occasional water shortages because of drought, and pollution.

In the arid and semiarid regions of the western half of the United States (**Core Case Study**), irrigation counts for as much as 85% of freshwater use. Much of it is lost to evaporation and a great deal of it is used to grow thirsty crops. The major water problem is a shortage of freshwater runoff caused by low precipitation (Figure 13.6), high evaporation, and recurring prolonged drought.

Groundwater is one of the most precious of all U.S. resources. About half of all Americans (and 95% of all rural residents) rely on it for drinking water. It makes up about half of all irrigation water, feeds about 40% of the country's streams and rivers, and provides about one-third of the water used by U.S. industries.

Water tables in many water-short areas, especially in the dry western states, are dropping quickly as farmers and rapidly growing urban areas draw down many aquifers faster than they can be recharged. In 2010 the USGS estimated total U.S. water withdrawals to be at the lowest level since 1970. However, in 2014 the U.S. Government Accountability Office found that even with per capita water use dropping, water managers from 40 of the 50 states expected water shortages in some areas by 2025 or before. Their projections factored in drought, population growth, urban sprawl, and rising consumption of meat and other water-intensive products.

The U.S. Department of the Interior has mapped out *water hotspots* in 17 western states (Figure 13.7). In these areas, competition for scarce freshwater 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. In addition, Columbia University climate researchers led by Richard Seager used well-tested climate models to project that the southwestern United States is very likely to have long periods of extreme drought throughout most of the rest of this century. According to current research, atmospheric warming does not cause drought. However, it makes a drought worse because warmer temperatures dry out the soil, reducing evaporation of soil moisture, which normally helps reduce drought conditions.

The Colorado River system (Figure 13.1) will be directly affected by such drought. There are three major problems associated with the use of freshwater from this river (**Core Case Study**). *First*, the Colorado River basin includes some

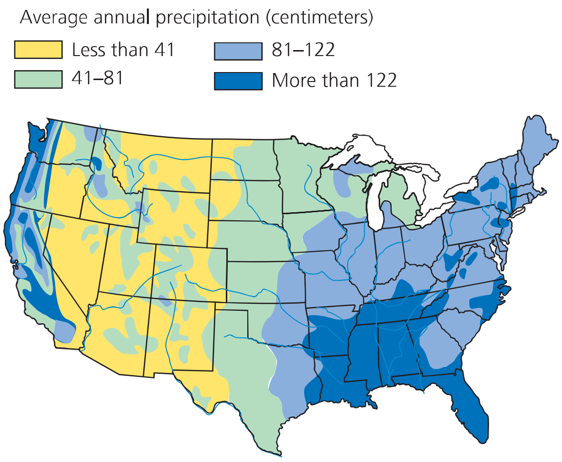


FIGURE 13.6 Long-term average annual precipitation and major rivers in the continental United States.

(Compiled by the authors using data from U.S. Water Resources Council and U.S. Geological Survey.)

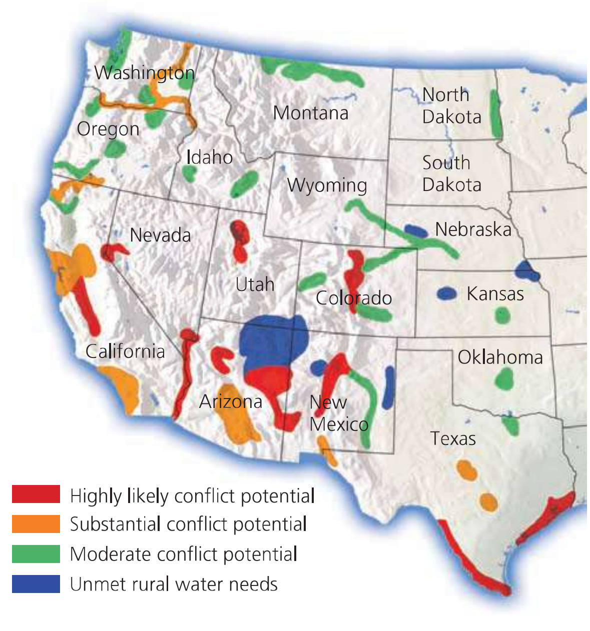


FIGURE 13.7 Water scarcity hotspots in 17 western states that, by 2025, could face intense conflicts over scarce water needed for urban growth, irrigation, recreation, and wildlife. ***Question:*** Which, if any, of these areas are found in the Colorado River basin (**Core Case Study**)?

(Compiled by the authors using data from U.S. Department of the Interior and U.S. Geological Survey.)

of the driest lands in the United States and Mexico. *Second*, long-standing legal agreements between Mexico and the affected western states allocated more freshwater for human use than the river can supply, even in rare years when there is no drought. These pacts allocated no water for protecting aquatic and terrestrial wildlife. *Third*, since 1960, because of drought, damming, and heavy withdrawals, the river has rarely flowed all the way to the Gulf of California and this has severely degraded the river's aquatic ecosystem (which we discuss further later in this chapter).

Freshwater Shortages Will Grow

Freshwater scarcity stress is a measure based on the amount of freshwater available compared to the amount used for human purposes. Like the Colorado River (**Core Case Study**), many of the world's major river systems are highly stressed (Figure 13.8). They include the Nile, Jordan, Yangtze, and Ganges Rivers, whose flows regularly dwindle to almost nothing in some locations.

More than 30 countries—most of them in the Middle East and Africa—now face stress from freshwater scarcity, according to the UN. By 2050, some 60 countries, many of them in Asia, with three-fourths of the world's population, are likely to be suffering from such freshwater scarcity stress. The Chinese government has reported that two-thirds of China's 600 major cities face freshwater shortages.

Currently, about 30% of the earth's land area—a total area roughly 5 times the size of the United States—experiences severe drought. By 2059, as much as 45% of the earth's land surface could experience an even higher level of drought, called *extreme drought*, due to natural cycles and projected climate change, according to a study by climate researcher David Rind and his colleagues.

In 276 of the world's water basins, two or more countries share the available freshwater supplies. However, not all of these countries participate in water-sharing agreements. As a result, international conflicts over water are likely to occur as populations grow, as demand for water increases, and as supplies shrink in many parts of the world.

In 2015 the United Nations (UN) and the WHO reported that about 783 million people—about 2.4 times the U.S. population—did not have regular access to enough clean water for drinking, cooking, and washing, mostly due to poverty (**Concept 13.1B).** The report also noted that more than 2 billion people had gained access to clean water between 1990 and 2012. GOOD NEWS

783 million
Number of people without regular access to clean water

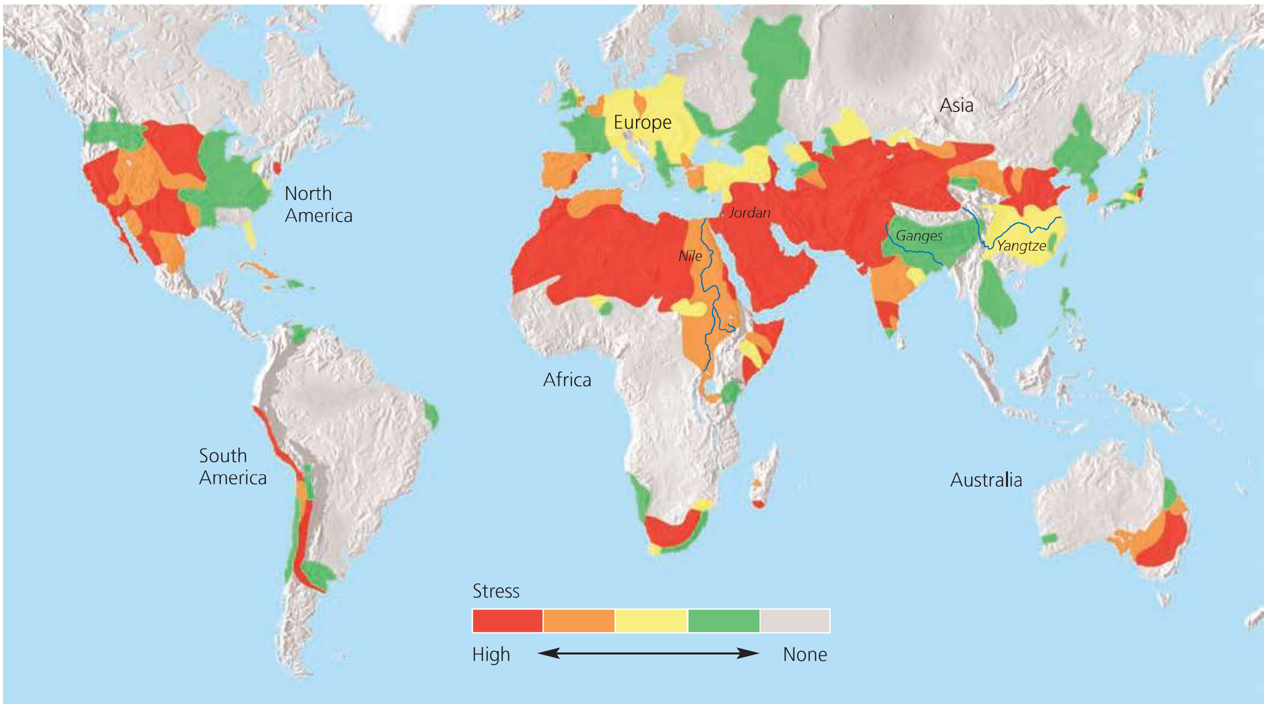


FIGURE 13.8 Natural capital degradation: The world's major river basins differ in their degree of freshwater *scarcity stress* (**Concept 13.1B).**

(Compiled by the authors using data from World Commission on Water Use for the 21st Century, UN Food and Agriculture Organization, and World Water Council.)

SCIENCEFOCUS 13.1

Using Satellites to Monitor Groundwater Supplies

Since 2002, hydrologist Jay S. Famiglietti and his colleagues have been using two twin satellites (Figure 13.A) to measure small variations in the planet's gravitational pull that tell them about changes in ice cover, snow cover, surface water, soil moisture, and groundwater supplies. The two satellites, each the size of a small car, travel in the same orbit, one about 217 kilometers (135 miles) behind the other. They constantly beam microwaves toward each other and can detect changes of less than the diameter of a human hair in this distance between the satellites. When the leading satellite speeds up, increasing the distance, it means the mass of the earth beneath the satellite has increased, tugging a bit harder on the satellite. Various forms of water content on and under the surface of the earth can cause such an increase.

By comparing thousands of these satellite measurements to data from ground measurements and computer modeling, Famiglietti and his team have learned what various changes in the data mean. In 2015 the team reported new data indicating that in 21 of the world's 37 largest aquifers, more water was withdrawn between 2003 and 2013 than had been replaced by snow and rainfall, and some were being depleted rapidly. These aquifers provide freshwater for hundreds of millions of people, and 13 of them were showing little or no recharge over that 10-year period.

For example, in California's agricultural Central Valley, aquifers were drawn down by more than enough to fill Lake Powell, the second-largest reservoir in the United States. According to the scientists, the satellite data indicate that large aquifers in several other areas, including North Africa, northeastern China, and northern India, are also being overpumped. These are all areas where water shortages are worsening every year.

NASA

FIGURE 13.A These twin satellites measure slight variations in the earth's gravitational field that scientists use to detect and measure changes in large bodies of groundwater.

CRITICAL THINKING

If you were a scientist on this team, how would you double-check the data you got from the satellites? (*Hint:* think of other ways to take such measurements.)

Many analysts view the likelihood of expanding water shortages as one of our most serious environmental, health, and economic challenges. Scientists have found a number of ways to obtain information that will help in meeting this challenge, including use of satellites (Science Focus 13.1). In the following section, we will explore some approaches to dealing with water shortages.

CONSIDER THIS . . .

CONNECTIONS Virtual Water, Grain, and Hunger

Some water-short countries are reducing their irrigation water needs by importing grain, thereby freeing up more of their own water supplies for industrial and urban development. The result is a competition for the world's grain, which includes indirect competition for water (virtual water used to grow grain). This competition could increase grain prices, lead to food shortages, and increase hunger among the poor.

13.2 IS GROUNDWATER A SUSTAINABLE RESOURCE?

CONCEPT 13.2 Groundwater used to supply cities and grow food is being pumped from many aquifers faster than it is renewed by precipitation.

Groundwater Withdrawals are Unsustainable in Some Areas

Aquifers provide drinking water for nearly half of the world's people. Most aquifers are renewable resources unless the groundwater they contain becomes contaminated or is removed faster than it is replenished. Relying more on groundwater has advantages and disadvantages (Figure 13.9).

Trade-Offs

Withdrawing Groundwater

Advantages	Disadvantages
Useful for drinking and irrigation	Aquifer depletion from overpumping
Exists almost everywhere	Sinking of land (subsidence) from overpumping
Renewable if not overpumped or contaminated	Some deeper aquifers are nonrenewable
Cheaper to extract than most surface waters	Pollution of aquifers lasts decades or centuries

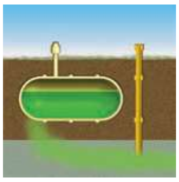


FIGURE 13.9 Withdrawing groundwater from aquifers has advantages and disadvantages. ***Critical thinking:*** Which two advantages and which two disadvantages do you think are the most important? Why?

Top: Ulrich Mueller/Shutterstock.com

Test wells and satellite data (Science Focus 13.1) indicate that water tables are falling in many areas of the world. One reason is that the rate at which water is being pumped out of most of the world's aquifers (mostly to irrigate crops) is greater than the rate of natural recharge from rainfall and snowmelt (**Concept 13.2**). The world's three largest grain producers—China, the United States, and India—as well as Mexico, Saudi Arabia, Iran, Iraq, Egypt, Pakistan, Spain, and other countries are overpumping many of their aquifers.

Every day, the world withdraws enough freshwater from aquifers to fill a convoy of large tanker trucks that could stretch 480,000 kilometers (300,000 miles)—well beyond the distance to the moon. According to the World Bank, in 2012 more than 400 million people were consuming grain produced through this unsustainable use of groundwater. This number is growing.

The widespread drilling of wells by farmers, especially in India and China, has accelerated aquifer overpumping. As water tables fall, farmers drill deeper wells and buy larger pumps to bring more water to the surface. This process eventually depletes the groundwater in some aquifers or at least removes all the water that can be pumped at an affordable cost.

In Saudi Arabia, freshwater has been pumped from a deep, nonrenewable aquifer to irrigate crops such as wheat (Figure 13.10). It also is used to fill fountains and

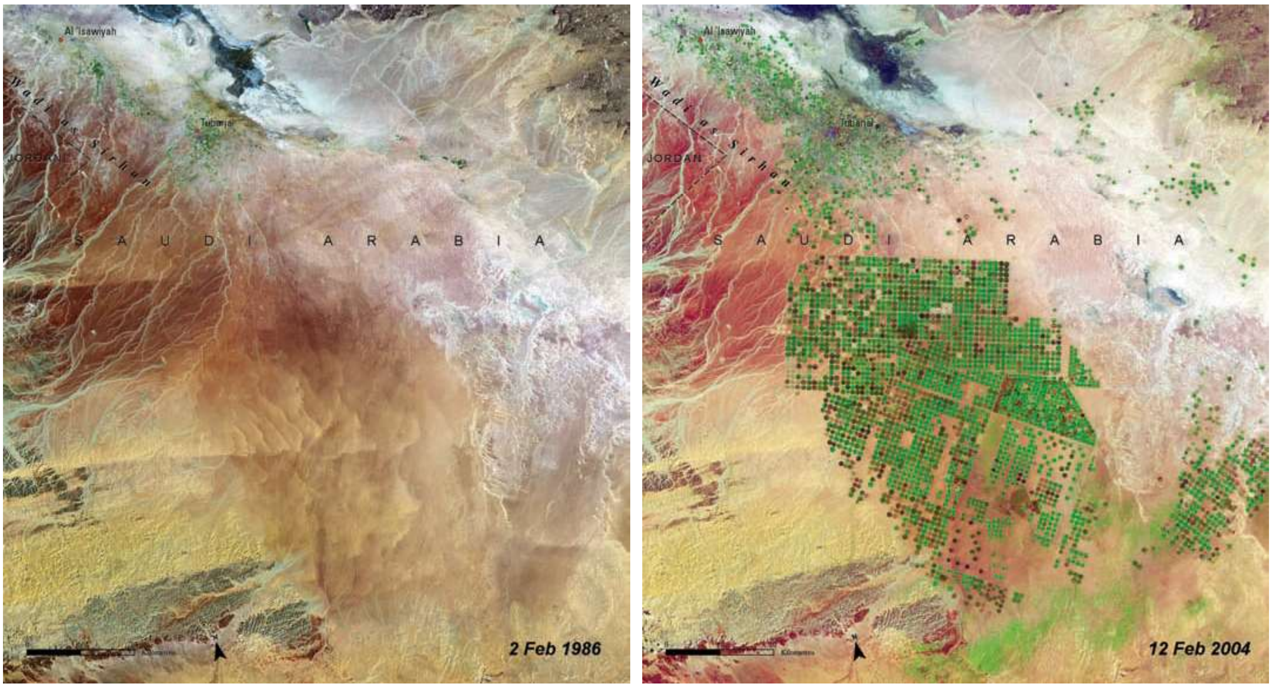


FIGURE 13.10 Natural capital degradation: Satellite photos of farmland irrigated by groundwater pumped from a deep aquifer in a vast desert region of Saudi Arabia between 1986 (left) and 2004 (right). Irrigated areas appear as green dots (each representing a circular spray system) and brown dots show areas where wells have gone dry and the land has returned to desert. Since 2004, many more wells have gone dry.

Left: U.N. Environment Programme and U.S. Geological Survey. Right: U.N. Environment Programme and U.S. Geological Survey.

swimming pools, which lose a great deal of water through evaporation into the dry desert air. In 2008 Saudi Arabia announced that it had largely depleted its major deep aquifer. The country stopped producing wheat in 2016 and will continue to import grain (virtual water) to help feed its 32 million people.

In the United States, aquifer depletion is a growing problem, especially in the vast Ogallala Aquifer (see Case Study that follows).

CASE STUDY

Overpumping the Ogallala Aquifer

In the United States, groundwater is being withdrawn from aquifers, on average, four times faster than it is replenished, according to the USGS. One of the most serious overdrafts of groundwater is in the lower half of the Ogallala Aquifer, one of the world's largest known aquifers, which lies under eight Midwestern states from southern South Dakota to Texas (Figure 13.11).

The Ogallala Aquifer supplies about one-third of all the groundwater used in the United States and turned the Great Plains into one of world's most productive irrigated agricultural regions (Figure 13.12). The Ogallala is essentially a one-time deposit of liquid natural capital with a slow rate of recharge. *Hydrogeologists* (scientists who study groundwater and its movements) estimate that since 1960, we have withdrawn between a third and half of this water and that if it were to be depleted, it could take 6,000 years to recharge naturally.

In parts of the southern half of the Ogallala, groundwater is being pumped out 10–40 times faster than the slow natural recharge rate. This, along with reduced access to Colorado River water (**Core Case Study**) and population growth, has led to the shrinkage of irrigated croplands in Texas, Arizona, Colorado, and California. It has also led to increased competition for water among farmers, ranchers, and growing urban areas.

Government *subsidies*—payments or tax breaks designed to increase crop production—have encouraged farmers to continue growing water-thirsty crops in dry areas, which has accelerated depletion of the Ogallala Aquifer. In particular, corn—a very thirsty crop—has been planted widely on fields watered by the Ogallala.

The aquifer also supports biodiversity. In various places, groundwater from the Ogallala flows out of the ground onto land or onto lake bottoms through exit points called *springs*. In some cases, springs feed wetlands, which are vital habitats for many species, especially birds. When the water tables fall, many of these aquatic oases of biodiversity dry out.

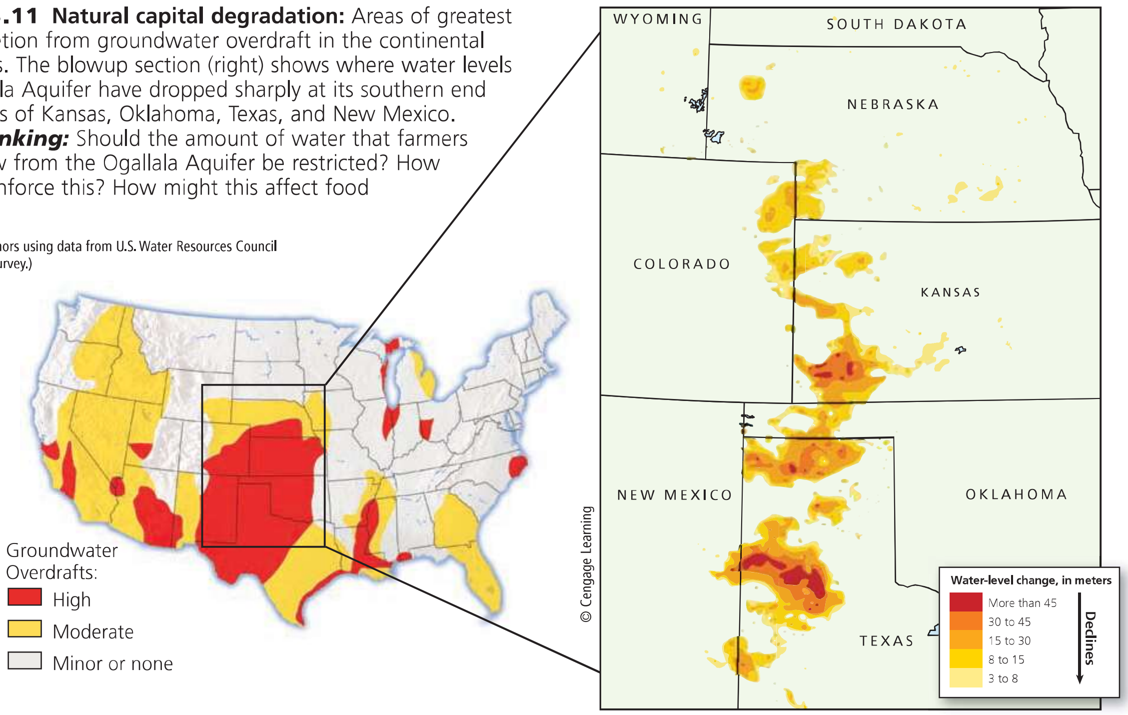
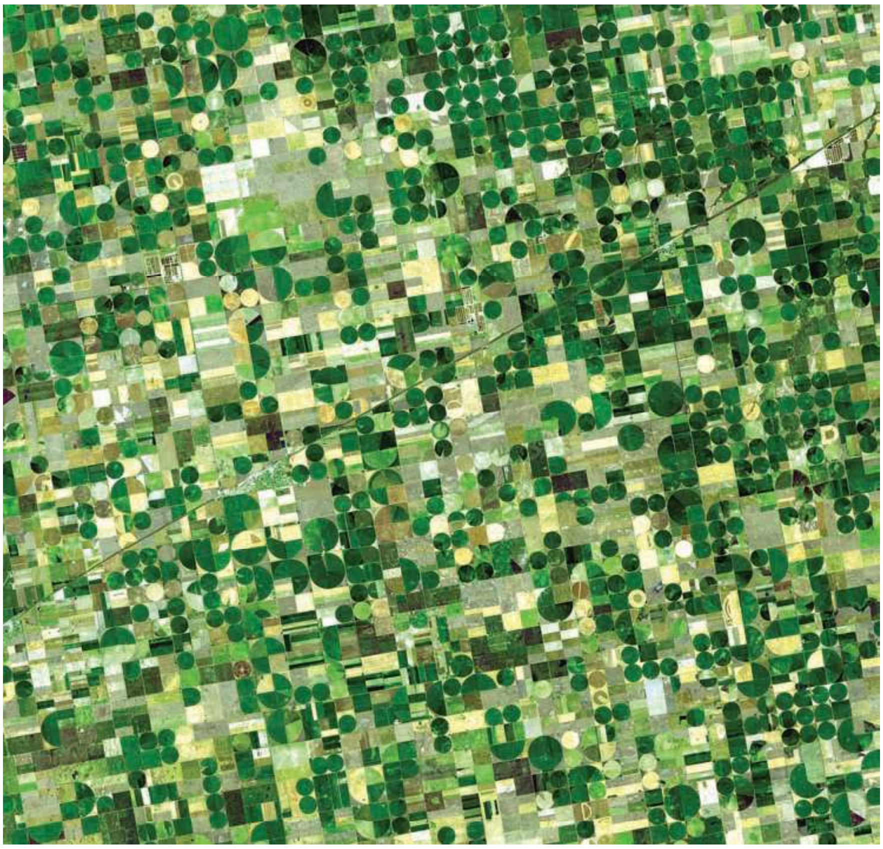


FIGURE 13.11 Natural capital degradation: Areas of greatest aquifer depletion from groundwater overdraft in the continental United States. The blowup section (right) shows where water levels in the Ogallala Aquifer have dropped sharply at its southern end beneath parts of Kansas, Oklahoma, Texas, and New Mexico. ***Critical thinking:*** Should the amount of water that farmers can withdraw from the Ogallala Aquifer be restricted? How would you enforce this? How might this affect food production?

(Compiled by the authors using data from U.S. Water Resources Council and U.S. Geological Survey.)



NASA/GSFC/METI/ERSDAC/JAROS, and U.S./Japan ASTER Science Team

FIGURE 13.12 Satellite photo of crop fields in the U.S. state of Kansas. Center-pivot irrigation uses long, suspended pipes that swing around a central point in each field. Dark green circles are irrigated fields of corn, light green circles are sorghum, and light yellow circles are wheat. Brown areas are fields that have been recently harvested and plowed under. The water used to irrigate these crops is pumped from the Ogallala Aquifer.

CONSIDER THIS . . .

CONNECTIONS Aquifer Depletion in California and Meat Consumption in China

Serious aquifer depletion is also taking place in California's Central Valley where farmers grow alfalfa as a supplemental feed for cattle and dairy cows. Alfalfa requires more water than any other crop in California. Because alfalfa growers make more money by shipping most of their crop to China, they export billions of gallons of virtual water from this drought-ridden area of California to China to support that country's growing consumption of meat and milk.

Overpumping Aquifers Can Have Harmful Effects

Overpumping aquifers contributes to limits on food production, rising food prices, and widening gaps between the rich and poor in some areas. This in turn can lead to rising hunger and social unrest. Much of the Middle East is facing such a crisis and increasing tensions among nations, brought on partly by falling water tables and rapid population growth.

Also, as water tables drop, the energy and financial costs of pumping the water from lower depths rise sharply because farmers must drill deeper wells, buy larger pumps, and use more electricity to run the pumps. Poor farmers cannot afford such costs and often lose their land. This forces them to work for richer farmers or to migrate to cities that are crowded with people struggling to survive.

Withdrawing large amounts of groundwater sometimes causes the sand and rock that is held in place by water pressure in aquifers to collapse. This can cause the land above the aquifer to *subside* or sink, a phenomenon known as *land subsidence*. Extreme and sudden subsidence, sometimes referred to as a *sinkhole*, can swallow cars and houses. Once an aquifer becomes compressed by subsidence, recharge is impossible. Land subsidence can also damage roadways, water and sewer lines, and building foundations.

Since 1925, overpumping of an aquifer to irrigate crops in California's San Joaquin Valley has caused half of the valley's land to subside by more than 0.3 meter (1 foot) and, in one area, by more than 8.5 meters (28 feet) (Figure 13.13). Mexico City and parts of Beijing, China, also suffer from severe subsidence problems.

Groundwater overdrafts in coastal areas, where many of the world's largest cities and industries are found, can pull saltwater into freshwater aquifers. The resulting

Dick Ireland/U.S. Geological Survey

FIGURE 13.13 This pole shows subsidence from overpumping of an aquifer for irrigation in California's San Joaquin Central Valley between 1925 and 1977. In 1925 this area's land surface was near the top of the pole. Since 1977, this problem has gotten worse.

contaminated groundwater is undrinkable and unfit for irrigation. This problem is especially serious in coastal areas of the U.S. states of California, Texas, Florida, Georgia, South Carolina, and New Jersey, as well as in coastal areas of Turkey, Thailand, and the Philippines.

Figure 13.14 lists ways to prevent or slow the problem of aquifer depletion by using this potentially renewable resource more sustainably. The challenge is to educate people about the dangers of depleting vital underground supplies of water that they cannot see.

Deep Aquifers Might Be Tapped

With global shortages of freshwater looming, scientists are evaluating deep aquifers as future sources of freshwater. Preliminary results suggest that some of these aquifers hold enough freshwater to support billions of people for centuries.

There are five major problems related to tapping these ancient deposits of freshwater. *First,* they are nonrenewable on a human time scale. *Second,* little is known about the geological and ecological impacts of pumping large amounts of freshwater from deep aquifers, especially those located under seabeds. *Third,* no international treaties govern access to deep aquifers that flow beneath more than one country. Without such treaties, wars could break out over this resource. *Fourth,* the costs of tapping deep aquifers are unknown and could be high. *Fifth,* recent research indicates that much of this water is salty and contaminated with arsenic and uranium.

Recent research indicates that the supply of freshwater available from renewable aquifers not too far underground is smaller than previous estimates. Thus, our current unsustainable use of many of these aquifers is a serious environmental problem that threatens this vital source of freshwater.

Solutions

Groundwater Depletion

Prevention	Control
Use water more efficiently	Raise price of water to discourage waste
Subsidize water conservation	Tax water pumped from wells near surface water
Limit number of wells	Build rain gardens in urban areas
Stop growing water-intensive crops in dry areas	Use permeable paving material on streets, sidewalks, and driveways

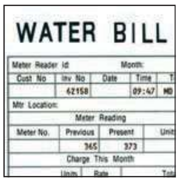


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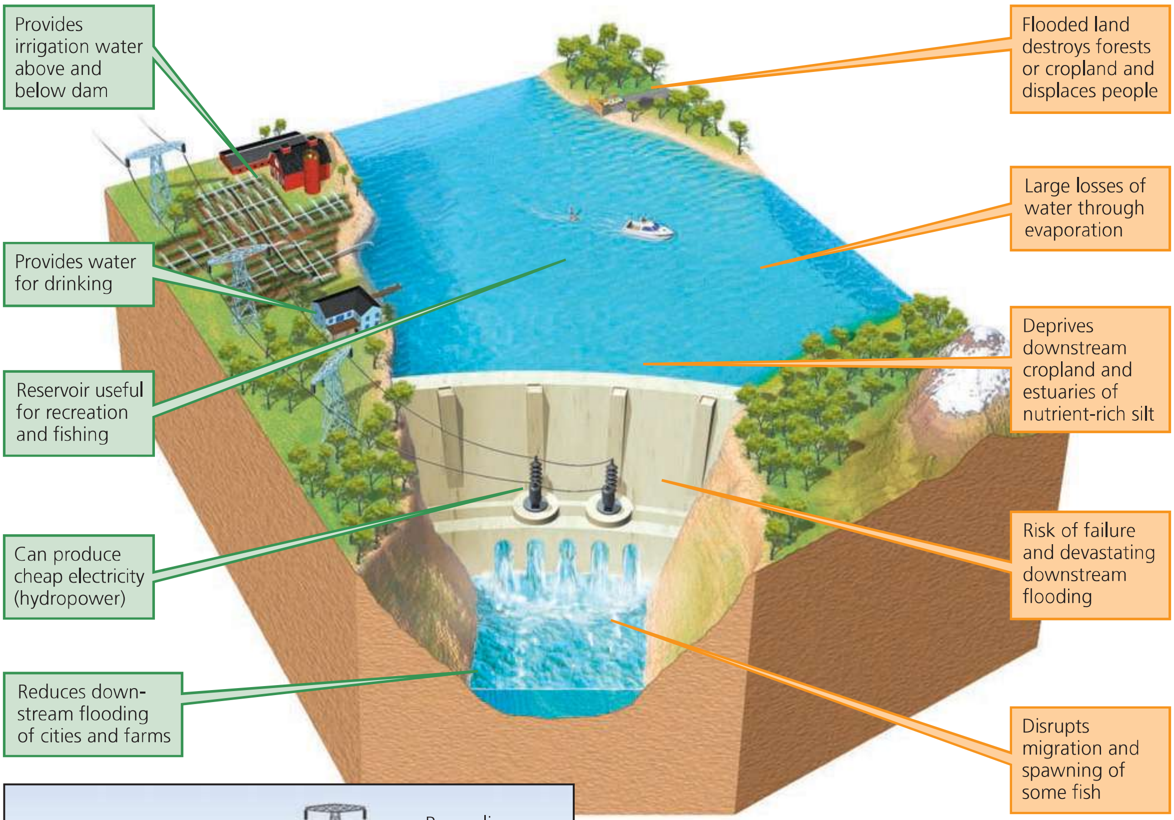
FIGURE 13.14 Ways to prevent or slow groundwater depletion by using freshwater more sustainably. ***Critical thinking:*** Which two of these solutions do you think are the most important? Why?

Top: Anhong/Dreamstime.com. Bottom: Banol2007/Dreamstime.com.

13.3 HOW CAN WE INCREASE FRESHWATER SUPPLIES?

CONCEPT 13.3A Large dam-and-reservoir systems and water transfer projects have greatly expanded water supplies in some areas, but have also disrupted ecosystems and displaced people.

CONCEPT 13.3B We can convert salty ocean water to freshwater, but the energy and other costs are high, and the resulting salty brine must be disposed of without harming aquatic or terrestrial ecosystems.



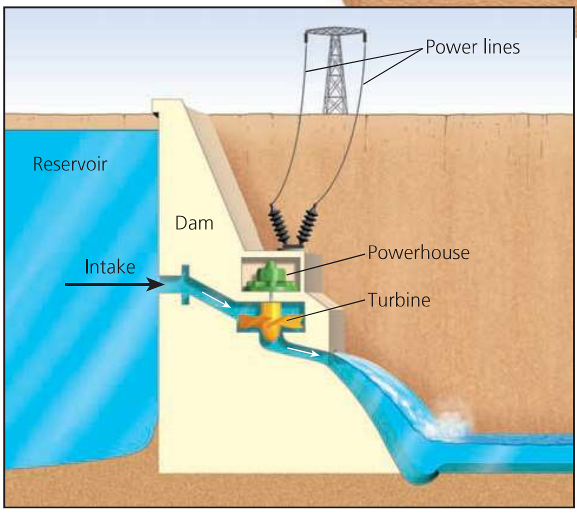


FIGURE 13.15 Trade-offs: Large dam and reservoir systems have advantages (green) and disadvantages (orange) (**Concept 13.3**). ***Critical thinking:*** Which single advantage and which single disadvantage do you think are the most important? Why?

Large Dams Provide Benefits and Create Problems

A **dam** is a structure built across a river to control its flow. Usually, dammed water creates an artificial lake, or **reservoir,** behind the dam (chapter-opening photo). The purpose of a dam-and-reservoir system is to capture and store the surface runoff from a river's watershed, and release it as needed to control floods, to generate electricity (hydropower), and to supply freshwater for irrigation and for towns and cities. Reservoirs also provide recreational activities such as swimming, fishing, and boating. Large dams and reservoirs provide benefits but they also have drawbacks (Figure 13.15).

Six of every ten of the world's rivers have at least one dam, and the total number of dams worldwide is estimated to be 800,000. The world's 45,000 large dams—those that are 15 meters (49 feet) or higher—capture and store about 14% of the world's surface runoff. They provide water for almost half of all irrigated cropland and supply more than half the electricity used in 65 countries. The United States has about 75,000 dams, according to the U.S. Army Corps of Engineers. They capture and store about half of the country's entire river flow.

Dams have increased the annual reliable runoff available for our uses by nearly 33%. As a result, the world's reservoirs now hold 3–6 times more freshwater than the total amount flowing at any moment in all of the world's natural rivers. On the downside, this engineering approach to river management has displaced 40 million to 80 million people from their homes and impaired some of the important ecosystem services that rivers provide (see Figure 8.14, left, p. 179) (**Concept 13.3A**).

A study by the World Wildlife Fund (WWF) estimated that about one out of five of the world's freshwater fish and plant species are either extinct or endangered, primarily because dams and water withdrawals have sharply decreased certain river flows. The study found that only 21 of the planet's 177 longest rivers consistently run all the way to the sea before running dry. As a result, aquatic habitat along rivers and at their mouths has been severely degraded (see Case Study that follows).

Within 50 years, reservoirs behind dams typically fill up with sediments (mud and silt), which makes them useless for storing water or producing electricity. In the Colorado River system (**Core Case Study**), the equivalent of roughly 20,000 dump-truck loads of silt are deposited on the bottoms of the Lake Powell and Lake Mead reservoirs every day. Eventually, these two reservoirs will be too full of silt to function as designed. According to American Rivers, almost 1,000 U.S. dams were removed between 1976 and 2014. More dams will be removed as they fill with silt, because about 85% of all U.S. dam-and-reservoir systems will be 50 years old or more by 2025.

If climate change occurs as projected, it will intensify shortages of water in many parts of the world. For example, mountain snows that feed the Colorado River system (**Core Case Study**) will melt faster and earlier, making less freshwater available to the river system when it is needed for irrigation during hot and dry summer months.

If some of the Colorado River's largest reservoirs keep dropping dramatically or become filled with silt during this century, the region will experience costly water and economic disruptions. For example, by 2013, the water level in Lake Mead had dropped below the Hoover Dam's intake pipes. The city of Las Vegas has been forced to spend more than $800 million to build lower intake pipes in order to maintain hydroelectric production.

Also likely are political and legal battles over who will get how much of the region's greatly diminished freshwater supply. Agricultural production would drop sharply and the region's major desert cities would be challenged to survive. A report from the U.S. Bureau of Reclamation concluded that over the next 50 years, the Colorado River will not be able to meet the projected water demands of Arizona, New Mexico, and California.

Nearly 3 billion people in South America, China, India, and other parts of Asia—that is, nearly half the world's population—depend on river flows fed by mountain glaciers, which act like aquatic savings accounts. They store precipitation as ice and snow in wet periods and release it slowly during dry seasons for use on farms and in cities. In 2015, according to the World Glacier Monitoring Service, many of these mountain glaciers had been shrinking for 24 consecutive years, mostly due to a warming atmosphere.

CASE STUDY

How Dams Can Kill an Estuary

Since 1905, the amount of water flowing to the mouth of the Colorado River (**Core Case Study**) has dropped dramatically. In most years since 1960, the river has dwindled to a small, sluggish stream by the time it reaches the Gulf of California (Figure 13.16).

The Colorado River once emptied into a vast *delta*, the wetland area at the mouth of a river containing the river's estuary. The delta covered an area of more than 800,000 hectares (2 million acres)—the size of the state of Rhode Island. It hosted forests, lagoons, and marshes rich in plant and animal life and supported a thriving coastal fishery for hundreds of years.

Since the damming of the Colorado River—within one human lifetime—this biologically diverse delta ecosystem has collapsed and is now covered mostly by mud flats and desert. All but one-tenth of the river's flow was diverted for use in seven U.S. states. Most of the remaining 10% is assigned to farms and to the growing cities of Mexicali and Tijuana in Mexico. The delta's wildlife are now mostly gone and its coastal fishery that fed many generations of area residents is disappearing.

Historically, about 80% of the water withdrawn from the Colorado has been used to irrigate crops and raise cattle. That is because the government paid for the dams and reservoirs and has supplied many farmers and ranchers with water at low prices. These government subsidies

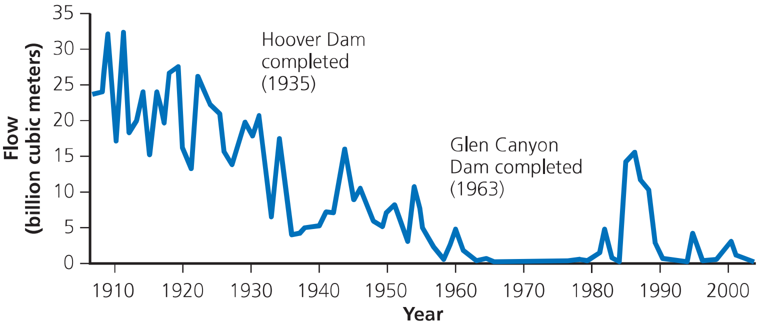


FIGURE 13.16 The measured flow of the Colorado River (**Core Case Study**) at its mouth has dropped sharply since 1905 as a result of multiple dams, water withdrawals for agriculture and urban areas, and prolonged drought. ***Data analysis:*** How much higher than the highest flow after 1935 (when the Hoover Dam was built) was the highest flow before 1935?

(Compiled by the authors using data from U.S. Geological Survey.)

have led to inefficient use of irrigation water for growing thirsty crops such as rice, cotton, almonds, and alfalfa.

In 2014 the floodgates of the Morelos Dam near Yuma, Arizona, were opened for 2 months to send Colorado River water through the delta to the Gulf of California for the first time in years. Researchers are evaluating the effects of this experiment, but short-term results were dramatic, according to National Geographic Fellow and water policy expert Sandra Postel. Thousands of trees began to grow along the river's banks and groundwater in the delta area was partially recharged for the first time in many years.

Water experts call for the seven states using the Colorado River to enact and enforce strict water conservation measures. They also call for phasing out state and federal government subsidies for agriculture in this region, shifting water-thirsty crops to less arid areas, and banning or severely restricting the watering of golf courses and lawns in the desert areas of the Colorado River basin. They suggest that the best way to implement such solutions is to sharply raise the historically low price of the river's freshwater over the next decade—another application of the full-cost pricing **principle of sustainability**.

CONSIDER THIS . . .

THINKING ABOUT The Colorado River

What are three steps you would take to deal with the problems of the Colorado River system?

Removing Salt from Seawater to Provide Freshwater

Desalination is the process of removing dissolved salts from ocean water or from brackish (slightly salty) water in aquifers or lakes. It is another way to increase supplies of freshwater.

The two most widely used methods for desalinating water are distillation and reverse osmosis. *Distillation* involves heating saltwater until it evaporates (leaving behind salts in solid form) and condenses as freshwater. *Reverse osmosis* (or *microfiltration*) uses high pressure to force saltwater through a membrane filter with pores small enough to remove the salt and other impurities.

According to the International Desalination Association, there are more than 17,000 desalination plants operating in 150 countries. Most of them arid nations of the Middle East, North Africa, the Caribbean Sea, and the Mediterranean Sea. In 2013 the number of U.S. plants was 324 and growing. Desalination supplies less than 1% of the demand for freshwater in the United States and in the world.

There are three major problems with the widespread use of desalination. *First* is the high cost, because it takes a lot of energy to remove salt from seawater. A *second* problem is that pumping large volumes of seawater through pipes requires the use of chemicals to sterilize the water and to keep down algae growth. This kills many marine organisms and requires large inputs of energy and money. *Third*, desalination produces huge quantities of salty wastewater that must be disposed of. Dumping it into nearby coastal ocean waters increases the salinity of those waters, which can threaten food resources and aquatic life, especially near coral reefs, marshes, and mangrove forests. Disposing of it on land could contaminate groundwater and surface water (**Concept 13.3B**).

Currently, desalination is practical only for water-short countries and cities that can afford its high cost. However, scientists and engineers are working to develop better and more affordable desalination technologies (Science Focus 13.2).

CONSIDER THIS . . .

LEARNING FROM NATURE

Scientists are trying to develop more efficient and affordable ways to desalinate seawater by mimicking how our kidneys take salt out of water and how fish in the sea survive in saltwater.

13.4 CAN WATER TRANSFERS EXPAND WATER SUPPLIES?

CONCEPT 13.4 Transferring water from one place to another has greatly increased water supplies in some areas but has also disrupted ecosystems.

Water Transfers Have Benefits and Drawbacks

In some heavily populated dry areas of the world, governments have tried to solve water shortage problems by transferring water from water-rich areas to water-poor areas. For example, in northern China, rapidly growing cities, including Beijing with 21 million people, have helped to deplete underlying aquifers. According to the Chinese Academy of Sciences, two-thirds of China's 669 major cities have water shortages. In addition, about 300 million rural residents—a number almost equal to the size of the U.S. population—do not have access to safe drinking water. To deal with this problem, the Chinese government is implementing its *South–North Water Diversion Project* to transfer water from the Yangtze River in southern China to the thirsty north.

In other cases, water has been transferred to arid areas primarily to irrigate farm fields. When you have lettuce in a salad in the United States, it was probably grown in the arid Central Valley of California, partly with

SCIENCEFOCUS 13.2

The Search for Better Desalination Technology

Reverse osmosis (Figure 13.B, left) is the favored desalination technology because it requires much less energy than distillation, but it is still energy intensive. In this process, high pressure is applied to seawater in order to squeeze the freshwater out of it. The membrane that filters out the salt must be strong enough to withstand such pressure. Seawater must be pretreated and treated again after desalination to make it pure enough for drinking and for irrigating crops.

Much of the scientific research in this field is aimed at improving the membrane and the pre- and post-treatment processes to make desalination more energy efficient. Scientists are working to develop new, more efficient and affordable membranes that can separate freshwater from saltwater under lower pressure, which would require less energy. One promising material that might serve this purpose is one-atom-thick graphene (see Chapter 14, Case Study, p. 369). Such technological advances have brought the cost of desalination down, but not enough yet to make it affordable or useful for large-scale irrigation or to meet much of the world's demand for drinking water.

At the University of Texas, doctoral student Kyle Knust has invented the Waterchip—a small device that removes salt from saltwater using an electrical current. Water flows down a Y-shaped channel and where it splits, an electrode emits a charge that separates water from salt. Knust says this small-scale device could be scaled up to produce larger amounts of desalinated water using half the energy of an osmosis plant. A team of scientists at the Massachusetts Institute of Technology (MIT), led by Martin Z. Bazant, is evaluating the use of an electric shock to separate saltwater and freshwater.

Scientists are considering ways to use solar and wind energy—applying one of the three **scientific principles of sustainability** (see Inside Back Cover)—in combination with conventional power sources to help bring down the cost of desalinating seawater. In 2012 Saudi Arabia completed the world's largest solar-powered desalination project. It uses concentrated solar energy to power new filtration technology at a plant that will meet the daily water needs of 100,000 people.

Two Australian companies, Energetech and H2AU, have joined forces to build an experimental desalination plant that uses the power generated by ocean waves to drive reverse-osmosis desalination. This approach produces no air pollution and uses renewable energy. Some scientists argue for building fleets of such floating desalination plants. They could operate out of sight from coastal areas and transfer the water to shore through seabed pipelines or in food-grade shuttle tankers. Because of their distance from shore, the ships could draw water from depths below where most marine organisms are found. The resulting brine could be returned to the ocean and diluted far away from coastal waters.

These methods would cut the costs of desalination, but they would still be high. Analysts expect desalination to be used more widely in the future, as water shortages become worse. However, there is still a lot of research to do before desalination can become an affordable major source of freshwater. **GREEN CAREER: Desalination engineer**

CRITICAL THINKING

Do you think that improvements in desalination will justify highly inefficient uses of water, such as maintaining swimming pools, fountains, and golf courses in desert areas? Explain.

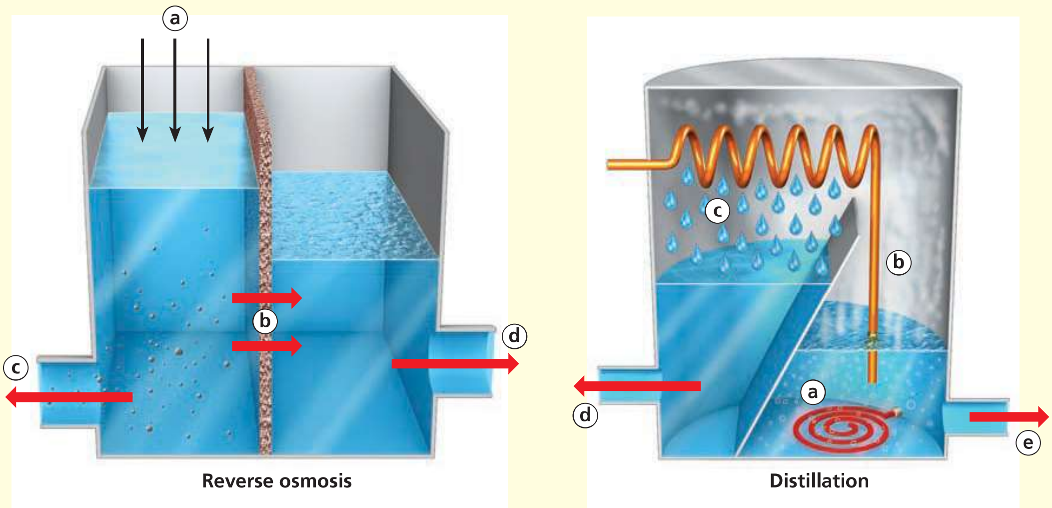


FIGURE 13.B *Desalination:* Reverse osmosis (left) involves applying high pressure **(a)** to force sea water from one chamber into another through a semipermeable membrane **(b)** that separates the salt **(c)**, producing freshwater **(d)**. Distillation (right) involves heating sea water **(a)** to produce steam **(b)**, which is then condensed **(c)** and collected as freshwater **(d)**, while brine is also collected **(e)** for processing.

the use of irrigation water from snow melting off the tops of the High Sierra Mountains of northeastern California. The California State Water Project (Figure 13.17) is one of the world's largest freshwater transfer projects. It uses a maze of giant dams, pumps, and lined canals, or *aqueducts* (photo in Figure 13.17), to transfer freshwater from the mountains to heavily populated cities and agricultural regions in water-poor central and southern California.

These massive water transfers have yielded many benefits. Some 440 million Chinese will be served by the South–North Water Diversion Project. California's Central Valley supplies half of the United States' fruits and vegetables, and the cities of San Diego and Los Angeles have grown and flourished because of the water transfer.

However, water transfers also have high environmental, economic, and social costs. They usually involve large water losses, through evaporation and leaks in the water-transfer systems. They also degrade ecosystems in areas from which the water is taken (**Concept 13.4**). China's water transfer—moving 23 trillion liters (6 trillion gallons of water) per year—will be expensive. It will displace more than 350,000 villagers who will have to move from lands they have farmed for generations. And scientists worry that removing huge volumes of water from the Yangtze River could severely damage its ecosystem, which has been suffering from its worst drought in 50 years.

In California, sending water south has degraded the Sacramento River and reduced the flushing action that helps to cleanse the San Francisco Bay of pollutants. As a result, the bay has suffered from pollution and the flow of freshwater to its coastal marshes and other ecosystems has dropped, putting stress on wildlife species that depend on these ecosystems. Water was also diverted from streams that flow into Mono Lake, an important feeding stop for migratory birds. This lake experienced an 11-meter (35-foot) drop in its water level before the diversions were stopped. For a while, the lake's entire ecosystem was in jeopardy.

Federal and state governments typically subsidize water transfers. In the California project, subsides have promoted inefficient use of large volumes of water to irrigate thirsty crops such as lettuce, alfalfa, and almonds in desert-like areas. In central California, agriculture consumes three-fourths of the water that is transferred, and much of it is lost through inefficient irrigation systems. Studies show that making irrigation just 10% more efficient would provide

Sarah Leen/National Geographic Creative

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FIGURE 13.17 The California State Water Project transfers huge volumes of freshwater from one watershed to another. The arrows on the map show the general direction of water flow. The photo shows one of the aqueducts carrying water within the system. ***Critical thinking:*** What effects might this system have on the areas from which the water is taken?

all the water necessary for domestic and industrial uses in southern California.

According to several studies, climate change will make matters worse in many areas where water is being removed for transfers. In southern China, climate change could intensify and prolong the drought and create a need for an even larger and more expensive transfer of water. California depends on *snowpacks*, bodies of densely packed, slowly melting snow in the High Sierra Mountains, for more than 60% of its freshwater, according to the Sierra Nevada Conservancy. Projected atmospheric warming could shrink the snowpacks by as much as 40% by 2050 and by as much as 90% by the end of this century. This will sharply reduce the amount of freshwater available for northern residents and ecosystems, as well for the transfer of water to central and southern California.

There are many other examples around the world of water transfers that have resulted in environmental degradation (see the following Case Study).

CASE STUDY

The Aral Sea Disaster: An Example of Unintended Consequences

The shrinking of the Aral Sea (Figure 13.18) is the result of a water transfer project in central Asia. Starting in 1960, enormous amounts of irrigation water were diverted from the two rivers that supply water to the Aral Sea. The goal was 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)—roughly the distance between the two U.S. cities of Boston, Massachusetts, and Chicago, Illinois.

This project, coupled with drought 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 an amount roughly equal to the height of a six-story building. The Southern Aral Sea has lost 90% of its volume of water and most of its lake bottom is now a white salt desert (Figure 13.18, right photo). Water withdrawals reduced the two rivers feeding the sea to mere trickles.

About 85% of the area's wetlands have been eliminated and about half the local bird and mammal species have disappeared. The sea's greatly increased salt concentration—three times saltier than ocean water—has caused the presumed local 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 a salty desert.

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.

The shrinkage of the Aral Sea has also altered the area's climate. The shrunken sea no longer acts as a thermal buffer to moderate 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.

1976 **2015**

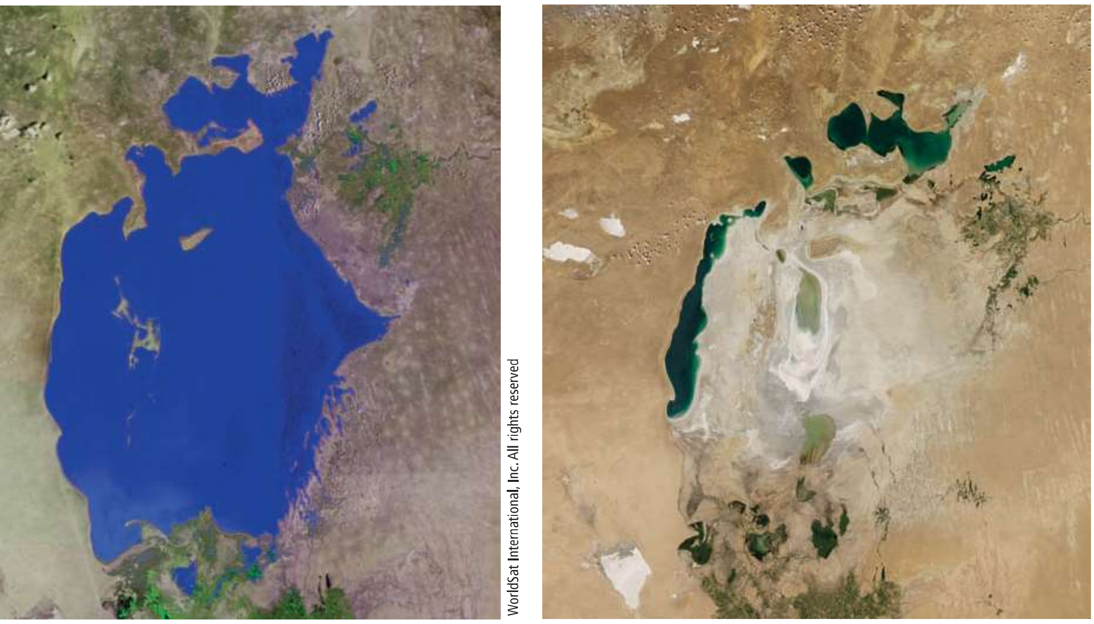


FIGURE 13.18 Natural capital degradation: The *Aral Sea*, straddling the borders of Kazakhstan and Uzbekistan, was one of the world's largest saline lakes. These satellite photos show the sea in 1976 (left) and in 2015 (right). ***Question:*** What do you think should be done to help prevent further shrinkage of the Aral Sea?

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—the opposite of the project's intended effects.

Since 1999, the UN, the World Bank, and the five countries surrounding the lake have worked to improve irrigation efficiency. They have also partially replaced thirsty crops with other crops that require less irrigation water. Because of a dike built to block the flow of water from the Northern Aral Sea into the southern sea, the level of the northern sea has risen by 2 meters (7 feet), its salinity has dropped, dissolved oxygen levels are up, and it supports a healthy fishery.

However, the formerly much larger southern sea is still shrinking. By 2012, its eastern lobe was essentially gone (Figure 13.18, right photo). The European Space Agency projects that the rest of the Southern Aral Sea could dry up completely by 2020.

13.5 HOW CAN WE USE FRESHWATER MORE SUSTAINABLY?

CONCEPT 13.5 We can use freshwater more sustainably by cutting water waste, raising water prices, slowing population growth, and protecting aquifers, forests, and other ecosystems that store freshwater.

Cutting Water Waste Would Have Many Benefits

According to water resource expert Mohamed El-Ashry of the World Resources Institute, about 66% of the freshwater used in the world and about 50% of the freshwater used in the United States is lost through evaporation, leaks, and inefficient use. El-Ashry estimates that it is economically and technically feasible to reduce such losses to 15%, thereby meeting most of the world's future freshwater needs.

Why do we have such large losses of freshwater? According to water resource experts, there are two major reasons. First, the cost of freshwater to most users is low due mostly to government subsidies—a violation of the full-cost pricing **principle of sustainability**. This gives users little or no financial incentive to invest in water-saving technologies.

Higher prices for freshwater 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*, which give each household a set amount of free or low-priced water to meet basic needs. When users exceed this amount, they pay increasingly higher prices as their water use increases. This is a *user-pays* approach.

The second major cause of unnecessary waste of freshwater is a lack of government subsidies for improving the efficiency of water use. Withdrawing some of the subsidies that encourage inefficient water use and replacing them with subsidies for more efficient water use would sharply reduce water losses. Understandably, farmers and industries that receive subsidies that keep water prices low have vigorously opposed efforts to eliminate or reduce them.

We Can Improve Efficiency in Irrigation

Since 1980, the amount of food that can be grown per drop of water has roughly doubled. In addition, since the 1970s, the amount of water used per person in the United States has dropped by about 33%, after rising for decades. Most of these water savings have come from improvements to irrigation efficiency in the United States and other more-developed countries.

GOOD NEWS

However, there is still a long way to go, especially in less-developed countries. Only about 60% of the world's irrigation water reaches crops, which means that most irrigation systems are highly inefficient. The most inefficient system, commonly used in less-developed countries, is *flood irrigation*. With this method, water is pumped from a groundwater or surface water source through unlined ditches where it flows by gravity to the crops being watered (Figure 13.19, left). This method delivers far more water than is needed for crop growth, and typically, about 45% of it is lost through evaporation, seepage, and runoff.

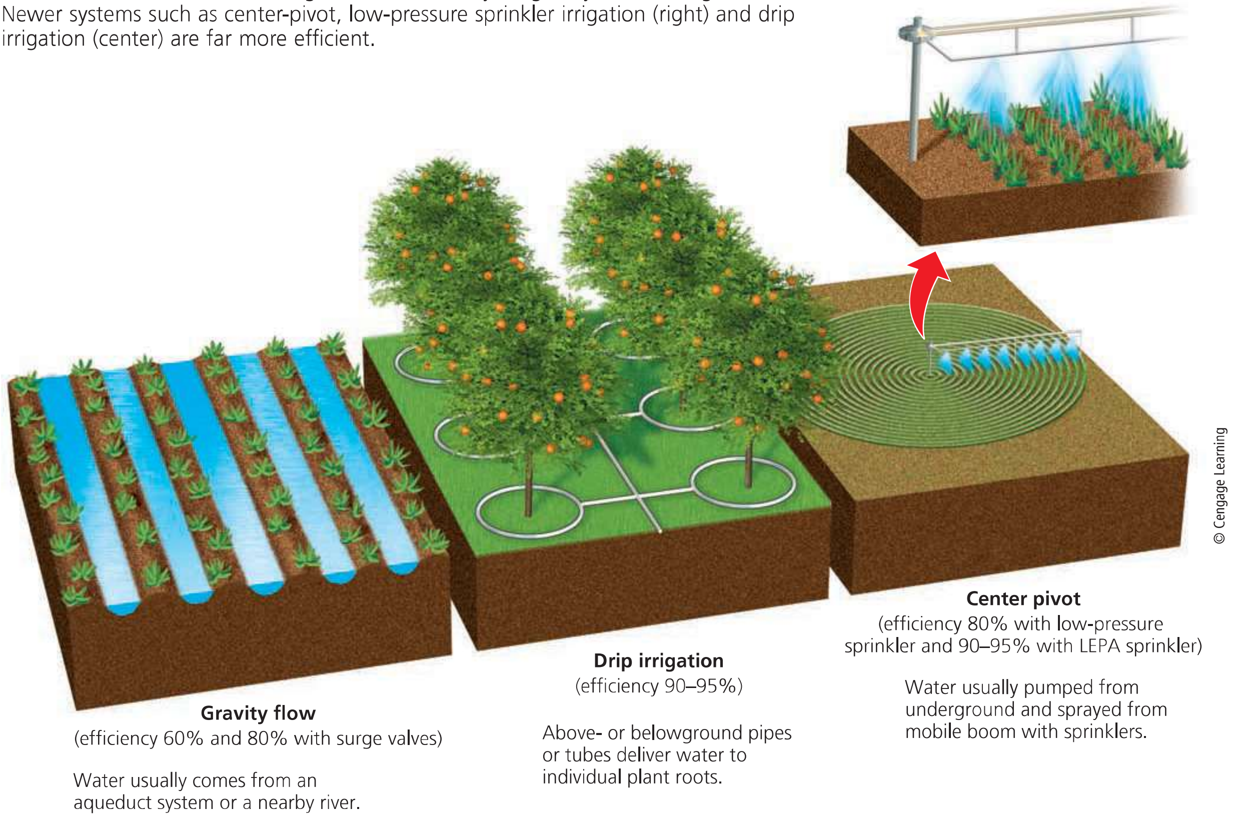
Another inefficient system is the traditional spray irrigation system, a widely used tool of industrialized crop production. It sprays huge volumes of water onto large fields, and as much as 40% of this water is lost to evaporation, especially in dry and windy areas, according to the U.S. Geological Survey. These systems are commonly used in the Midwestern United States and have helped to draw down the Ogallala Aquifer (Case Study, p. 333).

More efficient irrigation technologies greatly reduce water losses by delivering water more precisely to crops—a *more crop per drop* strategy. For example, a *center-pivot, low-pressure sprinkler* (Figure 13.19, right), which uses pumps to spray water on a crop, allow about 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 *micro-irrigation* (Figure 13.19, 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. These systems drastically reduce water waste because 90–95% of the water input reaches the crops.

Since the early 1990s, the global area of cropland on which drip irrigation is used has increased more than sixfold, with most of this growth happening in the United

FIGURE 13.19 Traditional irrigation methods rely on gravity and flowing water (left). Newer systems such as center-pivot, low-pressure sprinkler irrigation (right) and drip irrigation (center) are far more efficient.



States, China, and India. Still, drip irrigation is used on less than 4% of the irrigated crop fields in the world and in the United States, largely because most drip irrigation systems are costly. This percentage rises to 13% in the U.S. state of California, 66% in Israel, and 90% in Cyprus. If freshwater were priced closer to the value of the ecosystem services it provides, and if government subsidies for inefficient use of water were reduced or eliminated, drip irrigation could be used to irrigate most of the world's crops.

According to the UN, reducing the 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 the earth's cities and industries through 2025.

Poor Farmers Conserve Water Using Low-Tech Methods

Many of the world's poor farmers use low-cost, traditional irrigation technologies that are far more sustainable than most large-scale irrigation systems. For example, millions of farmers in Bangladesh and other countries where water tables are high use human-powered treadle pumps to bring groundwater up to the earth's surface and into irrigation ditches (Figure 13.20). These wooden devices are inexpensive and easy to build from local materials. One such pump developed by the nonprofit International Development Enterprises (IDE) uses 60–70% less water than a conventional gravity-flow system to irrigate the same amount of cropland at one-tenth the cost of conventional drip systems.

Other farmers in some less-developed countries use buckets, small tanks with holes, or simple plastic tubing systems for drip irrigation. One ingenious system makes use of solar energy to drive drip irrigation (Individuals Matter 13.1).

Rainwater harvesting is another simple and inexpensive way to provide water. It involves using pipes from rooftops and channels dug in the ground to direct rainwater that would otherwise run off the land. It can be stored in underground or aboveground storage tanks (cisterns), ponds, and plastic barrels for use during dry seasons. This is especially useful in countries such as India, where much of the rain comes in a short monsoon season.

In dry mountainous coastal areas, such as in Peru, some communities are capturing water from fog that rolls in off the ocean on most days. On the seaward hillsides, they erect large flat nets on which the fog condenses. The resulting water drops roll off the nets into troughs that channel the water into holding tanks.

INDIVIDUALS MATTER 13.1

Jennifer Burney: Environmental Scientist and National Geographic Explorer


UC San Diego

Environmental scientist and National Geographic Explorer Jennifer Burney notes that subsistence farmers represent the majority of the world's poorest people and need to boost their productivity for better standards of living and health. She is trying to help such farmers in Africa to grow, distribute, and cook their food using resources such as water, fertilizer, and energy as efficiently as possible. She also helps them avoid unsustainable practices such as wasteful irrigation and fertilizer runoff that are the legacy of large-scale industrial farming in the developed world.

For example, in arid sub-Saharan Africa, farmers must depend on rainfall for raising crops on small plots because only 20% of the rainfall flows into streams and aquifers while the rest evaporates. Overpumping can quickly deplete the groundwater. These factors, worsened by drought, make it hard for farmers to feed their families.

To deal with this problem, Burney has helped farmers to connect two technologies—solar energy systems and drip irrigation. Drip irrigation systems sip water and drip it directly onto plant roots instead of pumping and dumping it. Solar-powered pumps work without the need for batteries or fuel. On sunny days, when crops need water more, the solar panels speed the pumping; on cloudy days when there is less evaporation, the pumping slows down. Thus, only the amount of water that is needed is pumped on most days. This has allowed farmers to grow fruits and vegetables on a larger scale and to improve their incomes and food security.

CONSIDER THIS . . .

LEARNING FROM NATURE

The Namibian beetle survives in Africa's arid Namib Desert by using tiny bumps on its shell to extract water from night fog. Engineers hope to collect water in the world's dry areas by designing building surfaces and other materials that mimic the beetle's shell.


Courtesy of International Development Enterprises

FIGURE 13.20 **Solutions:** In areas of Bangladesh and India, where water tables are high, many small-scale farmers use treadle pumps to supply irrigation water to their fields.

Other strategies used by poor farmers to increase the amount of crop per drop of rainfall include polyculture farming to create more canopy cover and reduce evaporative water losses; planting deep-rooted perennial crop varieties (see Figure 12.B, p. 315); controlling weeds; and mulching fields to retain more moisture.

Figure 13.21 summarizes several ways to reduce water losses in crop irrigation. Since 1950, Israel has used many of these techniques to slash irrigation water losses 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, which is now one of the highest in the world. GOOD NEWS

We Can Cut Freshwater Losses in Industries and Homes

Producers of chemicals, paper, oil, coal, primary metals, and processed foods consume almost 90% of the freshwater used by industries 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 can be recycled. Even so, most industrial processes could be redesigned to use much less water. GOOD NEWS **GREEN CAREER: Water conservation specialist**

Solutions

Reducing Irrigation Water Losses

- Avoid growing thirsty crops in dry areas
- Import water-intensive crops and meat
- Encourage organic farming and polyculture to retain soil moisture
- Monitor soil moisture to add water only when necessary
- Expand use of drip irrigation and other efficient methods
- Irrigate at night to reduce evaporation
- Line canals that bring water to irrigation ditches
- Irrigate with treated wastewater

FIGURE 13.21 Ways to reduce freshwater losses in irrigation. ***Critical thinking:*** Which two of these solutions do you think are the best ones? Why?

Flushing toilets with freshwater (most of it clean enough to drink) is the single largest use of domestic freshwater in the United States and accounts for about 27% of home water use. 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. Even at this rate, just two flushes of such a toilet use more than the daily amount of water available for all uses to many of the world's poor people living in arid regions.

Other water-saving appliances are widely available. Low-flow showerheads can save large amounts of water by cutting the flow of a shower in half. Front-loading clothes washers use 30% less water than top-loading machines use. According to the American Water Works Association, if the typical American household were to stop all water leaks and use these devices, along with low-flow toilets and faucets, it could cut its daily water use by nearly a third. According to UN studies, 30–60% of the water supplied in nearly all of the world's major cities in less-developed countries is lost, primarily through leakage from water mains, pipes, pumps, and valves. Water experts say that fixing these leaks should be a high priority for water-short countries, because it would increase water supplies and cost much less than building dams or importing water.

Even in advanced industrialized countries such as the United States, these losses to leakage average 10–30%. However, leakage losses have been reduced to about 3% in Copenhagen, Denmark, and to 5% in Fukuoka, Japan. In 1 year, a faucet leaking water at the rate of 1 drop per second can waste 10,000 liters (2,650 gallons). The customer's water bill goes up and so does the energy bill if the water is leaking from a hot water faucet. Not detecting and fixing water leaks from faucets, pipes, and toilets is equivalent to burning money.

Many homeowners and businesses in water-short areas are using drip irrigation on their properties to cut water losses. Some are also using smart sprinkler systems with moisture sensors that have cut water used for watering lawns by up to 40%. Others are copying nature by replacing green lawns with a mix of native plants that need little or no watering (Figure 13.22). Such water-thrifty landscaping saves money by reducing water use by 30–85% and by sharply reducing labor, fertilizer, and fuel requirements. It also can help landowners to reduce polluted runoff, air pollution, and yard wastes.

In some more-developed countries, people who live in arid areas maintain green lawns by watering them heavily. Some communities and housing developments in water-short areas have even passed ordinances that require green lawns and prohibit the planting of native vegetation in place of lawns.

Water used in homes can be reused and recycled. About 50–75% of a typical household's *gray water*—used water from bathtubs, showers, sinks, dishwashers, and clothes washers—could be recovered and stored. This water can be reused to irrigate lawns and nonedible plants, to flush toilets, and to wash cars. Such efforts mimic the way nature recycles water, and thus they follow the chemical cycling **principle of sustainability**.

The relatively low cost of water in most communities is one of the major causes of excessive water use and waste in homes and industries. About one-fifth of all U.S. public water systems do not use water meters and charge a single low annual rate for almost unlimited use of high-quality freshwater.

When the U.S. city of Boulder, Colorado, introduced water meters, water use per person dropped by 40%. In some cities in Brazil, people buy *smart cards*, each of which contains a certain number of water credits that entitle their owners to measured amounts of freshwater. Brazilian officials say this approach saves water and typically reduces household water bills by 40%.

Figure 13.23 summarizes various ways to use water more efficiently in industries, homes, and businesses (**Concept 13.3**).

We Can Use Less Water to Remove Wastes

Currently, we use large amounts of freshwater to flush away industrial, animal, and household wastes. According to the UN Food and Agriculture Organization (FAO), if current growth trends in population and water use 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 each year.

We could save much of this freshwater by recycling and reusing gray water from homes and businesses for flushing wastes and cleaning equipment. In Singapore, all sewage water is treated at reclamation plants for reuse by

karolinapatryk/Thinkstock

FIGURE 13.22 This yard in a dry area of the southwestern United States uses a mix of plants that are native to the arid environment and require little watering.

industry. U.S. cities such as Las Vegas, Nevada, and Los Angeles, California, are also beginning to clean up and reuse some of their wastewater. However, only about 7% of the water in the United States is recycled, cleaned up, and reused. Sharply raising this percentage would be a way to apply the chemical cycling **principle of sustainability**.

Another way to keep freshwater out of the waste stream is to rely more on waterless composting toilets. These devices 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) used a composting toilet for over a decade with no problems, while living and working deep in the woods in a small passive solar home and office used for evaluating solutions to water, energy, and other environmental problems (see p. xxxiii).

As water shortages grow in many parts of the world, people are using methods discussed here to use water more sustainably. Their experiences can be instructive to people who want to avoid water shortages in the first place. (See the Case Study that follows.)

CASE STUDY

How Californians Are Dealing with Water Woes

In 2015 the state of California had been experiencing drought for 4 years. Due to climate change, the state's climate in the future is projected to be hotter and drier than it was during the 20th century. It is also likely to see more extreme weather events, including large flooding episodes, as well as more intense droughts.

In some areas of California, the effects of drought include dwindling aquatic ecosystems and municipal water supplies, increasingly frequent wildfires, crop losses, and parched lawns. In 2014 NASA satellite data (Science Focus 13.1)

Solutions

Reducing Water Losses

- Redesign manufacturing processes to use less water
- Recycle water in industry
- Fix water leaks
- Landscape yards with plants that require little water
- Use drip irrigation on gardens and lawns
- Use water-saving showerheads, faucets, appliances, and toilets (or waterless composting toilets)
- Collect and reuse gray water in and around houses, apartments, and office buildings
- Raise water prices and use meters, especially in dry urban areas

FIGURE 13.23 Ways to reduce freshwater losses in industries, homes, and businesses (**Concept 13.6**). ***Critical thinking:*** Which three of these solutions do you think are the best ones? Why?

showed the state's major river basins to be well below normal (Figure 13.24). In 2015 the Sierra Nevada snowpack, which has provided a third to half of the state's water supply in the past, was just 5% of its historical average size. As of late 2015, the drought across 97% of the state was classified as *severe* or worse.

According to the Natural Resources Defense Council (NRDC), agriculture uses 78% to 80% of California's available water in most years. Due to water restrictions imposed by the state in 2013, along with complex water rights laws, some Central Valley farmers have lost their surface water irrigation sources. In turn, many have drilled deeper wells into the valley's aquifers that require decades to recharge. Hydrologists see this overpumping of the aquifers as unsustainable and dangerous in the long term.

The strategies that Californians are using to deal with drought could teach us much about how to use freshwater more sustainably. First, many water supply agencies raised their water rates to encourage conservation. One common approach involves an increasing-step rate structure. Users pay a certain rate for a set amount of water. Once they surpass that amount, their rate goes up. There are typically three or four such thresholds within the structure, so the largest users pay much more per volume of water than do those who use water at the lowest level.

Second, California residents are conserving water in a number of ways. According to the Public Policy Institute of California, at least 40% of residential water use is for watering lawns. The next three largest uses are for swimming pools, toilets, and showers. Many Californians are replacing their grass lawns with water-saving ground cover or native vegetation adapted to dry conditions. Others are installing more efficient toilets and showerheads and are showering and washing clothes less frequently. A smaller number of people are fixing water leaks and draining their pools. In 2015 California's urban residents reached the 25% water use reduction goal set by the state government.

Third, there is growing interest in *conjunctive use*, also referred to as *water banking*—finding ways to save water

FIGURE 13.24 One of California's major reservoirs, Lake Oroville, dropped dramatically between 2011 (left) and 2014 (right), due largely to drought.

Justin Sullivan/Getty Images

for future use. Climate models indicate that much of California's future precipitation is likely to come in shorter high-volume bursts that could be captured and stored. One approach is to locate an empty aquifer, of which there are several in California. Excess water is then channeled to the overlying land area where it sinks into the ground to recharge the aquifer. This water does not evaporate and can be withdrawn in the future as needed.

The problem is that water does not travel predictably underground and often flows to other areas. Thus it cannot always be withdrawn from where it was deposited. Also, withdrawing water from the deposit area can pull water from other areas, lowering the water tables and causing water supply problems in those areas. Thus, conjunctive use is not a perfect solution.

Another strategy promoted by many is for farmers to shift from producing thirsty crops such as alfalfa, lettuce, and almonds, to producing less water-intensive crops. The Public Policy Institute of California estimated that the amount of water used to grow almonds in 2013 was larger than that used by all homes and businesses in San Francisco and Los Angeles combined. In addition, California is the leading dairy state and dairy products are among the most water-intensive. It has been estimated that the average American consumes 1,132 liters (300 gallons) of California water every week by eating foods produced in the state.

Desalination is another option that many are promoting (Science Focus 13.2). In 2015 the largest desalination plant in the western hemisphere was opened in Carlsbad, north of San Diego. It was designed to supply 300,000 state residents with freshwater. However, because of current high costs and potentially harmful environmental effects, desalination is a controversial and limited solution to water shortages.

Yet another strategy is the recycling of water—restoring wastewater to drinking water quality. Orange County's Groundwater Replenishment System takes sewer and other wastewater and processes it to the point where it exceeds all state and federal drinking water standards. It meets the needs of about 600,000 people. Water can also be reused through gray water systems. Many homes in California are equipped with new *purple pipes*—special pipes built in for this purpose and distinctively color-coded.

We Can Use Water More Sustainably

More sustainable water use would include a variety of strategies (Figures 13.14, 13.21, and 13.23) aimed not only at conserving water and using it efficiently, but also at protecting water supplies and the ecosystems that sustain them (**Concept 13.5**). Such strategies would have to be applied at local and regional levels, as well as national and international levels.

However, to be successful, these strategies would also have to be applied at the personal level. Each of us can reduce our water footprints by using less freshwater and using it more efficiently (Figure 13.25).

What Can You Do?

Water Use and Waste

- Use water-saving toilets, showerheads, and faucets
- Take short showers instead of baths
- 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
- Repair water leaks
- Wash your car from a bucket of soapy water, use gray 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 gardens only in the early morning or evening and use gray water
- Use drip irrigation and mulch for gardens and flowerbeds

FIGURE 13.25 Individuals matter: You can reduce your use and waste of freshwater. ***Question:*** Which of these steps have you taken? Which would you like to take?

13.6 HOW CAN WE REDUCE THE THREAT OF FLOODING?

CONCEPT 13.6 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 freshwater, 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 freshwater in a stream overflows its normal channel and spills into the adjacent area, called the **floodplain.**

Human activities contribute to flooding in several ways. People settle on floodplains to take advantage of their many assets. They include fertile soil on flat land suitable for crops, ample freshwater for irrigation, and availability of nearby rivers for transportation and recreation. In efforts to reduce the threat of flooding on floodplains, rivers have been narrowed and straightened (or *channelized*), surrounded by protective dikes and *levees* (long mounds of earth along their banks), and dammed to create reservoirs that store and release water as needed. However, such measures can lead to greatly increased flood damage when heavy snowmelt or prolonged rains overwhelm them.

Floods provide several benefits. They have created some of the world's most productive farmland by depositing nutrient-rich silt on floodplains. They also help recharge groundwater and refill wetlands that are commonly found on floodplains, thereby supporting biodiversity and aquatic ecosystem services.

At the same time, floods kill thousands of people every year and cost tens of billions of dollars in property damage (see the Case Study that follows). Floods are usually considered natural disasters, but since the 1960s, human activities have contributed to a sharp rise in flood deaths and damages, meaning that such disasters are partly human-made.

One such human activity is the *removal of water-absorbing vegetation*, especially on hillsides (Figure 13.26). Once the trees on a hillside have been cut for timber, fuelwood, livestock grazing, or farming, freshwater from precipitation rushes down the barren slopes, erodes precious topsoil, and can increase flooding and pollution in local streams. Such deforestation can also make landslides and mudflows more likely. A 3,000-year-old Chinese proverb says, "To protect your rivers, protect your mountains."

The second human activity that increases the severity of flooding is the *draining of wetlands* that naturally absorb floodwaters. These areas are then often covered with pavement and buildings that greatly increase runoff, which contributes to flooding and pollution of surface waters. When Hurricane Katrina struck the Gulf Coast of the United States in August 2005 and flooded the city of New Orleans, Louisiana, the damage was intensified because of the degradation or removal of coastal wetlands. These wetlands had historically helped to absorb water and buffer this low-lying land from storm surges. For this reason, Louisiana officials are now working to restore some coastal wetlands.

Another human-related factor that will likely increase flooding is a rise in sea levels, projected to occur during this century (mostly the result of climate change related to human activities). Climate change models project that, by 2075, as many as 150 million people living in the world's largest coastal cities—a number nearly equal to half of the current U.S. population—could be flooded out by rising sea levels.

CASE STUDY

Living Dangerously on Floodplains in Bangladesh

Bangladesh is one of the world's most densely populated countries. In 2015 its 160 million people were packed into an area roughly the size of the U.S. state of Wisconsin (which has a population of less than 6 million). And the

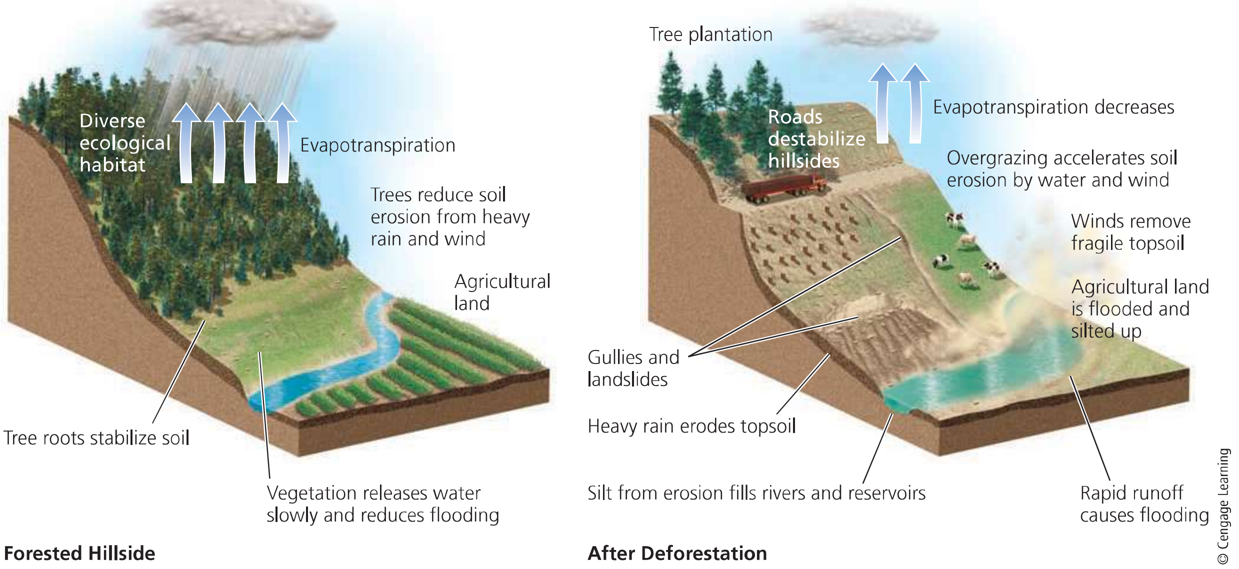


FIGURE 13.26 Natural capital degradation: A hillside before and after deforestation.
Question: How might a drought in this area make these effects even worse?

country's population is projected to increase to 202 million by 2050. Bangladesh is a very flat country, only slightly above sea level, and it is one of the world's poorest countries.

The people of Bangladesh depend on moderate annual flooding during the summer monsoon season to grow rice and help maintain soil fertility in their country's delta basin region, which is fed by numerous river systems. The annual floods also deposit eroded Himalayan soil on the country's crop fields. Bangladeshis have adapted to moderate flooding. Most of the houses have flat thatch roofs on which families can take refuge with their belongings in case of rising waters. The roofs can be detached from the walls, if necessary, and floated like rafts. After the waters have subsided, the roof can be reattached to the walls of the house. However, great floods can overwhelm such defenses.

In the past, great floods occurred every 50 years or so. However, between 1987 and 2015 there were seven severe floods, each covering a third or more of the country with water. Bangladesh's flooding problems begin in the Himalayan watershed, where rapid population growth and unsustainable farming have resulted in deforestation. Monsoon rains now run more quickly off the barren Himalayan foothills, carrying vital topsoil with them (Figure 13.26, right).

This increased runoff of topsoil, combined with heavier-than-normal monsoon rains, has led to more severe flooding along Himalayan rivers, as well as downstream in Bangladesh's delta areas. In 1998 a disastrous flood covered two-thirds of Bangladesh's land area, in some places for 2 months, drowning at least 2,000 people and leaving 30 million homeless. It also destroyed more than one-fourth of the country's crops, which caused thousands of people to die of starvation. Another flood in 2014 affected nearly 3 million people by leaving hundreds of thousands homeless and destroying crops and access to clean water.

Many of the coastal mangrove forests in Bangladesh (and elsewhere; see Figure 8.8, p. 172) have been cleared for fuelwood, farming, and shrimp farming ponds. The result: more severe flooding because these coastal wetlands had helped to shelter Bangladesh's low-lying coastal areas from storm surges, cyclones, and tsunamis. In areas of Bangladesh still protected by mangrove forests, damages and death tolls from cyclones have been much lower than they were in areas where the forests have been cleared.

Projected rises in sea level and storm intensity during this century, primarily due to projected climate change, will likely be a major threat to Bangladeshis who live on the flat delta adjacent to the Bay of Bengal. This would create millions of environmental refugees with no place to go in this already densely populated country.

Bangladesh is one of the few less-developed nations that is implementing plans to adapt to projected rising sea levels. This includes using varieties of rice and other crops that can better tolerate flooding, saltwater, and drought. People are also planting small vegetable gardens in bare patches between houses to help reduce their dependence on rice. In addition, they are building ponds to collect monsoon rainwater and a network of earthen embankments to help protect against high tides and storm surges. Bangladesh has been praised in recent years for its work on disaster preparedness, including construction of storm shelters and improved evacuation procedures. Such measures have resulted in declining death tolls and property damage in the face of more frequent storms and flooding.

We Can Reduce Flood Risks

Many scientists argue that we could improve flood control by relying less on engineered devices such as dams and levees and more on nature's systems such as wetlands and forests in watersheds.

One engineering approach is the channelizing of streams, which does reduce upstream flooding. However, it also eliminates the aquatic habitats that lie along a meandering stream by taking the water from those systems and sending it in a faster flow straight down a channel. It also reduces groundwater recharge and often leads to downstream flooding.

Similarly, levees or floodwalls along the banks of a river contain and speed up stream flow and can lead to flooding downstream. They also do not protect against unusually high and powerful floodwaters such as those that occurred in 1993 when two-thirds of the levees along the Mississippi River were damaged or destroyed. Similar flooding occurred along the Mississippi in 2011.

Damming, the most common engineering approach, can reduce the threat of flooding by storing water in a reservoir and releasing it gradually. However, dams also have a number of drawbacks (Figure 13.15).

A more ecologically oriented approach to reducing flooding is to *preserve existing wetlands* and *restore degraded wetlands* that lie in floodplains to take advantage of the natural flood control they provide. We would also be wise to sharply reduce emissions of greenhouse gases that contribute to atmospheric warming and climate change, which will likely raise sea levels and flood many of the world's coastal areas during this century.

Figure 13.27 summarizes these various ways to reduce flooding risks (**Concept 13.6**).

Solutions

Reducing Flood Damage

Prevention	Control
Preserve forests in watersheds	Strengthen and deepen streams (channelization)
Preserve and restore wetlands on floodplains	Build levees or floodwalls along streams
Tax development on floodplains	Build dams
Increase use of floodplains for sustainable agriculture and forestry	

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FIGURE 13.27 Methods for reducing the harmful effects of flooding (**Concept 13.7**). ***Critical thinking:*** Which two of these solutions do you think are the best ones? Why?

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BIG IDEAS

- One of the major global environmental problems is the growing shortage of freshwater in many parts of the world.
- We can expand water supplies in water-short areas in a number of ways, but the most important ways are to reduce overall water use and to use water much more efficiently.
- We can use water more sustainably by reducing water use, using water more efficiently, cutting water losses, raising water prices, and protecting aquifers, forests, and other ecosystems that store and release water.

Tying It All Together

The Colorado River and Sustainability

The Core Case Study that opens this chapter discusses the problems and tensions that can occur when a large number of U.S. states share a limited river water resource in a water-short region. Such problems are representative of those faced by many other dry regions of the world, especially areas where the population is growing rapidly and water resources are dwindling for various reasons.

Large dams, river diversions, levees, and other big engineering schemes have helped to provide much of the world with electricity, food from irrigated crops, drinking water, and flood control. However, they have also degraded the aquatic natural capital necessary for long-term economic and ecological sustainability by seriously disrupting rivers, streams, wetlands, aquifers, and other aquatic systems.

The three **scientific principles of sustainability** can guide us in using water more sustainably during this century. Scientists hope to use solar energy to desalinate water and expand freshwater supplies. Recycling more water and reducing water waste will help reduce water losses. Preserving biodiversity by avoiding disruption of aquatic systems and their bordering terrestrial systems is a key factor in maintaining water supplies and water quality.

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Chapter Review

Core Case Study

1. Summarize the importance of the Colorado River basin in the United States and how human activities are stressing this system. Define **drought** and explain how it has affected the Colorado River system.

Section 13.1

2. What are the two key concepts for this section? Define **freshwater**. Explain why access to water is a health issue, an economic issue, a national and global security issue, and an environmental issue. What percentage of the earth's freshwater is available to us? Explain how water is recycled by the hydrologic cycle and how human activities can interfere with this cycle. Define **groundwater**, **zone of saturation**, **water table**, and **aquifer**, and explain how aquifers are recharged. What are deep aquifers and why are they considered nonrenewable? Define and distinguish between **surface water** and **surface runoff**. What is a **watershed (drainage basin)**?

3. What is **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? How is most of the world's water used? Define **water footprint** and **virtual water** and give two examples of each. Describe the availability and use of freshwater resources in the United States and the water shortages that could occur during this century. What are three major problems resulting from the way people are using water from the Colorado River basin?

4. How many countries face water scarcity today and how many could face water scarcity by 2050? What percentage of the earth's land suffers from severe drought today and how might this change by 2059? How many people in the world lack regular access to clean water today and how high might this number grow by 2025? Why do many analysts view the likelihood of steadily worsening water shortages as one of the world's most serious environmental problems? Explain the connection between water shortages and hunger. How do scientists use satellites to measure changes in water supplies?

Section 13.2

5. What is the key concept for this section? What are the advantages and disadvantages of withdrawing groundwater? Summarize the problem of groundwater depletion in the world and in the United States, especially in the Ogallala Aquifer. List three problems that result from the overpumping of aquifers. List some ways to prevent or slow groundwater depletion. What is the potential for using deep aquifers to expand water supplies?

Section 13.3

6. What are the two key concepts for this section? What is a **dam**? What is a **reservoir**? What are the advantages and disadvantages of using large dams and reservoirs? How do dams affect aquatic wildlife? What has happened to water flows in the Colorado River (**Core Case Study**) since 1960? Explain how the damming of this river has affected its delta. What other problems are likely to further shrink this supply of water? List three possible solutions to the supply problems in the Colorado River basin.

7. Define **desalination** and distinguish between distillation and reverse osmosis as methods for desalinating water. What are three limitations of desalination? What are scientists doing to try to deal with these problems?

Section 13.4

8. What is the key concept for this section? What is a water transfer? Describe two large water-transfer programs, explain how they came about, and summarize the controversy around each of these programs. Summarize the story of the Aral Sea water-transfer project and its disastrous consequences.

Section 13.5

9. What is the key concept for this section? What percentage of available freshwater is lost through inefficient use and other causes in the world and in the United States? What are two major reasons for those losses? Describe three major irrigation methods and list ways to reduce water losses in irrigation. What are three ways in which people in less-developed countries conserve water? List four ways to reduce water waste in industries and homes and three ways to use less water to remove wastes. What are five ways in which Californians are dealing with their severe drought and water shortages? List four ways in which you can reduce your use and waste of water.

Section 13.6

10. What is the key concept for this section? What is a **floodplain** and why do people like to live on floodplains? What are the benefits and harms of flooding? List two human activities that increase the risk of flooding. Describe the flooding risks that many people in Bangladesh face and what they are doing about it. List and compare two engineering approaches to flood control and two ecologically oriented approaches. What are this chapter's *three big ideas*? Explain how the **scientific principles of sustainability** can guide us in using water more sustainably during this century.

Note: Key terms are in bold type.

Critical Thinking

1. What do you think are the three most important priorities for dealing with the water resource problems of the Colorado River basin, as discussed in the **Core Case Study** that opens this chapter? Explain your choices.
2. List three ways in which human activities are affecting the water cycle. How might these changes to the water cycle affect your lifestyle? How might your lifestyle be contributing to these effects?
3. Explain how our current use of the earth's water resources can be viewed as a good example of the tragedy of the commons (see Chapter 1, p. 12).
4. Many argue that government freshwater subsidies promote the expansion of productive farmland, stimulate local economies, and help to keep food and electricity prices low. Do you think this is reason enough for governments to continue providing subsidies to farmers and cities? Explain.
5. Explain why you are for or against **(a)** raising the price of water while providing lower lifeline rates for poor consumers, **(b)** withdrawing government subsidies that provide farmers with water at low cost, and **(c)** providing government subsidies to farmers for improving irrigation efficiency.
6. Calculate how many liters (and gallons) of water are lost in 1 month by a toilet or faucet that leaks 2 drops of water per second. (One liter of water equals about 3,500 drops and 1 liter equals 0.265 gallon.) How many bathtubs (each containing about 151 liters or 40 gallons) could be filled with this lost water?
7. List the three most important ways in which you could use water more efficiently. Which, if any, of these measures do you already take?
8. List three ways in which human activities increase the harmful effects of flooding. What is the best way to prevent each of these human impacts? Do you think they should be prevented? Why or why not?

Doing Environmental Science

Investigate water use at your school. Try to determine all specific sources of any water losses, taking careful notes and measurements for each of them, and estimate how much water is lost per hour, per day, and per year from each source. Sum these estimated amounts to arrive at an estimate of total water losses for a year at your school. Develop a water conservation plan for your school and submit it to school officials.

Global Environment Watch Exercise

Go to your MindTap course to access the GREENR database. Using the "Basic Search" box at the top of the page, search for *Ogallala Aquifer*. Research articles that quantify how much the aquifer has declined and list areas over the aquifer where the decline is the worst. Look for projections on how much more the aquifer could decline in the future and take notes on this. Find information on the causes of this decline and determine which are the largest causes. Learn what is being done to address each of these causes and write a report explaining the causes, projections, and possible ways to slow the decline of the Ogallala Aquifer.

Ecological Footprint Analysis

The following table is based on data from the Water Footprint Network, a science-based organization that promotes the sustainable use of water through sharing knowledge and building awareness of how water is used. It shows the amounts of *embedded water*, or water required to produce each of the products listed in the first column. Study the table and then answer the questions that follow.

Product	Liters per kilogram (kg) or product	Gallons per pound (lb) or product
Beef	15,400/kg	1,855/lb.
Pork	5,990/kg	722/lb.
Chicken	4,325/kg	521/lb.
Milk	255/glass (250 ml)	68/glass (8 oz.)
Eggs	196/egg	52/egg
Coffee	132/cup	35/cup
Beer	74/glass (250 ml)	20/glass (8 oz.)
Wine	54/glass (250 ml)	14/glass (8 oz.)
Apple	125/average size apple	33/apple
Banana	160/large banana	42/banana
Tomato	50/medium tomato	13/tomato
Rice	2,500/kg	301/lb.
Bread	1,608/kg	426/lb.
Cotton t-shirt	2,495/shirt	661/shirt

Questions:

1. Find a loaf of common wheat bread, count the slices per loaf, and calculate the amount of water used to produce each slice. Calculate the amount of water used to produce one-third pound of beef. Combine these two to arrive at the approximate amount of water used to produce an average restaurant hamburger.
2. In terms of embedded water, how many tomatoes can be produced for each pound of pork? For each pound of beef?
3. If you drank coffee and/or milk today, how many gallons (or liters) of embedded water did you drink?
4. In terms of embedded water, how many kilograms (and pounds) of rice are represented in one t-shirt? How many bananas? How many apples?
5. In terms of embedded water, how many pounds of chicken can be produced for each pound of beef? How many pounds of rice?