CHAPTER 18

Water Supply, Use, and Management

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

LEARNING OBJECTIVES

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

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

CASE STUDY

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

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

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

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

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

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

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

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

18.1 Water

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

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

A Brief Global Perspective

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

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

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

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

Source: U.S. Geological Survey

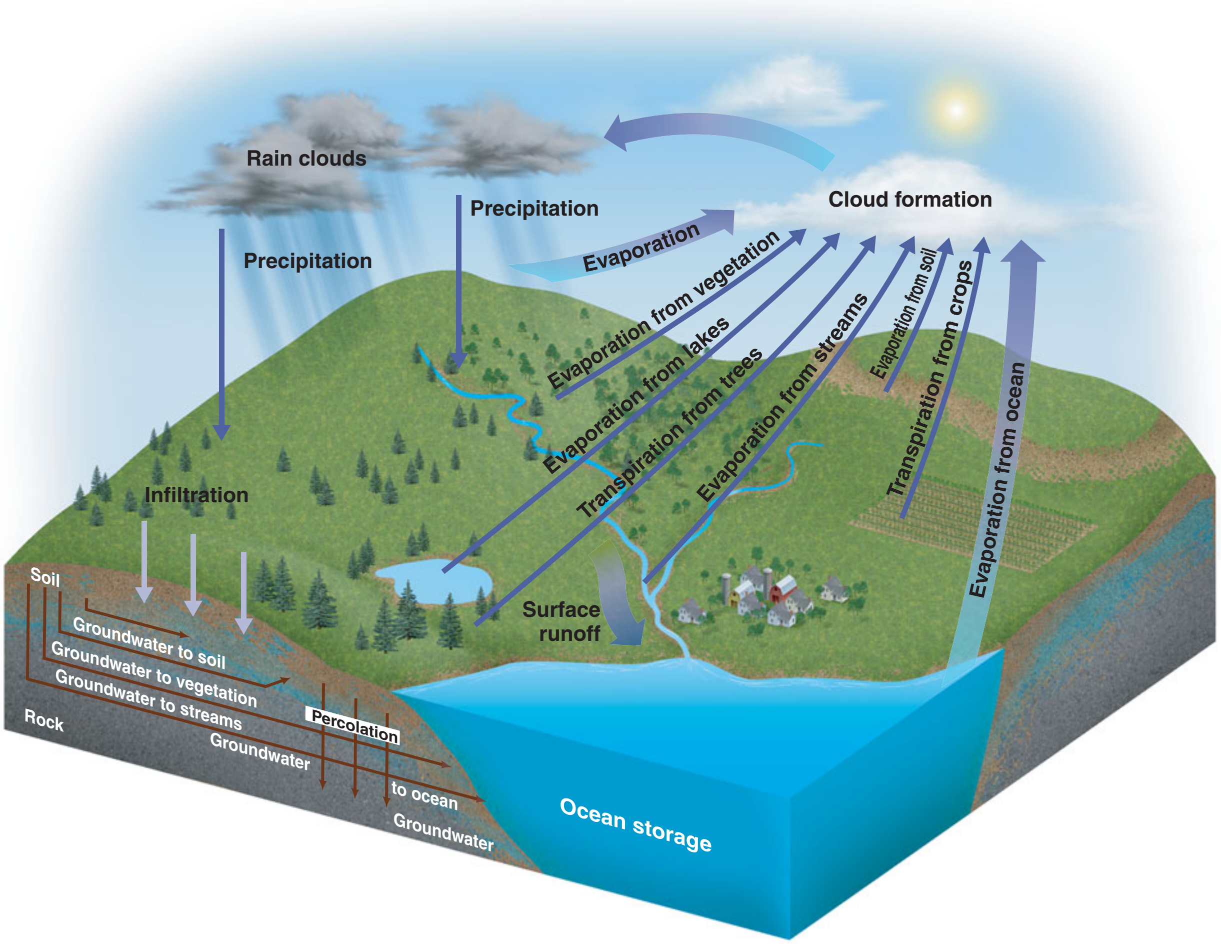

FIGURE 18.2 The hydrologic cycle, showing important processes and transfer of water. (*Source:* Modified from Council on Environment Quality and Department of State, *The Global 2000 Report to the President*, vol. 2 [Washington, DC].)

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

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

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

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

Groundwater and Streams

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

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

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

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

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

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

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

Interactions between Surface Water and Groundwater

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

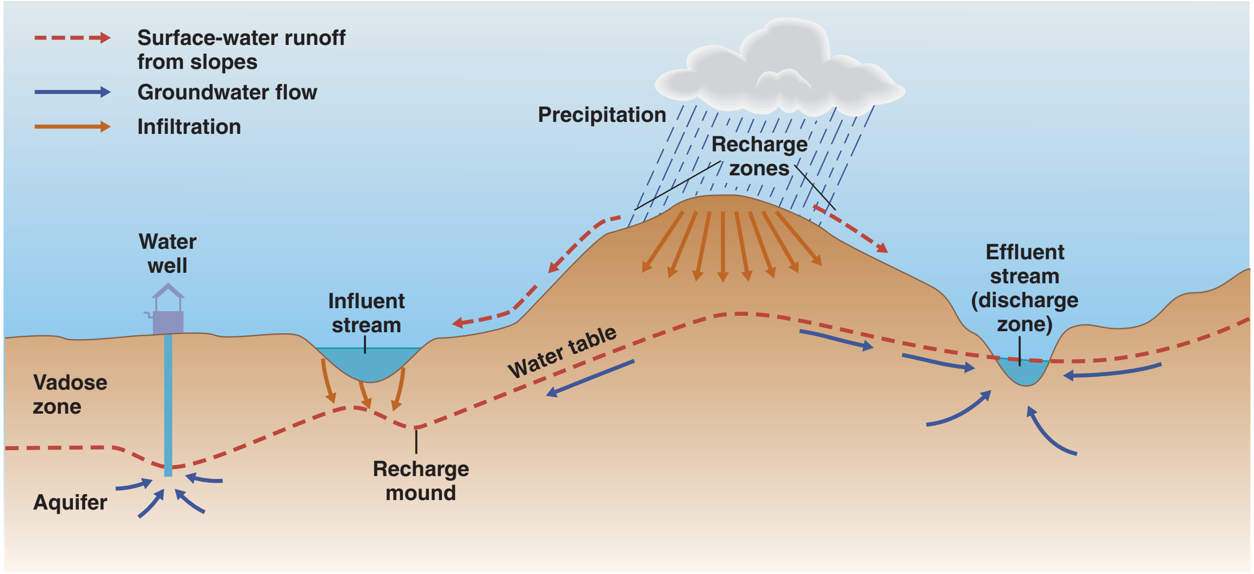

FIGURE 18.3 Groundwater and surface-water flow system.

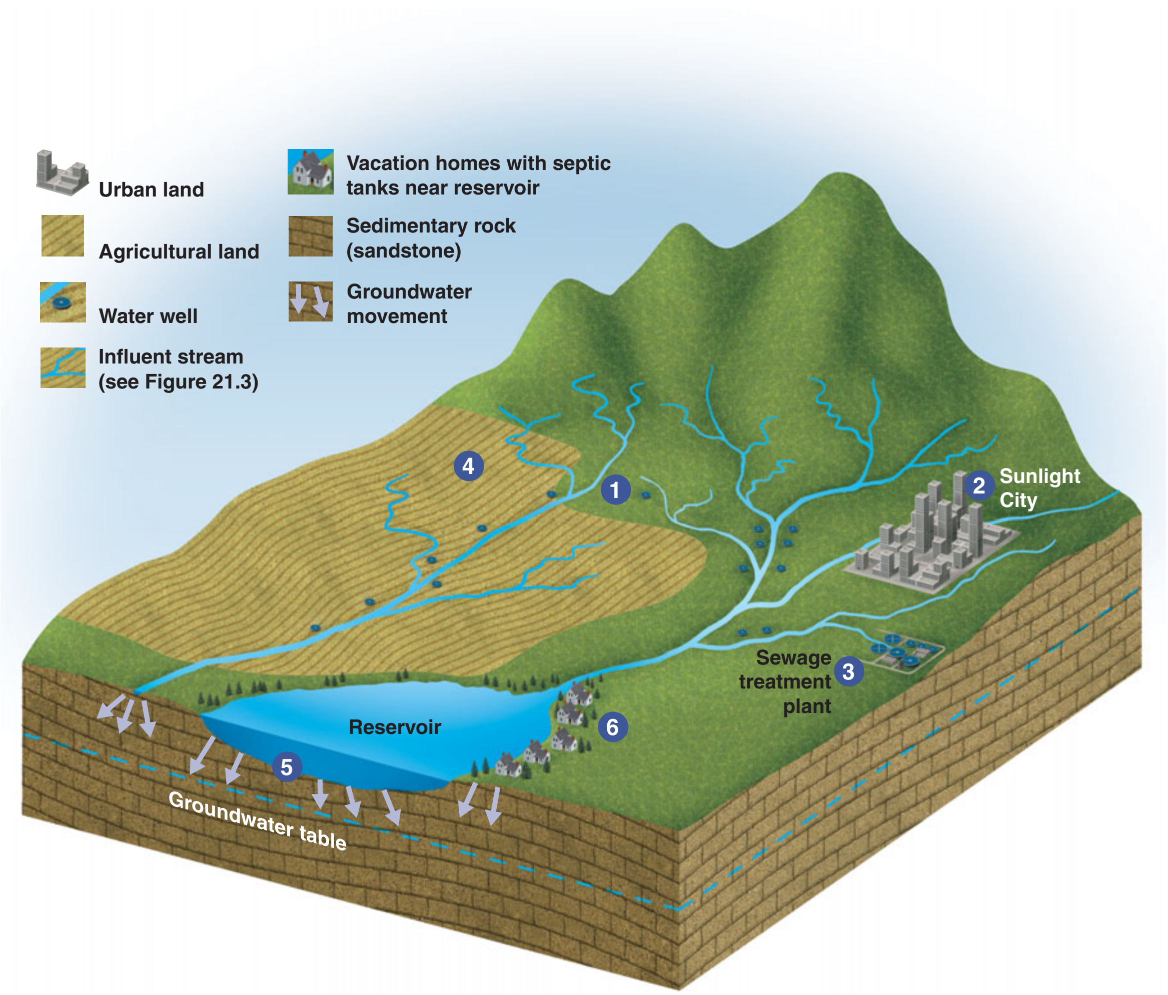

FIGURE 18.4 Idealized diagram illustrating some interactions between surface water and groundwater for a city in a semiarid environment with adjacent agricultural land and reservoir. (1) Water pumped from wells lowers the groundwater level. (2) Urbanization increases runoff to streams. (3) Sewage treatment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

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

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

18.2 Water Supply: A U.S. Example

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

Table 18.2 ANNUAL WATER BUDGETS FOR THE CONTINENTS[a]

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

[a] Precipitation – evaporation = runoff.

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

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

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

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

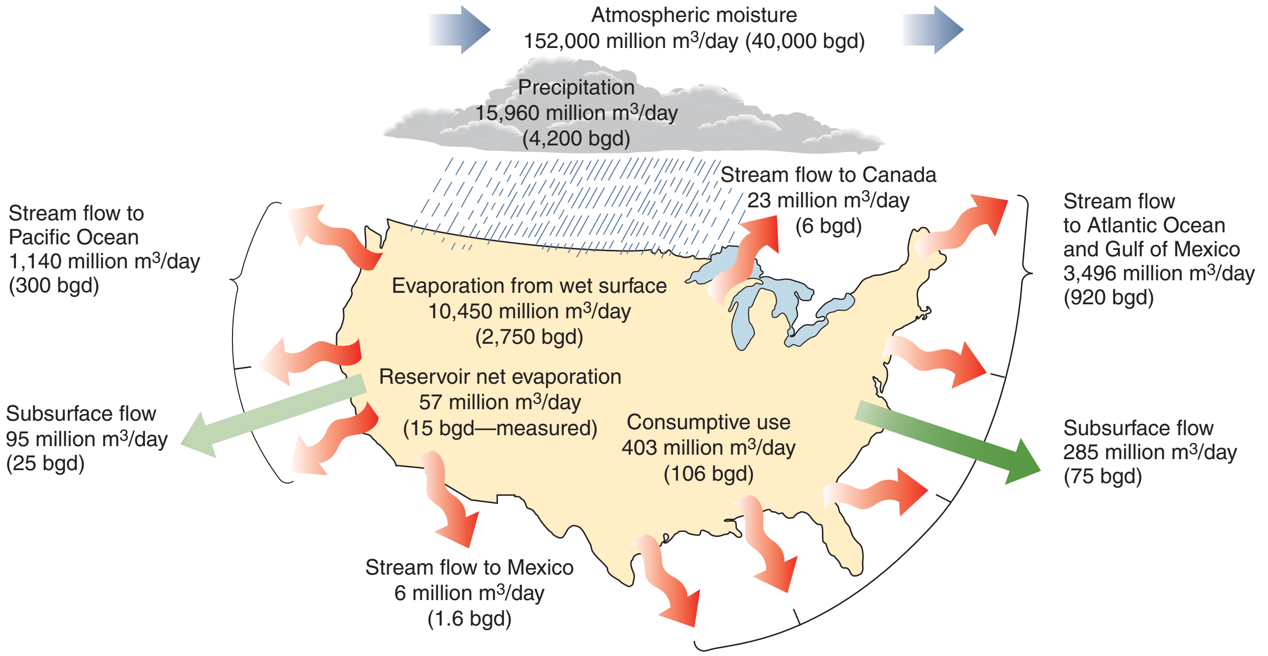

FIGURE 18.5 Water budget for the United States (bgd = billion gallons per day). (*Source:* Water Resources Council, *The Nation's Water Resources 1975–2000* [Washington, DC: Water Resources Council, 1978].)

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

Precipitation and Runoff Patterns

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

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

Droughts

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

Groundwater Use and Problems

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

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

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

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

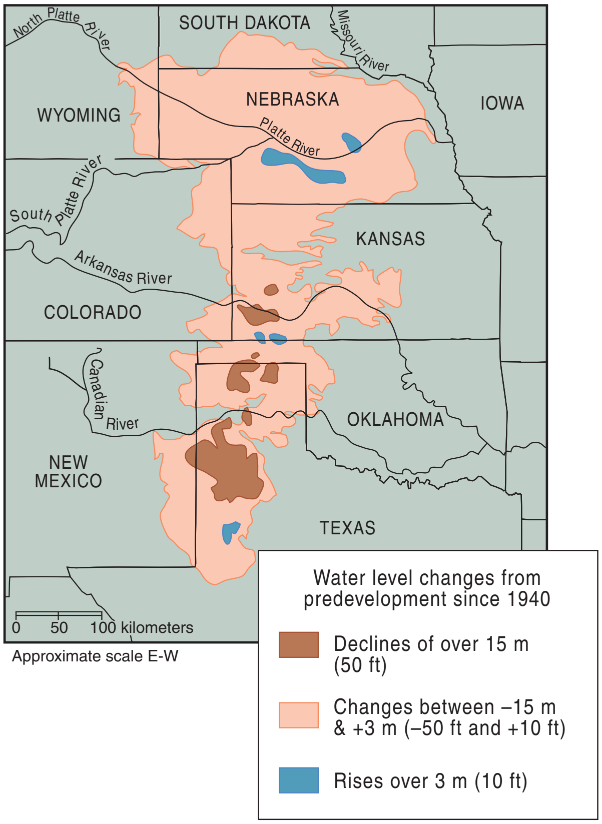

FIGURE 18.6 Groundwater-level changes as a result of pumping in the Texas–Oklahoma–High Plains region. (*Source:* U.S. Geological Survey.)

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

Desalination as a Water Source

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

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

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

18.3 Water Use

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

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

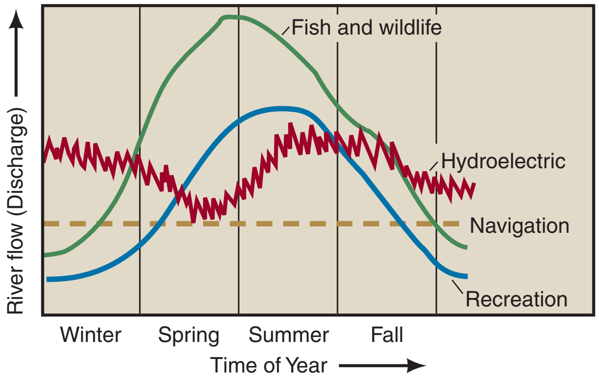

FIGURE 18.7 In-stream water uses and optimal discharge (volume of water flowing per second) for each use. Discharge is the amount of water passing by a particular location and is measured in cubic meters per second. Obviously, all these needs cannot be met simultaneously.

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

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

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

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

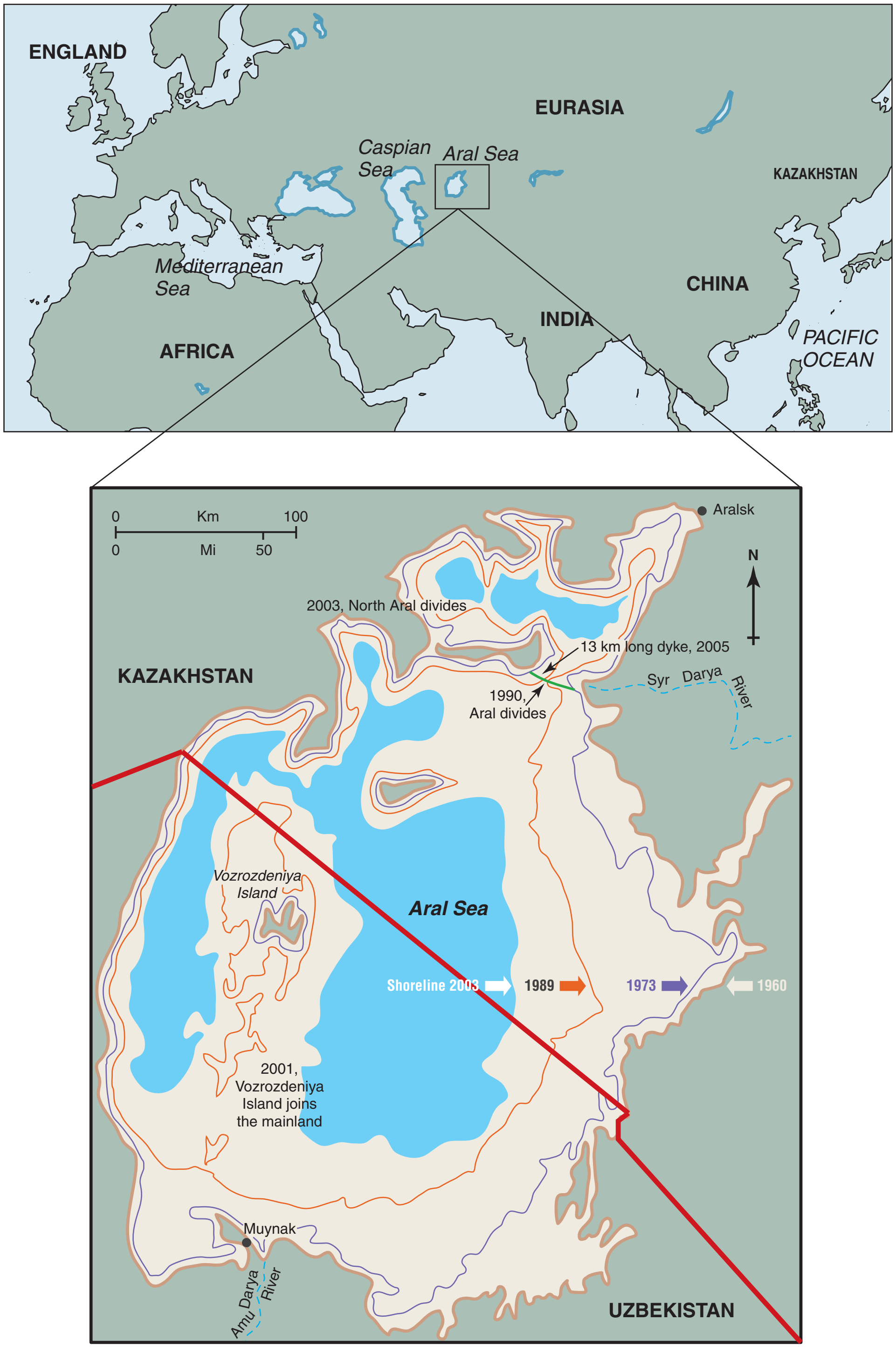

FIGURE 18.8 The Aral Sea from 1960 to 2003. A strong dike (dam), 13 km long, was constructed in 2005, and the northern lake increased in area by 18% and in depth by 2 km by 2007. (Modified after *unimaps.com 2004.*)

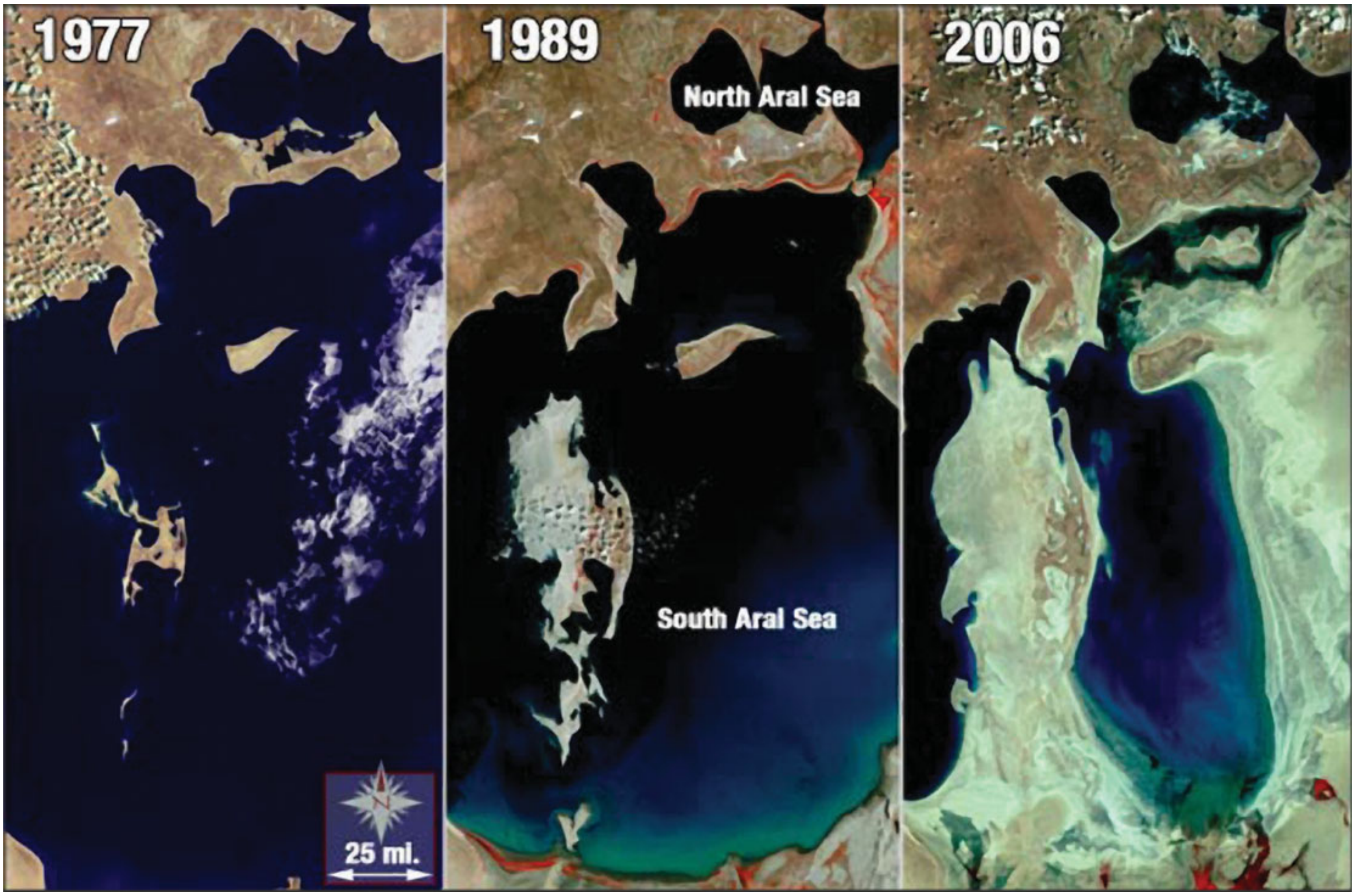

FIGURE 18.9 Three images of the Aral Sea from 1977 to 2006. By 2006, the sea had been reduced to about 10% of its original size. Wetlands around the sea were reduced by 85%; fish species declined 80%, and birds 50%.

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

Transport of Water

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

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

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

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

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

Some Trends in Water Use

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

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

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

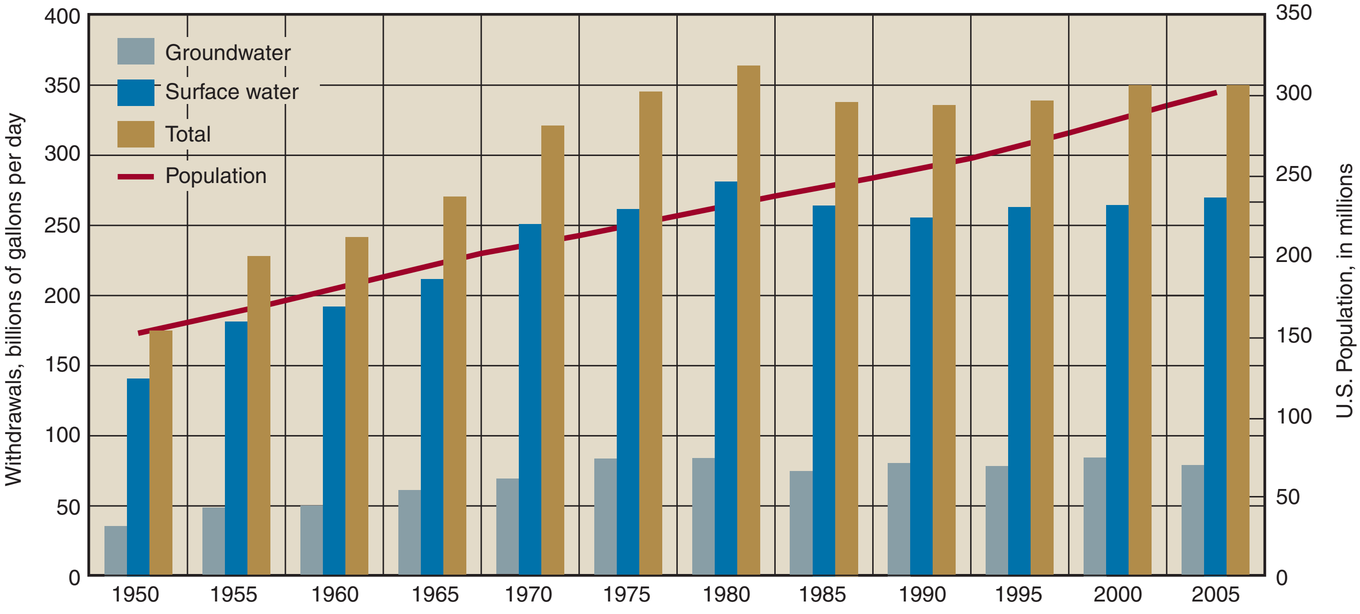

FIGURE 18.11 Trends in U.S. fresh groundwater and surface-water withdrawals and human population, 1950–2005. (*Source*: Kenny, J.F. et al., 2005. *Estimated Use of Water in the United States in 2005*. U.S. Geological Survey Circular 1344, 2010).

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

18.4 Water Conservation

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

Agricultural Use

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

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

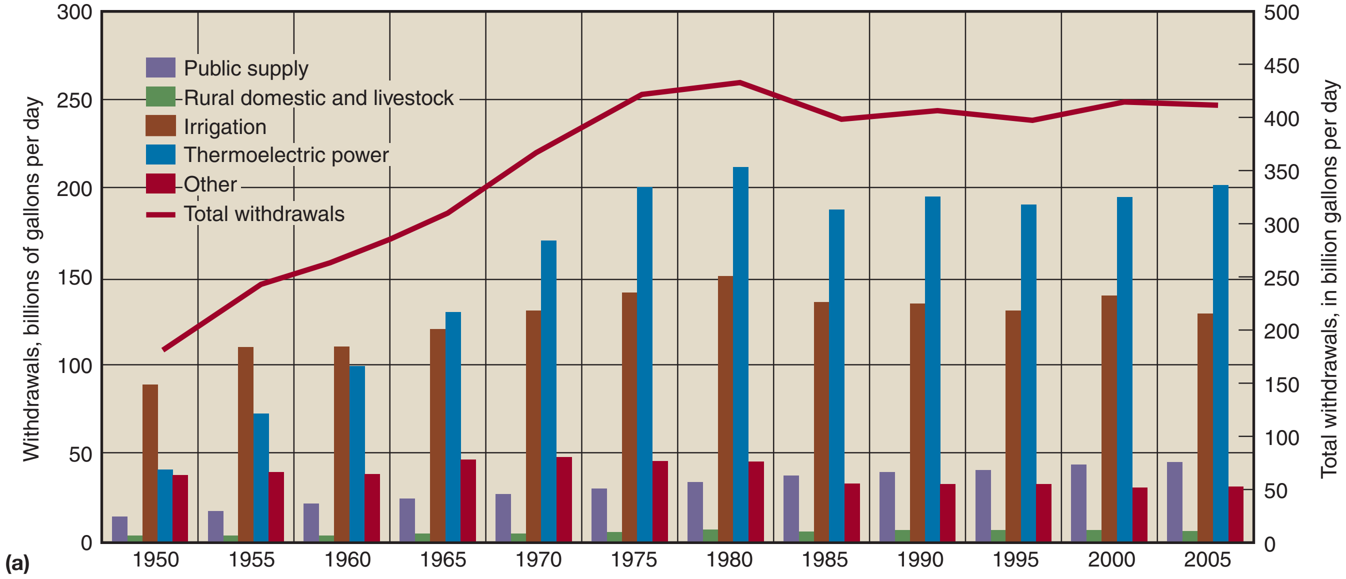

FIGURE 18.12 **(a)** Trends in total U.S. water withdrawals by water-use category (1950–2005). (*Source*: Kenny J. F. et al., 2010, *Estimated Use of Water in the United States in 2005.* U.S. Geological Survey Circular 1344); **(b)** U.S. water use in 2005 (by percent).

Public supply, 11 percent

Public supply water intake, Bay County, Florida

Richard L. Marella, USGS

Irrigation, 31 percent

Gated-pipe flood irrigation, Fremont County, Wyoming

Jeff Vanuga, USDA NRCS

Aquaculture, less than 2 percent

World's largest trout farm, Buhl, Idaho

Courtesy of Clear Springs Foods, Inc.

Mining, 1 percent

Spodumene pegmatite mine, Kings Mountain, North Carolina

Nancy L. Barber, USGS

Domestic, 1 percent

Domestic well, Early County, Georgia

Alan M. Cressler, USGS

Livestock, less than 1 percent

Livestock watering, Rio Arriba County, New Mexico

Jeff Vanuga, USDA NRCS

Industrial, 4 percent

Paper mill, Savannah, Georgia

Alan M. Cressler, USGS

Thermoelectric power, 49 percent

Cooling towers, Burke County, Georgia

Alan M. Cressler, USGS

(b)

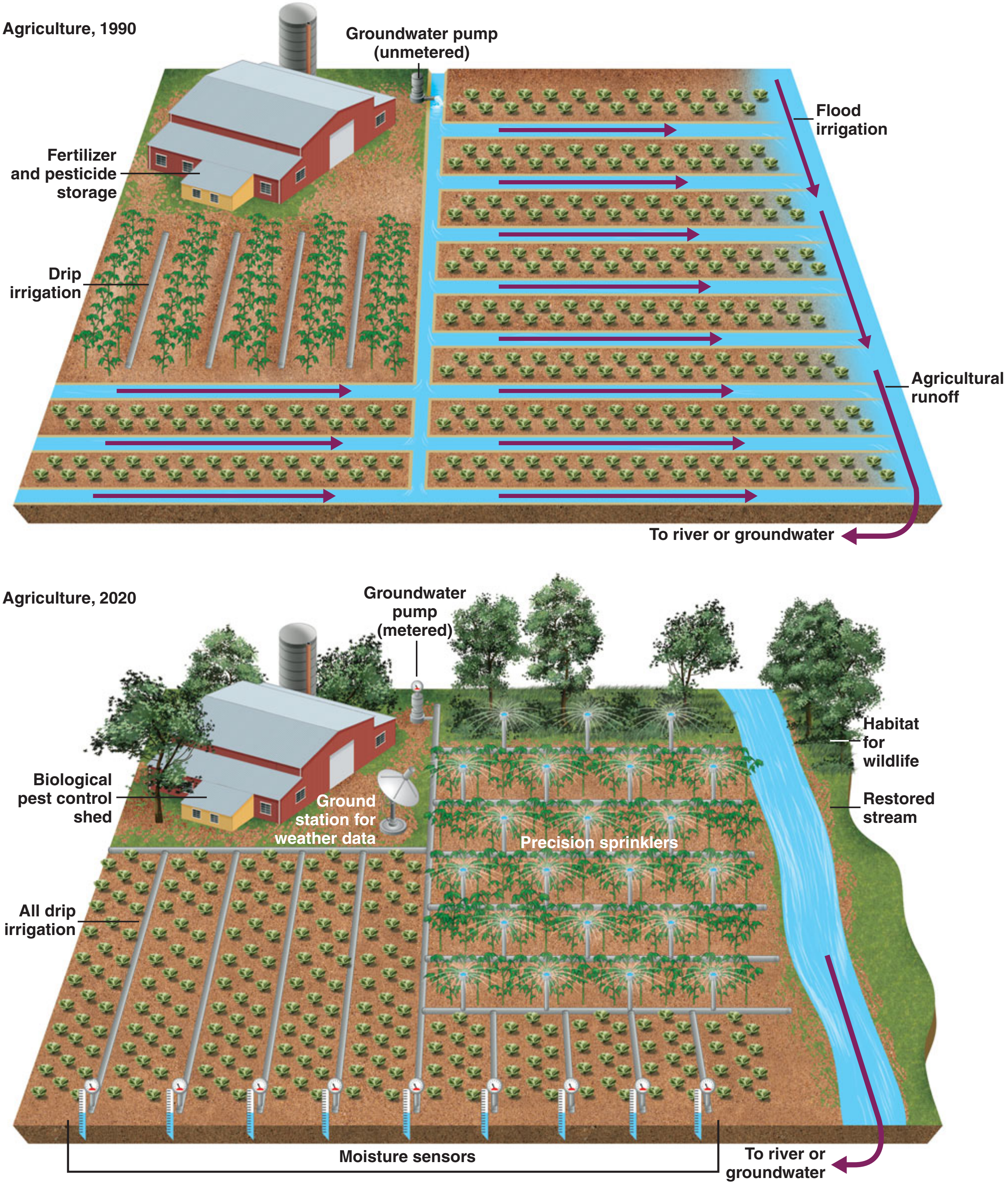

FIGURE 18.13 Comparison of agricultural practices in 1990 with what they might be by 2020. The improvements call for a variety of agricultural procedures, including biological pest control, more efficient irrigation, and restoration of water resources and wildlife habitat. (*Source:* P.H. Gleick, P.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

Public Supply and Domestic Use

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

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

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

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

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

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

Industry and Manufacturing Use

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

18.5 Sustainability and Water Management

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

Sustainable Water Use

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

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

Groundwater Sustainability

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

Water Management

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

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

A Master Plan for Water Management

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

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

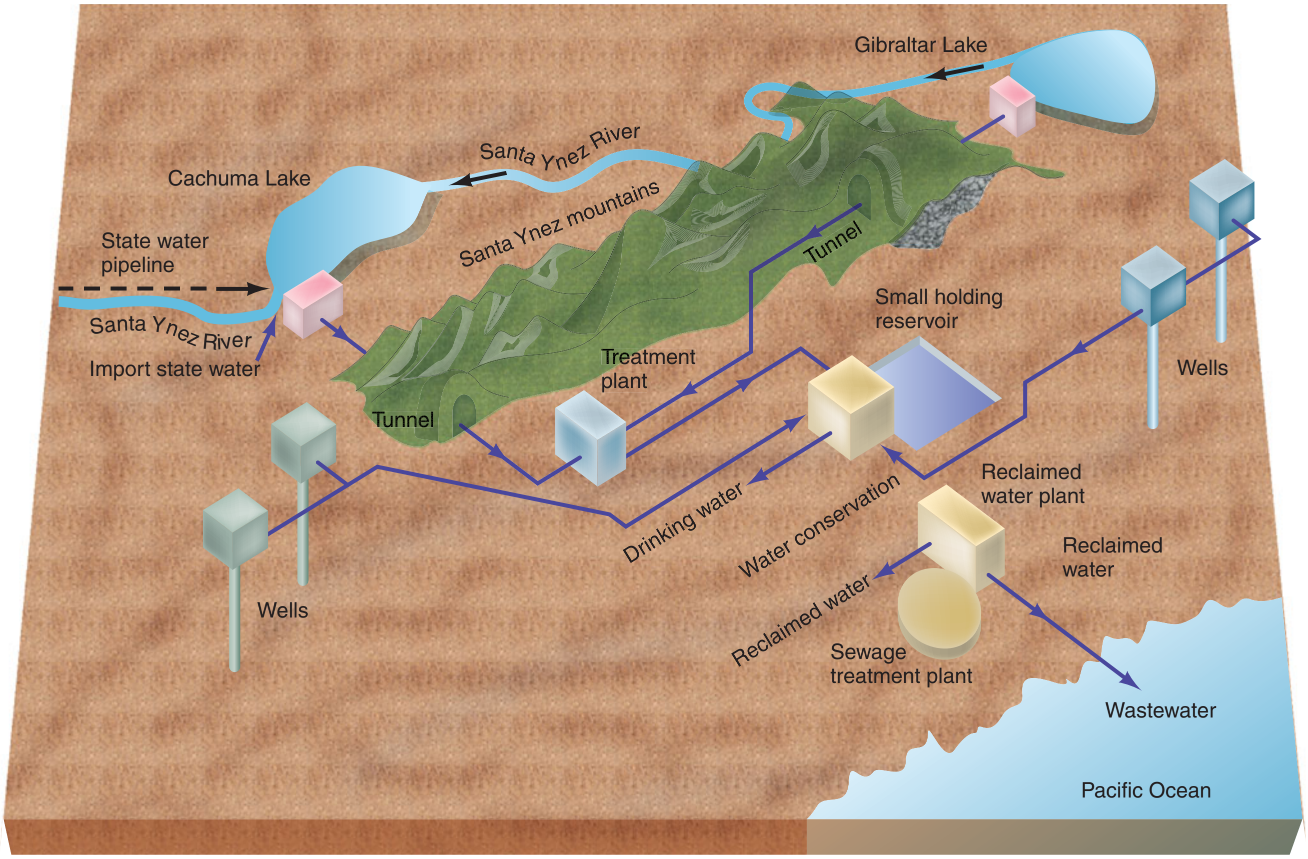

FIGURE 18.14 Schematic drawing of a variable source model (present and future) for water supply for the city of Santa Barbara, California. (*Source:* Santa Barbara City Council, data from 2009.)

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

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

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

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

Water Management and the Environment

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

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

Virtual Water

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

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

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

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

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

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

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

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

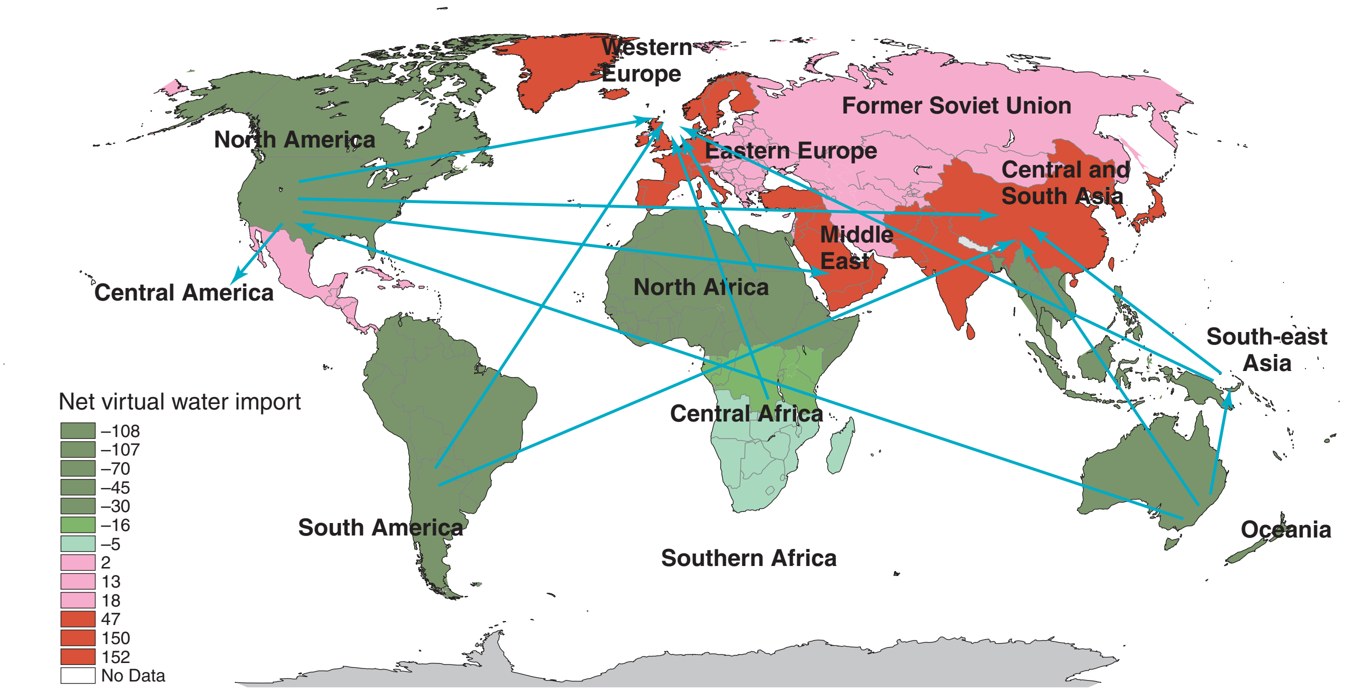

FIGURE 18.15 Virtual-water balances and transfers (6m^3 of water). 1 Gm^3 is 1 billion cubic meters. (*Source:* A.Y. Hoekstra, ed., 2003, Virtual water trade: Proceedings of the International Expert Meeting on Virtual Water Trade. Value of Water Research Report Series 12. IHE Delft. The Netherlands.)

Water Footprint

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

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

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

18.6 Wetlands

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

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

Natural Service Functions of Wetlands

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

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

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

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

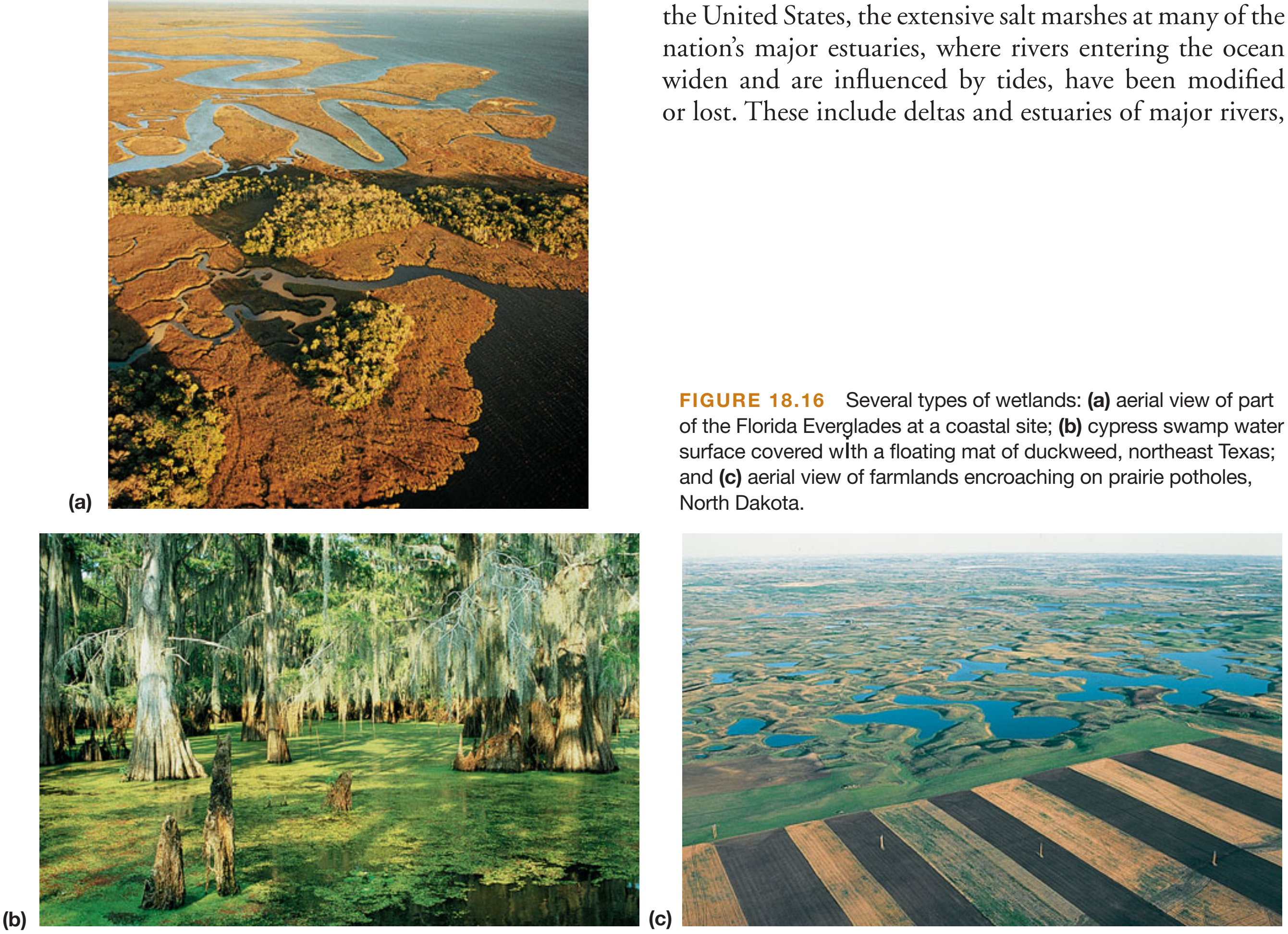

FIGURE 18.16 Several types of wetlands: **(a)** aerial view of part of the Florida Everglades at a coastal site; **(b)** cypress swamp water surface covered with a floating mat of duckweed, northeast Texas; and **(c)** aerial view of farmlands encroaching on prairie potholes, North Dakota.

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

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

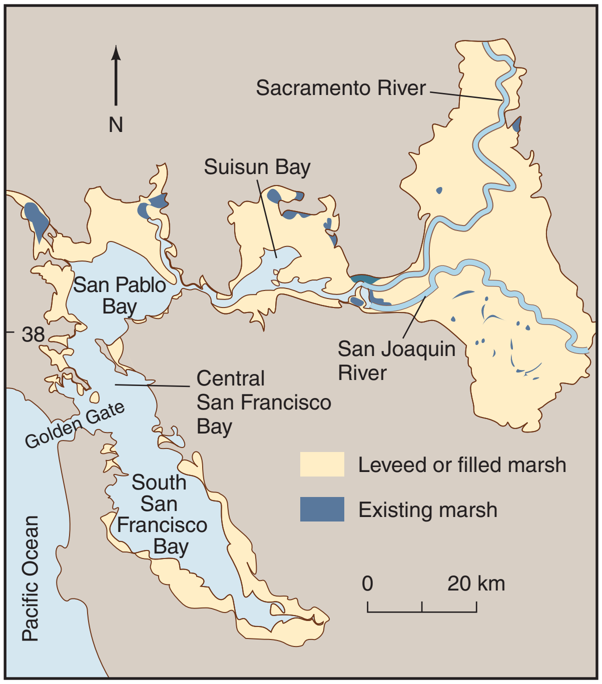

FIGURE 18.17 Loss of marshlands in the San Francisco Bay estuary from about 1850 to the present. (*Sources:* T.J. Conomos, ed., *San Francisco, the Urbanized Estuary* [San Francisco: American Association for the Advancement of Science, 1979]; F.H. Nichols, J.E. Cloern, S.N. Luoma, and D.H. Peterson,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

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

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

Restoration of Wetlands

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

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

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

18.7 Dams and the Environment

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Removal of Dams

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

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

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

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

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

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

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

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

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

18.8 Global Water Shortage Linked to Food Supply

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

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

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

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

CRITICAL THINKING ISSUE

What Is Your Water Footprint?

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

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

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

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

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

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

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

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

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

[a] Population (approx.) in 2000

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

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

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

Critical Thinking Questions

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

SUMMARY

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

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

REEXAMINING THEMES AND ISSUES

Human Population

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

Sustainability

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

Global Perspective

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

Urban World

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

People and Nature

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

Science and Values

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

KEY TERMS

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

STUDY QUESTIONS

1. If water is one of our most abundant resources, why are we concerned about its availability in the future?

2. Which is more important from a national point of view, conservation of water use in agriculture or in urban areas? Why?

3. Distinguish between in-stream and off-stream uses of water. Why is in-stream use controversial?

4. What are some important environmental problems related to groundwater use?

5. How might your community better manage its water resources?

6. Discuss how the concept of virtual water is related to water conservation and management at the global level.

7. What are some of the major environmental impacts associated with the construction of dams? How might these be minimized?

8. What are the most important factors in planning to remove a dam?

9. How can we reduce or eliminate the growing global water shortage? Do you believe the shortage is related to our food supply? Why? Why not?

10. Why is water such an important resource issue?

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