CHAPTER 17

Between 2000 and 2010, the surface level of Lake Mead, the largest reservoir on the Colorado River, fell more than 100 ft (30.5 m) during the worst drought in recorded history. If water levels fall another 100 ft, the reservoir will reach "dead pool" levels at which it can provide neither the water nor the electrical power on which millions of people depend.

Water Use and Management

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

~ John Wesley Powell

Learning Outcomes

After studying this chapter, you should be able to:

17.1 Summarize why water is a precious resource and why shortages occur.
17.2 Compare major water compartments.
17.3 Summarize water availability and use.
17.4 Investigate freshwater shortages.
17.5 Illustrate the benefits and problems of dams and diversions.
17.6 Appreciate how we might get by with less water.
17.7 Understand how we might increase water supplies.

Case Study When Will Lake Mead Go Dry?

The Colorado River is the lifeblood of the American Southwest. More than 30 million people and a $1.2 trillion regional economy in cities such as Los Angeles, Phoenix, Las Vegas, and Denver depend on its water. But the reliability of this essential resource is in doubt. Drought, climate change, and rapid urban growth are creating worries about the sustainability of the water supply for the entire watershed.

In 2008 Tim Barnett and David Pierce from the Scripps Institute in California published a provocative article suggesting that within a decade or so, both Lake Mead and Lake Powell could reach levels at which neither would be able to either produce power or provide water for urban or agricultural use, if no changes are made in current water allocations. For these huge lakes, which constitute more than 85 percent of the water storage for the entire Colorado system, to reach "dead pool" levels would be a catastrophe for the whole region. This warning is based on both historical records and climate models that suggest a 10 to 30 percent runoff reduction in the area over the next 50 years.

The roots of this problem can be traced to the Colorado Compact of 1922, in which state water rights were allocated. The previous decade had been the wettest in more than a thousand years. The estimated annual river flow of 18 million acre-feet (22 billion m^3) that negotiators thought they could allocate was about 20 percent higher than the twentieth-century average. The error didn't matter much at the time, because none of the states were able to withdraw their share of water from the river.

As cities have grown, however, and agriculture has expanded over the past century, competing claims for water have repeatedly caused tensions and disputes. Cumulatively, massive water diversion projects, such as the Colorado River Aqueduct, which provides water for Los Angeles, the All-American Canal, which irrigates California's Imperial Valley, or the Central Arizona Project, which transports water over the mountains and across the desert to Phoenix and Tucson, are capable of diverting as much water as the entire Colorado River flow. In 1944 the United States agreed to provide 1.5 million acre-feet to Mexico so there would be at least a little water (although of dubious quality) in the river when it crossed the border.

To make matters worse, climate change is expected to decrease western river flows by 10 to 30 percent over the next 50 years. The Southwest is currently in its eighth year of drought, which may be the first hint of that change. The maximum water level in Lake Mead (an elevation of 1,220 feet or 372 m) was last reached in 2000. Since then the lake level has been dropping about 12 feet (3.6 m) per year, reaching 1,097 feet in 2010. The minimum power level (the height at which electricity can be produced) is 1,050 feet (320 m). The minimum level at which water can be drawn off by gravity is 900 feet (274 m). Barnett and Pierce estimate that without changes in current management plans, there's a 50 percent chance that minimum power pool levels in both Lakes Mead and Powell will be reached by 2017 and there's an equal chance that live storage in both lakes will be gone by about 2021.

Already, we're at or beyond the sustainable limits of the river. Currently Lake Powell holds a little over half its maximum volume, and Lake Mead is only 43 percent full (fig. 17.1). The shores of both lakes now display a wide "bathtub ring" of deposited minerals left by the receding water. One suggestion has been to drain Lake Powell in order to ensure a water supply for Lake Mead. This solution is strenuously opposed by many of the 3 million people per year who recreate in its red rock canyons and sparkling blue water. On the other hand, think of the cost and disruption if Los Angeles, Phoenix, Las Vegas, and other major metropolitan areas of the Southwest were to run out of water and power.

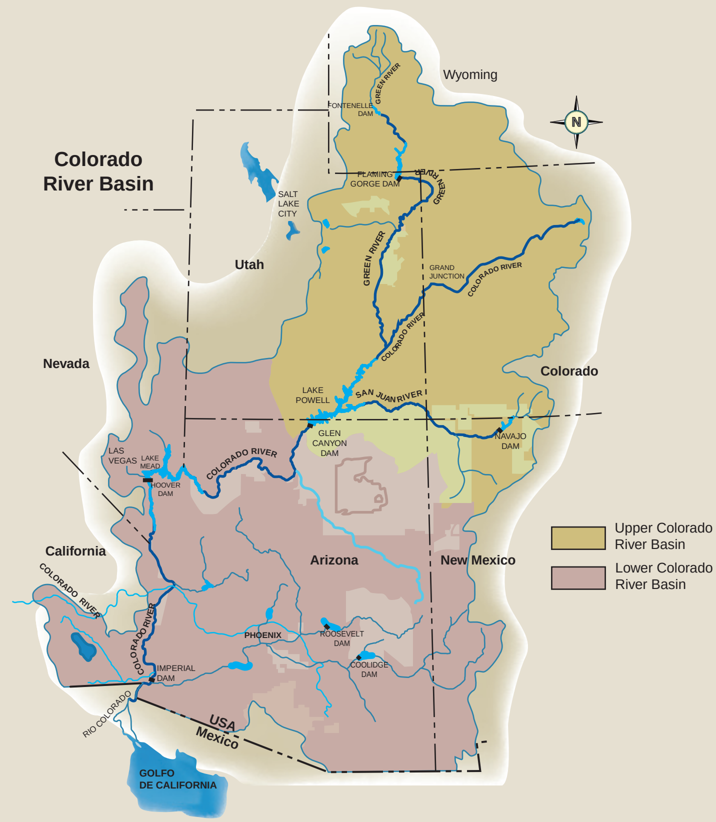


FIGURE 17.1 The Colorado River flows 2,330 km (1,450 mi) through seven western states. Its water supports 30 million people and a $1.2 trillion regional economy, but drought, climate change, and rapid urban growth threaten the sustainability of this resource.

The American Southwest isn't alone in facing this problem. The United Nations warns that water supplies are likely to become one of the most pressing environmental issues of the twenty-first century. By 2025 two-thirds of all humans could be living in places where water resources are inadequate. In this chapter we'll look at the sources of our fresh water, what we do with it, and how we might protect its quality and extend its usefulness.

For further reading, see:

Barnett, T. P., and D. W. Pierce. 2008. When will Lake Mead go dry? *Journal of Water Resources Research,* vol. 44, W03201.

Powell, James L. 2009. *Dead Pool: Lake Powell, Global Warming, and the Future of Water in the West.* University of California Press.

For related resources, including Google Earth™ placemarks that show locations where these issues can be seen, visit EnvironmentalScience-Cunningham.blogspot.com.

17.1 Water Resources

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

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

The hydrologic cycle constantly redistributes water

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

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

Table 17.1 Some Units of Water Measurement

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

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

Water supplies are unevenly distributed

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

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

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

Human activity also explains some regions of water deficit. As noted earlier, plant transpiration recycles moisture and produces rain. When forests are cleared, falling rain quickly

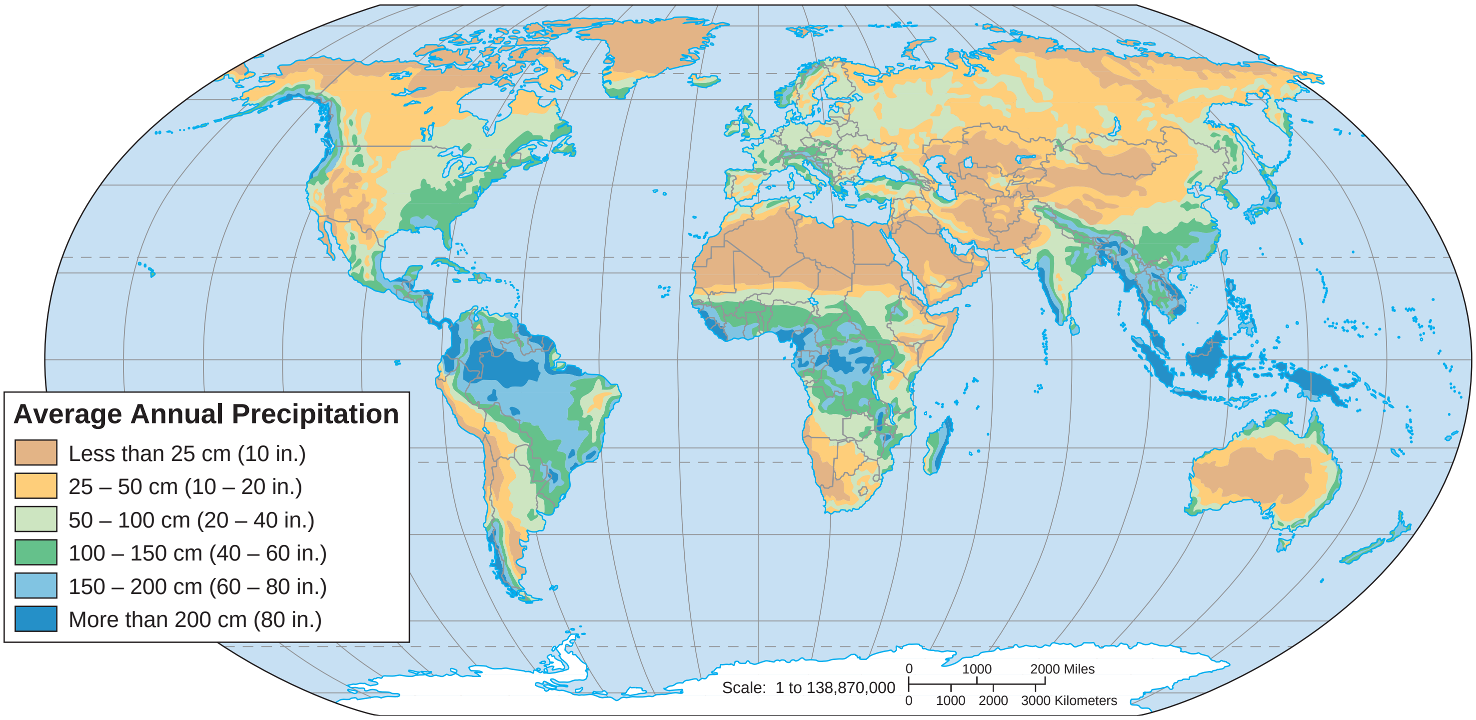


FIGURE 17.2 Average annual precipitation. Note wet areas that support tropical rainforests occur along the equator, while the major world deserts occur in zones of dry, descending air between 20° and 40° north and south.

enters streams and returns to the ocean. In Greece, Lebanon, parts of Africa, the Caribbean, South Asia, and elsewhere, desertlike conditions have developed since the original forests were destroyed.

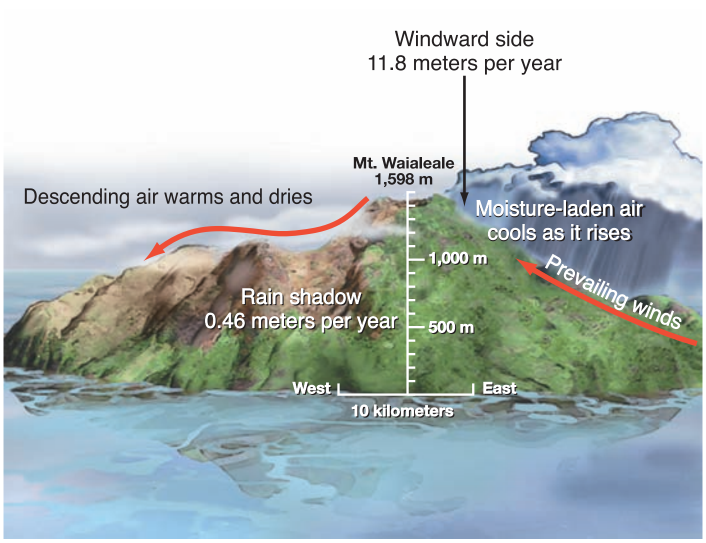


FIGURE 17.3 Rainfall on the east side of Mount Waialeale in Hawaii is more than 20 times as much as on the west side. Prevailing trade winds bring moisture-laden sea air onshore. The air cools as it rises up the flanks of the mountain and the water it carries precipitates as rain—11.8 m (38 ft) per year!

Think About It

We have noted three important natural causes of water surpluses and deficits. Which of these might be important where you live?

Does water availability affect your lifestyle? Should it?

17.2 Major Water Compartments

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

Oceans hold 97 percent of all water on earth

Together the oceans contain more than 97 percent of all the *liquid* water in the world. (The water of crystallization in rocks is far larger than the amount of liquid water.) Oceans are too salty for most human uses, but they contain 90 percent of the world's living biomass. Although the ocean basins really form a continuous

Table 17.2 Earth's Water Compartments

Compartment	Volume (1,000 km³)	Percent of Total Water	Average Residence Time
Total	1,386,000	**100**	2,800 years
Oceans	1,338,000	**96.5**	3,000 to 30,000 years*
Ice and snow	24,364	**1.76**	1 to 100,000 years*
Saline groundwater	12,870	**0.93**	Days to thousands of years*
Fresh groundwater	10,530	**0.76**	Days to thousands of years*
Fresh lakes	91	**0.007**	1 to 500 years*
Saline lakes	85	**0.006**	1 to 1,000 years*
Soil moisture	16.5	**0.001**	2 weeks to 1 year*
Atmosphere	12.9	**0.001**	1 week
Marshes, wetlands	11.5	**0.001**	Months to years
Rivers, streams	2.12	**0.0002**	1 week to 1 month
Living organisms	1.12	**0.0001**	1 week

*Depends on depth and other factors.

Source: Data from UNEP, 2002.

reservoir, shallows and narrows between them reduce water exchange, so they have different compositions, climatic effects, and even different surface elevations.

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

In tropical seas, surface waters are warmed by the sun, diluted by rainwater and runoff from the land, and aerated by wave action. In higher latitudes, surface waters are cold and much more dense. This dense water subsides or sinks to the bottom of deep ocean basins and flows toward the equator. Warm surface water

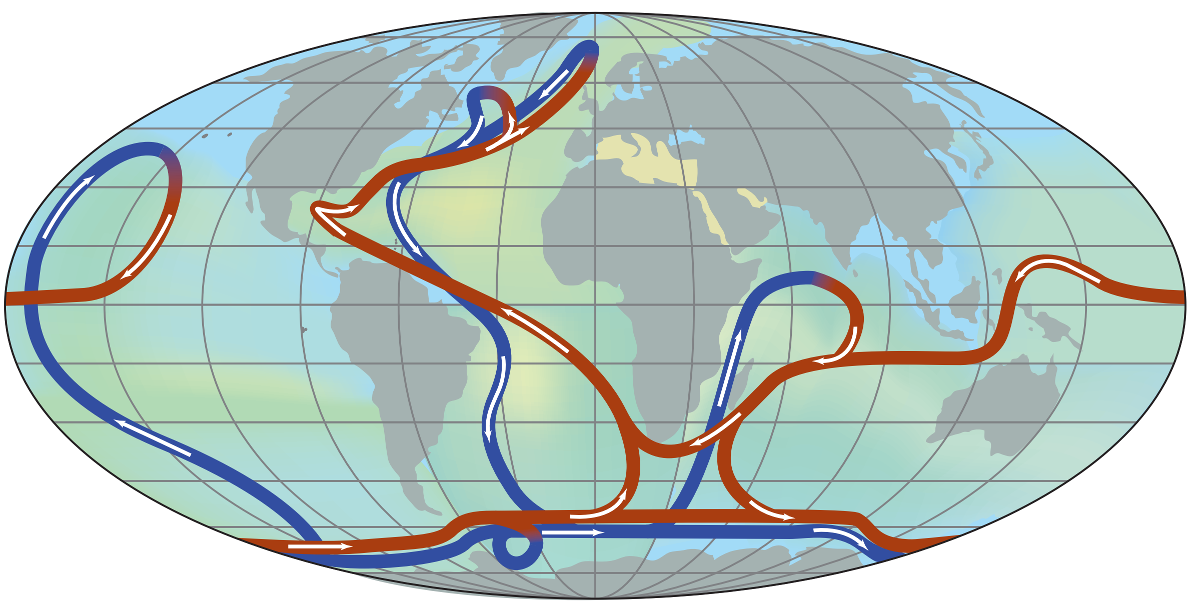


FIGURE 17.4 Ocean currents act as a global conveyor system, redistributing warm (red) and cold (blue) currents around the globe. These currents moderate our climate. For example, the Gulf Stream keeps northern Europe much warmer than northern Canada. Ocean colors show salinity variation from low (*blue*) to high (*yellow*).
Source: NASA.

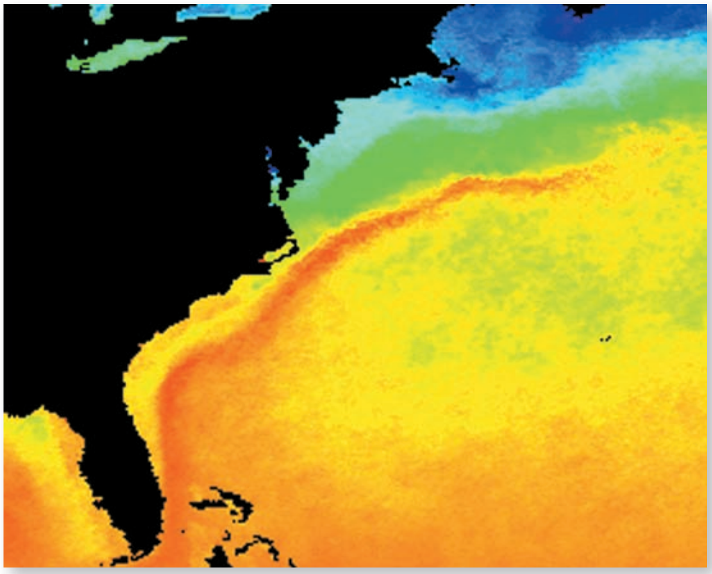


FIGURE 17.5 Ocean currents, such as the warm Gulf Stream, redistribute heat as they flow around the globe. Here, orange and yellow indicate warm water temperatures (25–30°C); blue and green are cold (0–5°C).

of the tropics stratifies or floats on top of this cold, dense water as currents carry warm water to high latitudes. Sharp boundaries form between different water densities, different salinities, and different temperatures, retarding mixing between these layers.

Glaciers, ice, and snow contain most surface fresh water

Of the 2.4 percent of all water that is fresh, nearly 90 percent is tied up in glaciers, ice caps, and snowfields (fig. 17.6). Although most of this ice is located in Antarctica, Greenland, and the floating ice cap in the Arctic, alpine glaciers and snowfields supply water to billions of people. The winter snowpack on the western slope of the Rocky Mountains, for example, provides 75 percent of the flow in the Colorado River described in the opening case study of this chapter. Drought conditions already have reduced snowfall (and runoff) in the western United States, and global warming is projected to cause even further declines.

As chapter 15 discusses, climate change is shrinking glaciers and snowfields nearly everywhere (fig. 17.7). In Asia, the Tibetan glaciers that are the source of six of the world's largest rivers and supply drinking water for three billion people are shrinking rapidly. There are warnings that these glaciers could vanish in a few decades, which would bring enormous suffering and economic loss in many places.

Groundwater stores large resources

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

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

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

Areas where water infiltrates into an aquifer are called **recharge zones**. The rate at which most aquifers are refilled is very slow, however, and groundwater presently is being removed faster than it can be replenished in many areas. Urbanization, road building, and other development often block recharge zones and prevent replenishment of important aquifers. Contamination of surface

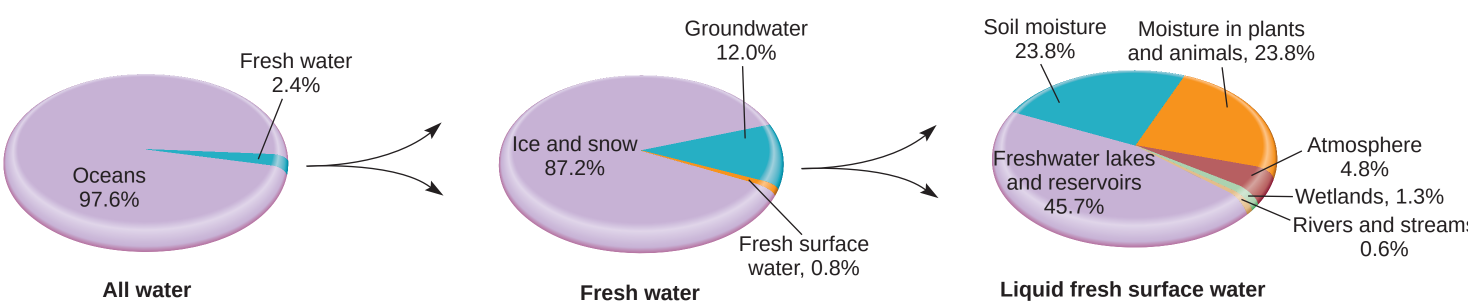


FIGURE 17.6 Less than 1 percent of fresh water, and less than 0.02 percent of all water, is fresh, liquid surface water on which terrestrial life depends.
Source: U.S. Geological Survey.

FIGURE 17.7 Glaciers and snowfields provide much of the water on which billions of people rely. The snowpack in the western Rocky Mountains, for example, supplies about 75 percent of the annual flow of the Colorado River. Global climate change is shrinking glaciers and causing snowmelt to come earlier in the year, disrupting this vital water source.

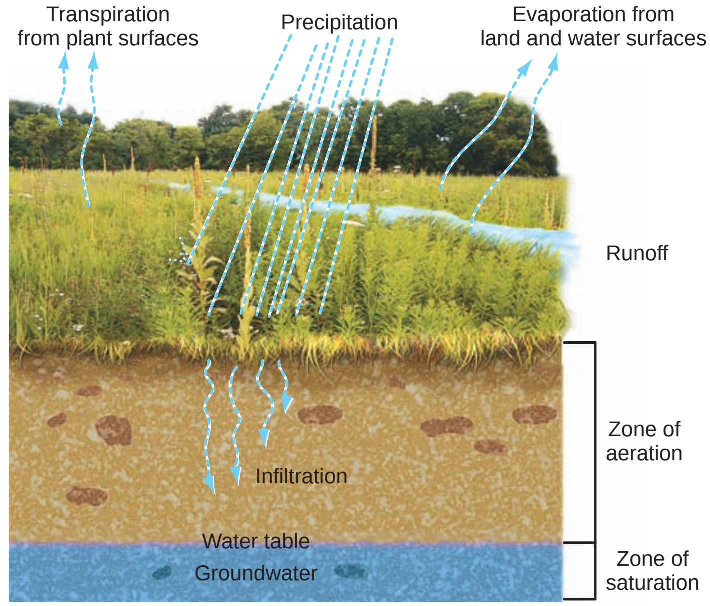


FIGURE 17.8 Precipitation that does not evaporate or run off over the surface percolates through the soil in a process called infiltration. The upper layers of soil hold droplets of moisture between air-filled spaces. Lower layers, where all spaces are filled with water, make up the zone of saturation,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

water in recharge zones and seepage of pollutants into abandoned wells have polluted aquifers in many places, making them unfit for most uses (chapter 18). Many cities protect aquifer recharge zones from pollution or development, both as a way to drain off rainwater and as a way to replenish the aquifer with pure water.

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

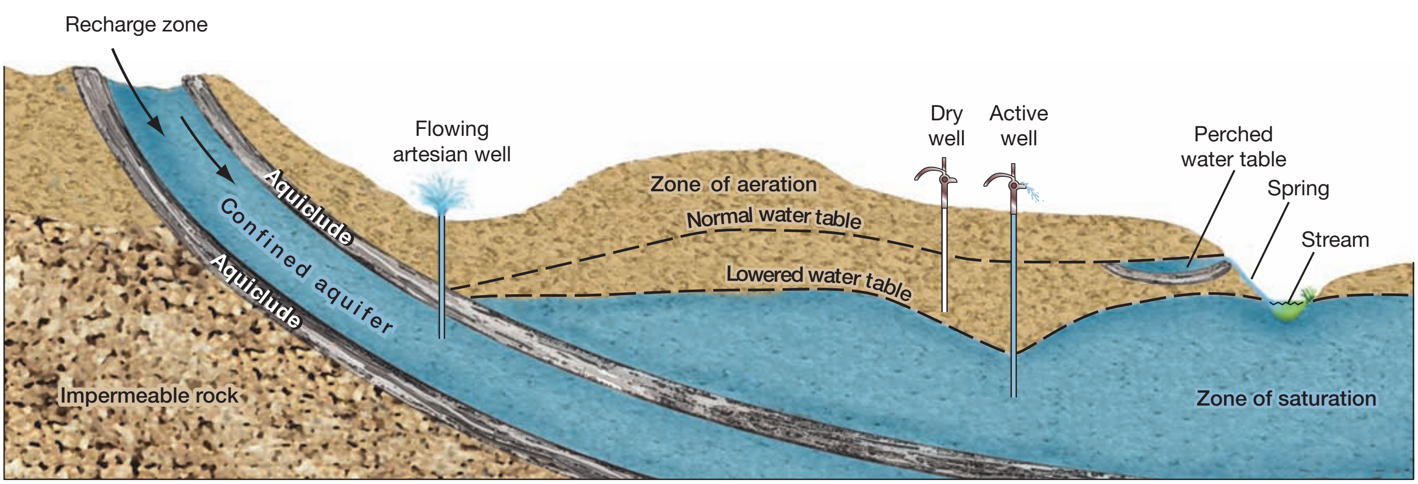


FIGURE 17.9 An aquifer is a porous or cracked layer of rock. Impervious rock layers (aquicludes) keep water within a confined aquifer. Pressure from uphill makes an artesian well flow freely. Pumping can create a cone of depression, which leaves shallower wells dry.

Rivers, lakes, and wetlands cycle quickly

Precipitation that does not evaporate or infiltrate into the ground runs off over the surface, drawn by the force of gravity back toward the sea. Rivulets accumulate to form streams, and streams join to form rivers. Although the total amount of water contained at any one time in rivers and streams is small compared to the other water reservoirs of the world (see table 17.2), these surface waters are vitally important to humans and most other organisms. Most rivers, if they were not constantly replenished by precipitation, meltwater from snow and ice, or seepage from groundwater, would begin to diminish in a few weeks.

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

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

Table 17.3 Major Rivers of the World

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

1 m^3 = 264 gallons.

Source: World Resources Institute.

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

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

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

The atmosphere is among the smallest of compartments

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

Think About It

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

17.3 Water Availability and Use

Clean, fresh water is essential for nearly every human endeavor. Perhaps more than any other environmental factor, the availability of water determines the location and activities of humans on earth (fig. 17.10). **Renewable water supplies** are made up, in general, of surface runoff plus the infiltration into accessible freshwater aquifers. About two-thirds of the water carried in rivers and streams every year occurs in seasonal floods that are too large or violent to be stored or trapped effectively for human uses. Stable runoff is the dependable, renewable, year-round supply of surface water. Much of this occurs, however, in sparsely inhabited regions

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

or where technology, finances, or other factors make it difficult to use it productively. Still, the readily accessible, renewable water supplies are very large, amounting to some 1,500 km^3 (about 400,000 gal) per person per year worldwide.

Many countries suffer water scarcity and water stress

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

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

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

Land-use practices often exacerbate drought effects. The worst drought in American history occurred in the 1930s. Poor soil conservation practices and a series of dry years in the Great Plains combined to create the "dust bowl." Wind stripped topsoil from millions of hectares of land, and billowing dust clouds turned day into night. Thousands of families were forced to leave farms and migrate to cities.

As the opening case study shows, much of the western United States has been exceptionally dry over the past decade. Many places are experiencing water crises (fig. 17.11). Is this just a temporary cycle or the beginning of a new climatic regime?

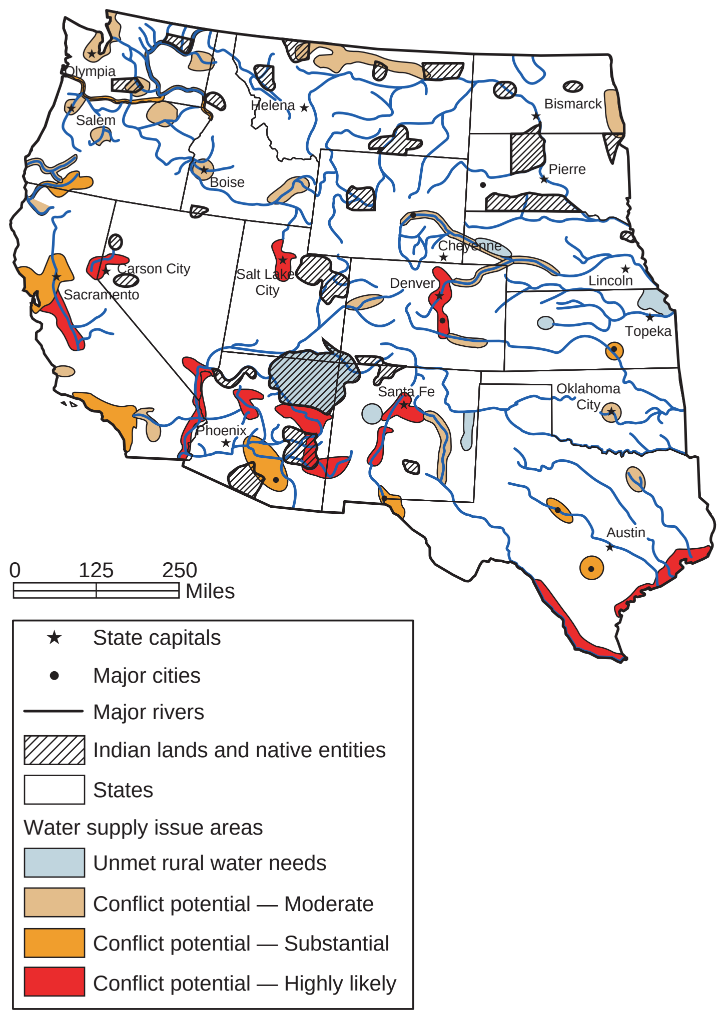


FIGURE 17.11 Rapidly growing populations in arid regions are straining available water supplies. By 2025, the Department of the Interior warns, shortages could cause conflicts in many areas.
Source: Data from U.S. Department of Interior.

The United States government projects that 36 states will have water deficits by 2012. Increased temperatures, disturbed weather patterns, population growth, urban sprawl, waste, and wasteful uses all will contribute to these shortages. The effects on water supplies may well be the most serious consequences of global climate change.

If the government had listened to Major John Wesley Powell, settlement patterns in the western United States would be very different from what we see there today. Powell, who led the first expedition down the Colorado River, went on to be the first head of the U.S. Geological Survey. In that capacity he did a survey of the agricultural and settlement potential of the western desert. His conclusion, quoted at the beginning of this chapter, was that there isn't enough water there to support a large human population.

Powell recommended that the political organization of the West be based on watersheds so that everyone in a given jurisdiction would be bound together by the available water. He thought that farms should be limited to local surface water supplies, and that cities should be small oasis settlements. Instead we've built huge metropolitan areas, such as Los Angeles, Phoenix, Las Vegas, and Denver, in places where there is little or no natural water supply. Will those cities survive impending shortages?

Water use is increasing

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

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

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

In contrast to energy resources, which usually are consumed when used, water can be used over and over if it is not too badly contaminated. Water **withdrawal** is the total amount of water taken from a water body. Much of this water could be returned to circulation in a reusable form. Water **consumption**, on the other hand, is loss of water due to evaporation, absorption, or contamination.

Agriculture is the greatest water consumer worldwide

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

A tragic case of water overconsumption is the Aral Sea, which lies in Kazakhstan and Uzbekistan (see map at the end of this book). Once the fourth largest inland water body in the world, this giant saline lake lost 75 percent of its surface area and 90 percent of its volume between 1975 and 2009 (fig. 17.13) when, under the former Soviet Union, 90 percent of the natural flow of the Amu Dar'ya and Syr Dar'ya rivers was diverted to irrigate rice and cotton. Towns that once were

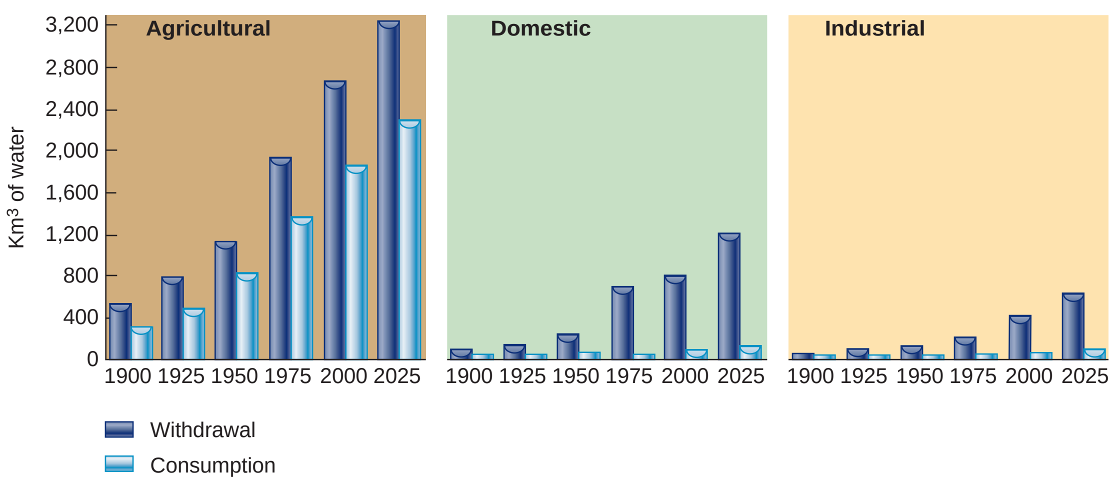


FIGURE 17.12 Growth of water withdrawal and consumption, by sector, with projected levels to 2025.
Source: UNEP, 2002.

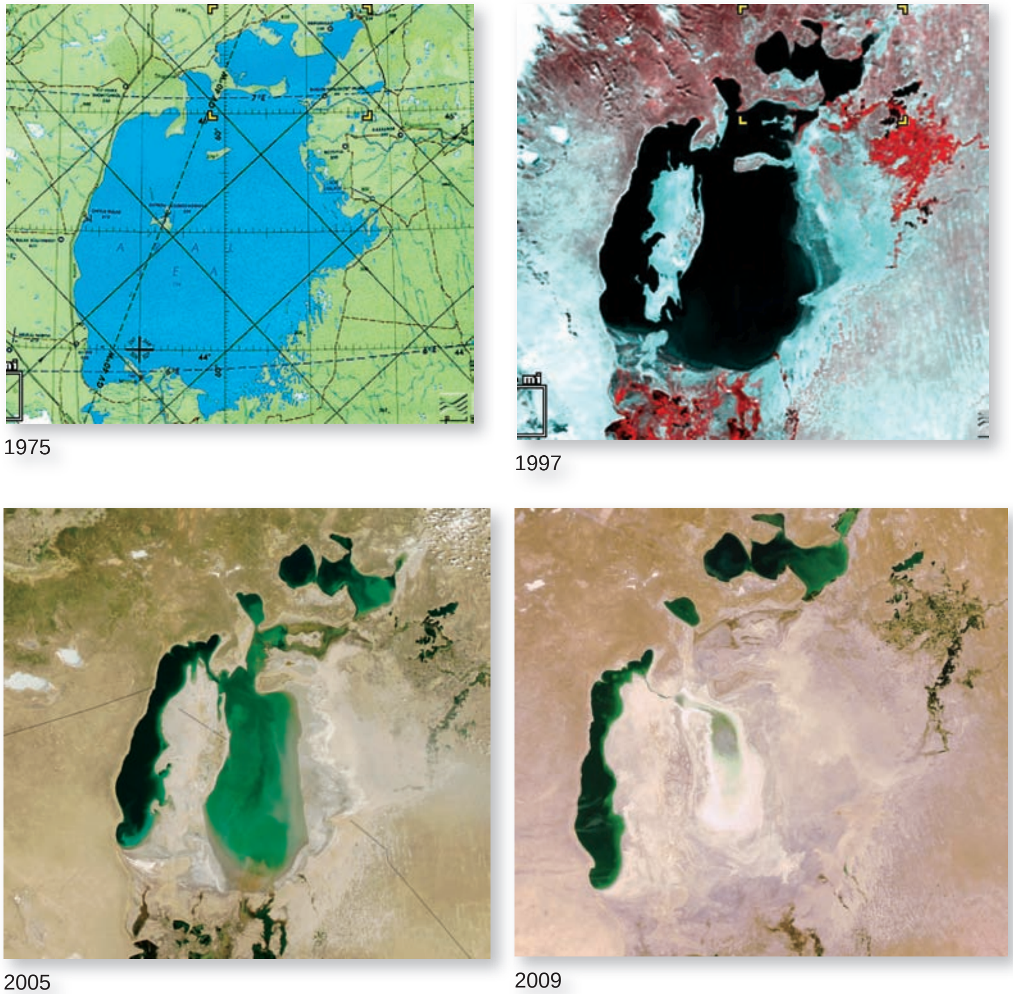


FIGURE 17.13 For 30 years, rivers feeding the Aral Sea were diverted to irrigate cotton and rice fields. The Sea has lost more than 90 percent of its water. The “Small Aral” (upper right lobe) has separated from the main lake, and is now being refilled.

prosperous fish-processing and shipping ports now lie 100 km from the lake shore.

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

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

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

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

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

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

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

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

Domestic and industrial water use is greatest in wealthy countries

Worldwide, domestic water use accounts for only about 6 percent of water withdrawals. Because little of this water evaporates or seeps into the ground, consumptive water use is slight, about 10 percent on average. Where sewage treatment is unavailable, however, water can be badly degraded by urban uses. In wealthy countries, each person uses about 500 to 800 l per day (180,000 to 280,000 l per year), far more than in developing countries (30 to 150 l per day). In North America the largest single use of domestic water is toilet flushing (fig. 17.15). On average, each person in the United States uses about 50,000 l (13,000 gal) of drinking-quality water annually to flush toilets. Bathing accounts for nearly a third of water use, followed by laundry and washing. In western cities such as Palm Desert and Phoenix, lawn watering is also a major water user.

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

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

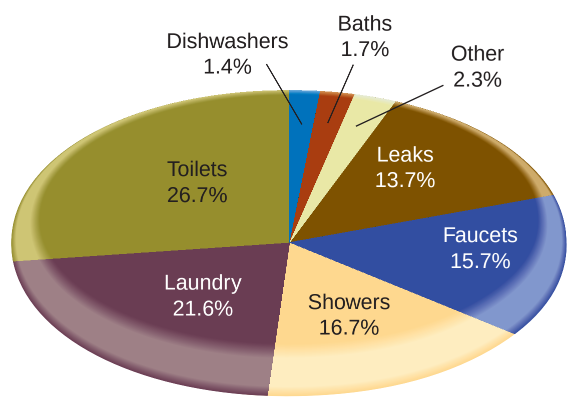


FIGURE 17.15 Typical household water use in the United States.
Source: Data from the American Water Works Association, 2010.

17.4 Freshwater Shortages

Clean drinking water and basic sanitation are necessary to prevent communicable diseases and to maintain a healthy life. For many of the world's poorest people, one of the greatest environmental threats to health remains the continued use of polluted water. The United Nations estimates that at least a billion people lack access to safe drinking water and 2.5 billion don't have adequate sanitation. These deficiencies result in hundreds of millions of cases of water-related illness and more than 5 million deaths every year. As populations grow, more people move into cities, and agriculture and industry compete for increasingly scarce water supplies, water shortages are expected to become even worse.

By 2025 two-thirds of the world's people may be living in countries that are water-stressed—defined by the United Nations as consumption of more than 10 percent of renewable freshwater resources. One of the United Nations Millennium goals is to reduce by one-half the proportion of people without reliable access to clean water and improved sanitation.

There have been many attempts to enhance local supplies and redistribute water. Towing icebergs from Antarctica has been proposed, and creating rain in dry regions has been accomplished, with mixed success, by cloud seeding—distributing condensation nuclei in humid air to help form raindrops. Desalination is locally important: in the arid Middle East, where energy and money are available but water is scarce, desalination is sometimes the principal source of water. Some American cities, such as Tampa, Florida, and San Diego, California, also depend partly on energy-intensive desalination (Exploring Science, p. 389).

Many people lack access to clean water

The World Health Organization considers an average of 1,000 m^3 (264,000 gal) per person per year to be a necessary amount of water for modern domestic, industrial, and agricultural uses. Some 45 countries, most of them in Africa or the Middle East, cannot meet the minimum essential water needs of all their citizens. In some countries the problem is access to clean water. In Mali, for example, 88 percent of the population lacks clean water; in Ethiopia, it is 94 percent. Rural people often have less access to clean water than do city dwellers. Causes of water shortages include natural deficits, overconsumption by agriculture or industry, and inadequate funds for purifying and delivering good water.

More than two-thirds of the world's households have to fetch water from outside the home (fig. 17.16). This is heavy work, done mainly by women and children and sometimes taking several hours a day. Improved public systems bring many benefits to these poor families.

Availability doesn't always mean affordability. A typical poor family in Lima, Peru, for instance, uses one-sixth as much water as a middle-class American family but pays three times as much for it. If they followed government recommendations to boil all water to prevent cholera, up to one-third of the poor family's income could be used just in acquiring and purifying water.

FIGURE 17.16 Village water supplies in Ghana.

Investments in rural development have brought significant improvements in recent years. Since 1990 nearly 800 million people—about 13 percent of the world's population—have gained access to clean water. The percentage of rural families with safe drinking water has risen from less than 10 percent to nearly 75 percent.

Groundwater is being depleted

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

In many areas of the United States, groundwater is being withdrawn from aquifers faster than natural recharge can replace it. The Ogallala Aquifer, for example, underlies eight states in the arid high plains between Texas and North Dakota (fig. 17.17). As deep as 400 m (1,200 ft) in its center, this porous bed of sand, gravel, and sandstone once held more water than all the freshwater lakes, streams, and rivers on earth. Excessive pumping for irrigation and other uses has removed so much water that wells have dried up in many places, and farms, ranches, even whole towns are being abandoned.

On a local level, this causes a cone of depression in the water table, as is shown in figure 17.18. A heavily pumped well can lower the local water table so that shallower wells go dry. On a broader scale, heavy pumping can deplete a whole aquifer. Many aquifers have slow recharge rates, so it will take thousands of years to refill them once they are emptied. Much of the groundwater we now are using probably was left there by the glaciers thousands of years ago. It is fossil water, in a sense. It will never be replaced in our lifetimes, and is, essentially, a nonrenewable resource. Covering aquifer recharge zones with urban development or diverting runoff that once replenished reservoirs ensures that they will not refill.

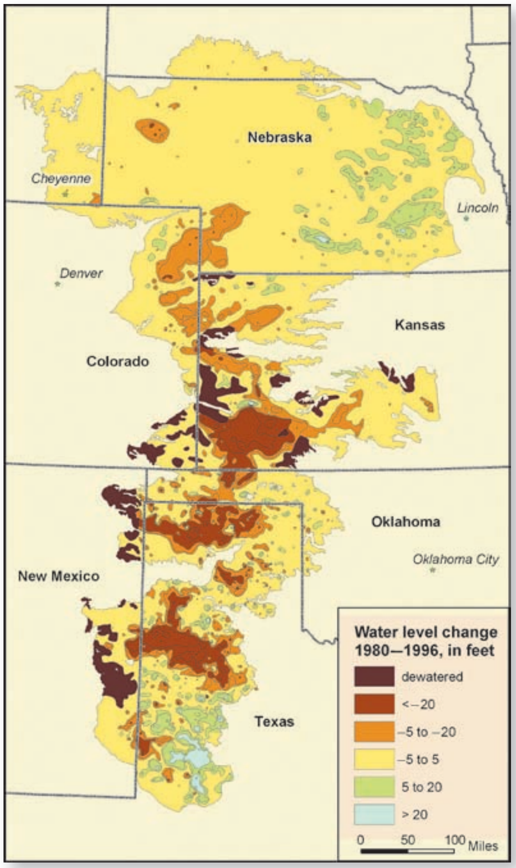


FIGURE 17.17 The Ogallala/High Plains regional aquifer supports a multimillion-dollar agricultural economy, but withdrawal far exceeds recharge. Some areas are down to less than 3 m of saturated thickness.

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

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

Diversion projects redistribute water

Dams and canals are a foundation of civilization because they store and redistribute water for farms and cities. Many great civilizations, including ancient empires of Sumeria, Egypt, and India, have been organized around large-scale canal systems. As modern dams and water diversion projects have grown in scale and number, though, their environmental costs have raised serious questions about efficiency, costs, and the loss of river ecosystems.

More than half of the world's 227 largest rivers have been dammed or diverted (fig. 17.19). Of the 50,000 large dams in the world, 90 percent were built in the twentieth century. Half of those are in China, and China continues to build and plan dams on its remaining rivers. Dams are justified in terms of flood control, water storage, and electricity production. However, the costs of relocating villages, lost fishing and farming, and water losses to evaporation are enormous. Economically speaking, at least one-third of the world's large dams should never have been built.

As the chapter-opening case study shows, many southwestern cities are facing a crisis with the drying of Lake Mead. Las Vegas, Nevada, which gets 40 percent of its water from the lake, has started a \$3.5 billion, 525 km (326 m) pipeline to tap aquifers in the northeastern part of the state. Local ranchers fear that groundwater pumping will decimate the range, destroy native vegetation, and cause massive dust storms. They point to the Owens Valley in California, where a similar water grab by Los Angeles in 1913 dried up the river and destroyed both natural vegetation and the ranching economy. Las Vegas also has suggested that if local water supplies fail, they may ask states east of the Mississippi to share some of their water.

Las Vegas is also digging a \$3.5 billion tunnel that will burrow into Lake Mead, 100 m (300 ft) below the normal outlet (fig. 10.10). Even if the lake reaches the "dead pool" level as warned in the beginning of this chapter, the city will still be

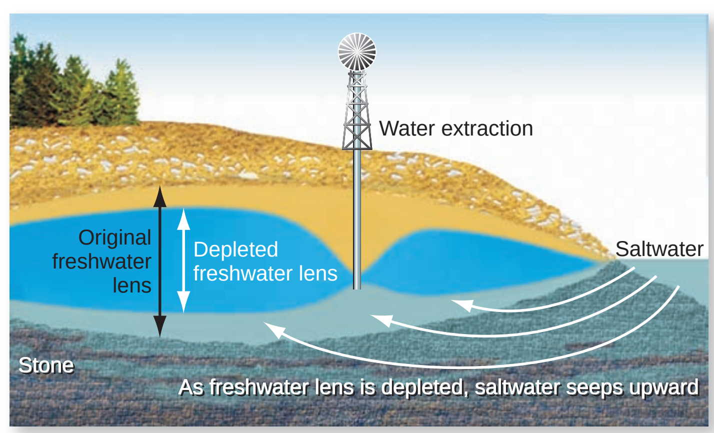


FIGURE 17.18 Saltwater intrusion into a coastal aquifer as the result of groundwater depletion. Many coastal regions of the United States are losing freshwater sources due to saltwater intrusion.

FIGURE 17.19 Hoover Dam powers Las Vegas, Nevada. Lake Mead, behind the dam, loses about 1.3 billion m^3 per year to evaporation.

able to draw off water. Of course, this might prevent refilling the reservoir to provide water and power to downstream users. If you lived downstream, how would you feel about this outcome?

Similarly, China faces a massive water crisis. Northern and western parts of the country are dry and getting drier. The Gobi desert is moving eastward; its leading edge is now only 100 km (60 mi) from Beijing. Of 600 major Chinese cities, more than two-thirds have water shortages, and 100 of those cities have acute water problems. Without a new water source, planners warn, the entire national capital, Beijing, might have to be moved to a new location. To combat this crisis, the Chinese government has embarked on a massive water distribution scheme called the South-Water-North project (What Do You Think? p. 387).

FIGURE 17.20 The five North American Great Lakes contain about 20 percent of all the freshwater in the world. But diverting water from them would have massive repercussions for shipping, recreation, wildlife, and industry. Will those who live along their shores be willing to share?

Might we do something similar in the United States? While the desert Southwest is getting drier, a huge supply of water sits temptingly not so far to the northeast. Together, the five Great Lakes contain about 20 percent of all the freshwater in the world (fig. 17.20). The states and provinces bordering this treasure have signed a compact promising to never allow large-scale transfers out of the watershed. But if Los Angeles, Phoenix, Tucson, Las Vegas, and Denver were faced with the prospect of becoming ghost towns, will this resolve hold? Can we tell western states they should have listened to Major Powell?

Dams often have severe environmental and social impacts

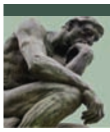
According to the World Dam Commission, there were only about 250 high dams (more than 15 m tall) in the world before 1900. In the twentieth century, however, at least 45,000 dams were built, about half of them in China. Other countries with many dams include Turkey, Japan, Iran, India, Russia, Brazil,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

Though dams provide hydroelectric power and water to distant cities, they also can have unintended consequences. Reservoirs in hot, dry climates lose tremendous amounts of water to evaporation. Lake Powell, on the Colorado River, loses more than 1 billion m^3 of water to evaporation and seepage every year. As the water level drops, it leaves a bathtub ring of salt deposits on the canyon walls (photo, p. 372).

International Rivers, an environmental and human rights organization, reports that dam projects have forced more than 23 million people from their homes and land, and many are still suffering the impacts of dislocation years after it occurred. Often the people being displaced are ethnic minorities. On India's Narmada River, for example, a proposed series of 30 dams have displaced about 1 million villagers and tribal people. Many who have been relocated have never successfully integrated either socially or economically. Protests around this project have raged for 20 years or more.

There's increasing concern that big dams in seismically active areas can trigger earthquakes. In more than 70 cases worldwide, large dams have been linked with increased seismic activity. Geologists suggest that filling the reservoir behind the nearby Zipingpu Dam on the Min River caused the devastating 7.9-magnitude Sichuan earthquake that killed an estimated 90,000 people in 2008. If true, it would be the world's deadliest dam-induced earthquake. But it pales in comparison to the potential catastrophe if the Three Gorges Dam on the Yangtze were to collapse. As one engineer says, "It would be a flood of Biblical proportions for the 100 million people who live downstream."

Dams are also lethal for migratory fish, such as salmon. Adult fish are blocked from migrating to upstream spawning areas. And juvenile fish die if they go through hydroelectric turbines. The slack water in reservoirs behind dams is also a serious problem. Juvenile salmon evolved to ride the surge of spring runoff downstream to the ocean in two or three weeks. Reservoirs slow this journey to as



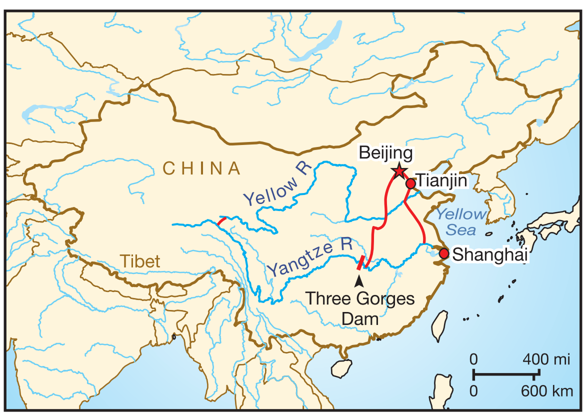
What Do You Think?

China's South-Water-North Diversion

Water is inequitably distributed in China. In the south, torrential monsoon rains cause terrible floods. A 1931 flood on the Yangtze displaced 56 million people and killed 3.7 million (the worst natural disaster in recorded history). Northern and western China, on the other hand, are too dry, and getting drier. At least 200 million Chinese live in areas without sufficient fresh water. The government has warned that unless new water sources are found soon, many of those people (including the capital Beijing, with roughly 20 million residents) will have to be moved. But where could they go? Southern China has water, but doesn't need more people.

The solution, according to the government, is to transfer some of the extra water from south to north. A gargantuan project is now under way to do just that. Work has begun to build three major canals to carry water from the Yangtze River to northern China. Ultimately it's planned to move 45 billion m^3 per year (more than twice the annual flow of the Colorado River through the U.S. Grand Canyon) 1,600 km (1,000 mi) north. The initial cost estimate of this scheme is about 400 billion yuan (roughly U.S. $62 billion), but it could easily be twice that much.

The eastern route uses the Grand Canal, built by Zhou and Sui emperors 1,500 years ago across the coastal plain between Shanghai and Beijing. This project is already operational. It's relatively easy to pump water through the existing waterways, but they're so polluted by sewage and industrial waste that northern cities—even though they're desperately dry—are reluctant to use this water.



With the Yellow River nearly depleted by overuse, northern China now plans canals (*red*) to deliver Yangtze water to Beijing.

The central route will draw water from the reservoir behind the recently completed Three Gorges Dam on the Yangtze. Part of the motivation for building this controversial dam and flooding the historic Three Gorges was to provide energy and raise the river level for the South-to-North project. This middle canal will cross several major mountain ranges and dozens of rivers, including the Han and Yellow rivers. Already at least 1.5 million people have been displaced by this project, but planners say it's justified by the benefits to a much greater number of people in northern China.

It's hoped this segment will be finished by 2020. The western route is the most difficult and expensive. It would tunnel through rugged mountains, across aqueducts, and over deep canyons for more than 250 km (160 mi), from the upper Yangtze to the Yellow River where they both spill off the Tibetan Plateau. This phase won't be finished until at least 2050. If global warming melts all Tibet's glaciers, however, it may not be feasible anyway.

Planners have waited a lifetime to see this project move forward. Revolutionary leader Mao Zedong proposed it 50 years ago. Environmental scientists worry, however, that drawing down the Yangtze will worsen pollution problems (already exacerbated by the Three Gorges Dam), dry up downstream wetlands, and possibly even alter ocean circulation and climate along China's eastern coast. Although southern China has too much water during the rainy season, southern cities face water shortages because of rapidly growing populations and severe pollution. At least half of all major Chinese rivers are too polluted for human consumption. Drawing water away from the rivers on which millions rely only makes pollution problems worse.

What do you think? Are there other ways that China could adapt to uneven water distribution? If you were advising the Chinese government, what safeguards might you recommend to avoid unexpected consequences from the gargantuan project? And might we do something similar in the United States to relieve water shortages in the desert Southwest? It's about the same distance from Phoenix to Chicago as from Yichang to Beijing.

But residents in the U.S. Great Lakes states are worried about the possible effects of global climate change. They may need their water in the future. Furthermore, they may be reluctant to help pay the cost for people who continue to live in the desert. Over the past 50 years, cities in the industrialized "Rust Belt" have lost millions of jobs and residents to the "Sunbelt." Rather than pay billions of dollars to move water, they might prefer to say, "Come back to Detroit and Toledo and Cleveland, and bring your jobs with you." Is it inconceivable that we'd allow desert cities to become ghost towns? Great cities have risen, flourished, and crumbled to dust in the past. What do you think—could it happen again?

much as three months, throwing off the time-sensitive physiological changes that allow the fish to survive in salt water when they reach the ocean. Reservoirs expose young salmon to predators, and warm water in reservoirs increases disease in both young and older fish.

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

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

FIGURE 17.21 This dam is now useless because its reservoir has filled with silt and sediment.

Sedimentation limits reservoir life

Rivers with high sediment loads can fill reservoirs quickly (fig. 17.21). In 1957 the Chinese government began building the Sanmenxia Dam on the Huang He (Yellow River) in Shaanxi Province. From the beginning, engineers warned that the river carried so much sediment that the reservoir would have a very limited useful life. Dissent was crushed, however, and by 1960 the dam began filling the river valley and inundating fertile riparian fields that once had been part of China's traditional granaries.

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

Problems are similar, although not so severe, in some American rivers. As the muddy Colorado River slows behind the Glen Canyon and Boulder dams, it drops its load of suspended sand and silt. More than 10 million metric tons of sediment collect every year behind these dams. Even if there is enough water in the future to fill these reservoirs, within about a century they'll be full of mud and useless for either water storage or hydroelectric generation.

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

Climate change threatens water supplies

The Intergovernmental Panel on Climate Change (IPCC) warns us that climate change threatens to exacerbate water shortages caused by population growth, urban sprawl, wasteful practices, and pollution. The IPCC *Fourth Assessment Report* predicted with "very high confidence" that reduced precipitation and higher evaporation rates caused by higher temperatures will result in a 10 to 30 percent runoff reduction over the next 50 years in some dry regions at midlatitudes (see chapter 15).

Figure 17.22 shows a summary of predictions from several climate models for changes in precipitation in 2090–2099 compared to 1980–1999. White areas are where less than two-thirds of the models agree on likely outcomes: colored areas are where more than 90 percent of the models agree. How does this map compare to figure 17.2? Which areas do you think are most likely to suffer from water shortages by the end of this century? Which areas may benefit from climate change? Where will the largest number of people be affected?

In many parts of the world, severe droughts are already resulting in depleted rivers, empty reservoirs, and severe water shortages for millions of people. South Australia, for example, is suffering from extreme heat waves, dying vegetation, massive wildland fires, and increasing water deficits. The Australian

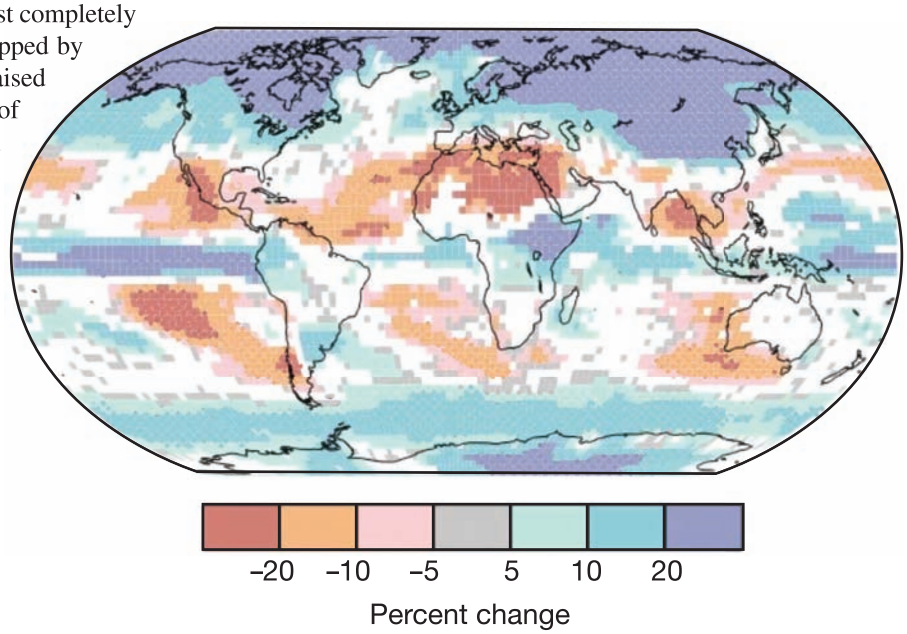


FIGURE 17.22 Relative changes in precipitation (in percentage) for the period 2090–2099 compared to 1980–1999, predicted by the Intergovernmental Panel on Climate Change.
Source: IPCC, 2007.

Exploring Science

How Does Desalination Work?

As you've learned in this chapter, the ocean has a vast amount of water. Unfortunately, it's too salty for most human uses. There are ways to remove salt and other minerals from water, but they tend to be energy-intensive and expensive. The most common form of desalination is distillation: water is boiled, and the steam is collected and condensed to make fresh water. This works well. Glass-distilled water remains the standard for purity in most science labs. The world's largest desalination plant is the Jebel Ali Plant in the United Arab Emirates. It uses multistage flash distillation and is capable of producing 300 million cubic meters of water per year. Distillation produces over 85 percent of all desalinated water in the world.

In a multistage distillation facility, water evaporates in a series of spaces called stages containing heat exchangers and condensate collectors. Each compartment has a partial vacuum, which causes water to boil at a much lower temperature than 100°C (212°F). As water passes from one stage to another, temperatures and pressures are adjusted to match the boiling point as salt concentration increases. The total evaporation in all the stages is about 15 percent of the input water. The main limitations of this design are the corrosion caused by the warm brine as well as the energy required to heat and pump water and to create a vacuum. In oil-rich countries, such as Saudi Arabia, where water costs more than pumping oil out of the ground, energy costs aren't important, but in other places it becomes a concern. However, coupling a desalination facility with a power plant can cut costs by as much as two-thirds. Waste heat from the power plant is used to preheat seawater, which simultaneously provides cooling for the power plant. Disposal of warm, salty brine can have serious adverse impacts on local coastal areas.

The other principal method of desalination is reverse osmosis. This filtration process removes large molecules from solutions by applying pressure to the solution on one side of a selectively permeable membrane. Every cell in your body is enclosed by a selectively permeable membrane. It's one of the things that make life possible. The plasma membrane around each cell has tiny pores that allow small molecules, such as water, to pass through but that exclude large molecules, such as salt. Ordinarily osmosis causes small molecules to move from an area of high concentration (pure water) to areas of lower concentration (a salt solution, which has fewer water molecules per unit area because some space is occupied by the salt). You may have observed osmosis in a biology lab. If you put an amoeba in a high salt solution, it shrivels (water is drawn out). If you put it in pure water, it bloats and explodes (the interior is saltier than the water).

Reverse osmosis drives this process backward by applying a pressure to the high-salt side of a semipermeable membrane to filter the water. In practice the membranes are packed in concentric coils inside a tube. A large facility may have tens of thousands of these tubes. Pore sizes can vary from 0.1 nanometers (3.9×10^{-9} in) to 5,000 nanometers (0.0002 in) depending on the solution to be filtered. Reverse osmosis systems can range from industrial-size facilities capable of purifying hundreds of thousands of gallons per day, to a pen-size straw that you can carry in your pocket to sip water from a contaminated source.

Although there are many more reverse osmosis facilities than thermal desalination plants, they produce a relatively small percentage of all desalinated water. Still, they can be more mobile and easier to operate than a distillation plant. And if the pores are less than 1 nanometer, the water produced can be cleaner than distillation (although the production rate is very low with such small pore sizes).

government has declared that this drought is most likely the result of global climate change. Although the country has recently agreed to reduce carbon emissions to combat climate change, the only short-term solution, leaders admit, is to try to adapt to these new conditions.

In Yemen, the national capital, Sanaa, may have to be abandoned because it has no water to support its rapidly growing population of more than 2 million. Yemen depends entirely on groundwater, which is rapidly being depleted. Some wells in Sanaa are now 800 to 1,000 meters deep and many are no longer usable because of the sinking water table. Millions of people may have to abandon Sanaa and other mountain cities for the coastal plain. A shrinking resource base played a role in the civil unrest in Yemen in 2011.

A more dire situation is taking place in Somalia where a severe drought threatens 10 million people. Hardest hit is the southwestern region where Somalia, Ethiopia, and Kenya meet. The U.N refugee agency called this the "worst humanitarian disaster" in the world. The agency estimates that 2 million children are severely malnourished and in need of lifesaving action. Hundreds of thousands of refugees are surging into temporary camps in search of food and water. Political instability in the region makes aid delivery difficult.

Would you fight for water?

Many environmental scientists warn that declining water supplies could lead to wars between nations. *Fortune* magazine wrote, "Water will be to the 21^{st} century what oil was to the 20^{th}." For its 2009 World Water Day, the United Nations is focusing on transboundary water supplies. Nearly 40 percent of the world's population lives in river and lake basins shared by two or more countries. These 263 watersheds include the territory of 145 countries and cover nearly half the earth's land surface. Figure 17.23 shows five of the world's major rivers and the countries they cross. Great reservoirs of fresh water also cross borders. There are more than 270 known transboundary aquifers.

Already we've seen skirmishes—if not outright warfare—over water access. An underlying factor in hostilities between Israel and its neighbors has been control of aquifers and withdrawals from the Jordan River. India, Pakistan, and Bangladesh also

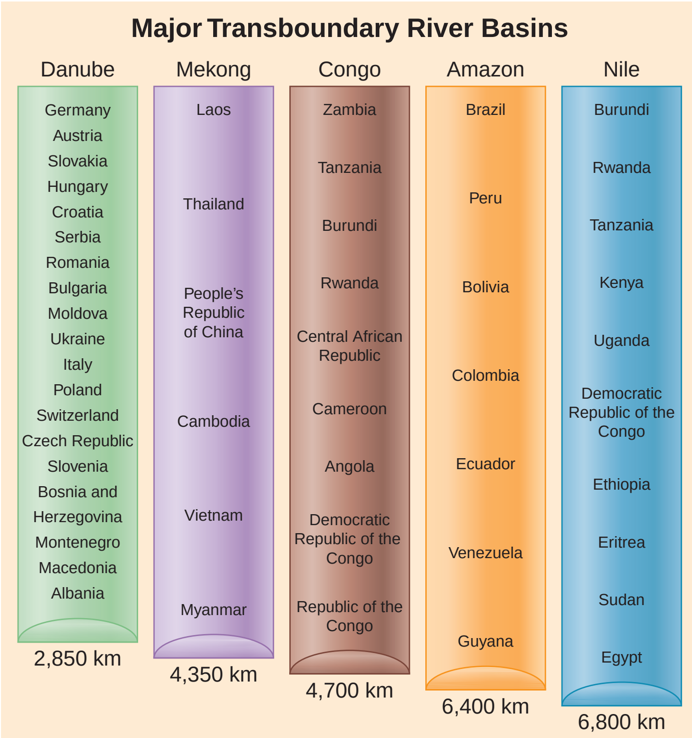


FIGURE 17.23 Together, these five rivers cross 54 countries. Already, skirmishes and sabre-rattling have occurred as neighbors squabble over scarce supplies.
Source: Data World Water Day, 2009.

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

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

17.5 Getting By with Less Water

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

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

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

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

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

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

17.6 Increasing Water Supplies

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

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

A technology that might have great potential for increasing freshwater supplies is desalination of ocean water or brackish saline lakes and lagoons. Worldwide, 13,080 desalination plants produce more than 12 billion gallons (45 billion liters) of water a day (see Exploring Science, p. 389). This is expected to grow to about 100 million m^3 (26 billion gal) per day by 2015. Middle Eastern oil-rich states produce about 60 percent of desalinated water. Saudi Arabia is the largest single producer, at about one-third of the world total. The United States is second, at 20 percent. Although desalination is still three to four times more expensive than most other sources of fresh water, it provides a welcome water supply in such places as Oman and Bahrain, where there is no other access to fresh water. If a cheap, inexhaustible source of energy were available, however, the oceans could supply all the water we would ever need.

Domestic conservation can save water

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

The use of conserving appliances, such as low-volume showerheads and efficient dishwashers and washing machines, can reduce water consumption greatly (What Can You Do? p. 393). If you live in an arid part of the country, you might consider whether you really need a lush green lawn that requires constant watering, feeding, and care. Planting native ground cover in a "natural lawn" or developing a rock garden or landscape in harmony with the surrounding ecosystem can be both ecologically sound and aesthetically pleasing (fig. 17.25). There are about 30 million ha (75 million acres) of cultivated lawns, golf courses, and parks in the United States. They receive more water, fertilizer, and pesticides per hectare than any other kind of land.

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

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

showers, and faucets be installed in all new buildings. The motivation was twofold: to relieve overburdened sewer systems and to conserve water.

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

Recycling can reduce consumption

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

Nearly half of all industrial water use is for cooling of electric power plants and other industrial facilities. Some of this water use could be avoided by installing dry cooling systems

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

similar to the radiator of your car. In many cases, cooling water could be reused for irrigation or other purposes in which water does not have to be drinking quality. The waste heat carried by this water could be a valuable resource if techniques were developed for using it.

Prices and policies have often discouraged conservation

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

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

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

Charging a higher proportion of real costs to users of public water projects has helped encourage conservation, and so have water marketing policies that allow prospective users to bid on water rights. Both the United States and Australia have had effective water pricing and allocation policies that encourage the most socially beneficial uses and discourage wasteful water uses. Market mechanisms for water allotment can be sensitive, however,

What Can You Do?

Saving Water and Preventing Pollution

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

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

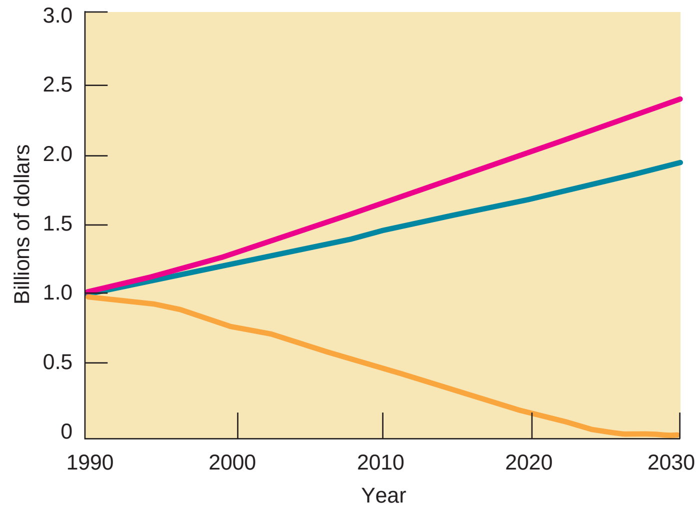


FIGURE 17.27 Three scenarios for government investments on clean water and sanitation services, 1990 to 2030.
Source: World Bank estimates based on research paper by Dennis Anderson and William Cavendish, "Efficiency and Substitution in Pollution Abatement: Simulation Studies in Three Sectors."

in developing countries where farmers and low-income urban residents could be outbid for irreplaceable water supplies.

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

CONCLUSION

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

There are many ways to make more water available. Huge projects, such as the Chinese scheme to ship water from the well-watered south to the dry north, are already under way. Would we want to do something similar in the United States? Building dams and shipping water between watersheds can have severe ecological and social effects. Perhaps a better way is to practice conservation and water recycling. These efforts, also, are under way in many places, and show great promise for meeting our needs for this irreplaceable resource. There are things you can do as an individual to save water and prevent pollution. Even if you don't have water shortages now where you live, it may be wise to learn how to live in a water-limited world.

REVIEWING LEARNING OUTCOMES

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

17.1 Summarize why water is a precious resource and why shortages occur.
- The hydrologic cycle constantly redistributes water.
- Water supplies are unevenly distributed.

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

17.3 Summarize water availability and use.
- Many countries suffer water scarcity and water stress.
- Water use is increasing.
- Agriculture is the greatest water consumer worldwide.
- Domestic and industrial water use are greatest in wealthy countries.

17.4 Investigate freshwater shortages.
- Many people lack access to clean water.
- Groundwater is being depleted.
- Diversion projects redistribute water.
- Dams often have severe environmental and social impacts.
- Sedimentation limits reservoir life.
- Climate change threatens water supplies.
- Would you fight for water?

17.5 Appreciate how we might get by with less water.

17.6 Understand how we might increase water supplies.
- Domestic conservation can save water.
- Recycling can reduce consumption.
- Prices and policies have often discouraged conservation.

PRACTICE QUIZ

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

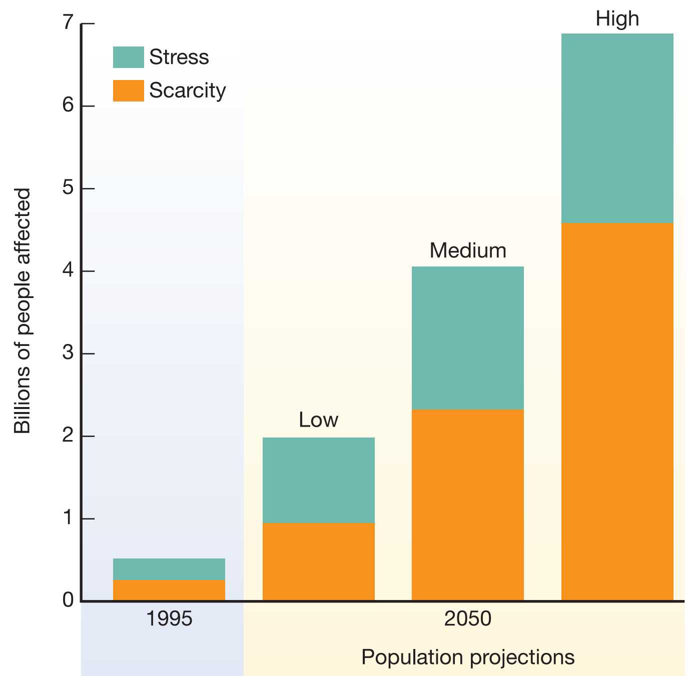
CRITICAL THINKING AND DISCUSSION QUESTIONS

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

Data Analysis: Graphing Global Water Stress and Scarcity

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

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



Global water stress and scarcity

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham12e. You will find additional practice quizzes and case studies, flashcards, regional examples, placemarks for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.