CHAPTER 9

Water Resources

The beautiful Klamath River flows from southern Oregon and down through northern California.

Dams and Salmon on the Klamath River
The Klamath River is a beautiful stretch of water that runs for 400 km (250 miles) from southern Oregon through northern California, where it empties into the ocean. The Klamath River was once a spectacular habitat for salmon—the third largest salmon fishery on the West Coast. During the past 100 years, however, the Klamath River has seen many changes. It has been dammed for electricity, and farmers have settled the land and diverted water for irrigation. The salmon population has been greatly reduced, and local Native American tribes and the commercial fishing industry have suffered as a result.

The Klamath River was once a spectacular habitat for salmon.

The story of the Klamath River began thousands of years ago, when six tribes of Native Americans were the sole inhabitants of the region. For more than 300 generations, these tribes relied on salmon as an important part of their diet. Historically, salmon eggs hatched in the upstream portion of the river. Young fish migrated down the river into the ocean, where they spent several years growing into mature fish. Once mature, they migrated up the river, returning to the same place where they had hatched to lay their own eggs. Several species of salmon were abundant in the river. An estimated 800,000 mature chinook salmon (*Oncorhynchus tshawytscha*)—which can grow as large as 45 kg (100 pounds)—migrated up the river each year.
The multiple uses of the water in the Klamath River have led to conflicts over water rights, including Native Americans who have depended on the river for salmon for many centuries.

This migratory behavior worked well for thousands of years, until the region began to change during the twentieth century. In the early 1900s, the U.S. Bureau of Reclamation decided to install canals to drain two large lakes that were the source of the river. The exposed lake bottoms were turned into farmland, and the water that drained into the canals provided a constant source of irrigation for this new farmland. In addition, four hydroelectric dams were built on the river between 1908 and 1962. These dams generated enough electricity to power 70,000 homes. Because hydroelectric dams generate less pollution than other sources of electricity, these dams provided a substantial benefit to the region. But their presence imposed a barrier to the natural migration of salmon. In addition, the formation of large pools behind the dams caused the water temperature to rise into a range that is not favorable to salmon. As the decades passed, the multiple uses of the Klamath River began to come into conflict. In addition, a gradual warming of temperatures in the region caused less snow
to fall in the mountains. Less winter snow meant less water for the river. Although there was now less water available, the same amount continued to be withdrawn for agricultural use. These withdrawals reduced the river’s flow to low levels that created an additional threat to the salmon. In 1997, the coho salmon (*Oncorhynchus kisutch*) was given protection under the U.S. Endangered Species Act. This protection meant that water withdrawals for irrigation could not reduce the river’s flow below a minimal level. That restriction, in turn, prevented the farmers from receiving enough water to irrigate their crops, which threatened their livelihood.

The debate among the various interest groups intensified. Native Americans, the hydroelectric company, farmers, the commercial fishing industry, conservationists, and multiple government agencies all had different interests and conflicting points of view about the best policy for water management in the region.

In 2002, the migrating salmon experienced a massive die-off in the river. This catastrophe was caused by unusually warm water, the growth of toxic algae in the dammed waters, and diseases. The sight of 30,000 large, dead chinook salmon brought worldwide attention to the Klamath River. Nearly 30 interest groups began to meet to find a solution to the river’s complex problems.

In 2009, the parties reached a decision. The hydroelectric company, which realized it would soon have to spend $300 million on dam renovations, agreed to remove the dams. The farmers agreed to conserve water by planting less water-thirsty crops and updating their irrigation technology. These changes are expected to improve river flow, thereby improving conditions for the salmon and those who depend on them. The agreement was signed in 2010, and the dams are scheduled to be removed in 2020. Once the project is completed, it will represent the largest dam removal in history.

Conflicts over the use of water resources are found throughout the world as human populations grow and place ever-increasing demands on limited water resources. The compromise reached on the Klamath has the potential to serve as a model for resolving such conflicts in the future.

Climate variation causes some regions of the world to possess abundant supplies of water, whereas other regions have very little water. Around the world, growing human populations are facing issues related to water availability.

After reading this chapter you should be able to
• identify Earth’s natural sources of water.
• discuss the ways in which humans manage water distribution.
• describe the major human uses of water.
• identify the factors that will affect the future availability of water.

9.1 Water is abundant, but usable water is rare

[Notes/Highlighting]

**Figure 9.1** Distribution of water on Earth. Fresh water represents less than 3 percent of all water on Earth, and only about three-fourths of that fresh water is surface water. Most of that surface water is frozen as ice and in glaciers. Therefore, less than 1 percent of all water on the planet is accessible for use by humans. [After R. W. Christopherson, *Geosystems*, 7 ed. Pearson/Prentice Hall, 2009.]

Nearly 70 percent of Earth’s surface is covered by water. As **FIGURE 9.1** shows, this water is found in five main repositories. The vast majority of Earth’s water, more than 97 percent, is found in the oceans as salt water. The remainder—less than 3 percent—is fresh water, the type of water that can be consumed by humans. Of this small percentage of Earth’s water that is fresh water, nearly one-fourth resides underground. The remaining three-fourths is above ground, but most of it is in the form of ice and glaciers and so is generally not available for human consumption. Very small fractions of Earth’s aboveground water are found in the atmosphere and in the form of water bodies such as streams, rivers, wetlands, and lakes.
9.1.1 Groundwater

Groundwater exists in the multitude of small spaces found within permeable layers of rock and sediment called aquifers. FIGURE 9.2 shows how different types of aquifers are situated. Many aquifers are porous rock covered by soil. Because water can easily flow in and out of such aquifers, they are called unconfined aquifers. In contrast, some aquifers are surrounded by a layer of impermeable rock or clay. These aquifers are called confined aquifers because the impermeable, or confining, layer impedes water flow to or from the aquifer. The uppermost level at which the water in a given area fully saturates the rock or soil is called the water table. The water table is considered to be the surface of the groundwater in an area.

Figure 9.2 Aquifers. Aquifers are sources of usable groundwater. Unconfined aquifers are rapidly recharged by water that percolates downward from the land surface. Confined aquifers are capped by an impermeable layer of rock or clay, which can cause water pressure to build up underground. Artesian wells are formed when a well is drilled into a confined aquifer and the natural pressure causes water to rise toward the ground surface.

Water from precipitation can percolate through the soil and work its way into an aquifer. This input process is known as groundwater recharge. If water falls on land that contains a confined aquifer, however, it cannot penetrate the impermeable layer of rock. Therefore, a confined aquifer cannot be recharged unless the impermeable layer has an opening at the land’s surface that can serve as a recharge area.
Aquifers serve as important sources of fresh water for many organisms. Plant roots can access the groundwater in an aquifer and draw down the water table. Water from some aquifers naturally percolates up to the ground surface as springs (FIGURE 9.3). Springs serve as a natural source of water for freshwater aquatic biomes, and they can be used directly by humans as sources of drinking water. Humans discovered centuries ago that water can also be obtained from aquifers by digging a well—essentially a hole in the ground. Most modern wells contain pumps that move the water up to the ground surface against the force of gravity. The water in some confined aquifers, however, is under tremendous pressure due to the impermeable layer of rock that surrounds it. Drilling a hole into a confined aquifer releases the pressure on the water, allowing it to burst out of the aquifer and rise up in the well, as shown in FIGURE 9.2. Such wells are called artesian wells. If the pressure is sufficiently great, the water can rise all the way up to the ground surface, in which case no pump is required to extract the water from the ground.

The age of water in aquifers varies, as does the rate at which aquifers are recharged. The water in an unconfined aquifer may originate from water that fell to the ground last year or even last week. This direct and rapid connection with the surface is one of the reasons why water from unconfined aquifers is much more likely to be contaminated with chemicals released by human activities. Confined aquifers, on the other hand, are generally recharged very slowly, perhaps over 10,000 to 20,000 years. For this reason, water from a confined aquifer is usually much older, and less likely to be contaminated by anthropogenic chemicals, than water from an unconfined aquifer.
The Ogallala aquifer, also called the High Plains aquifer, is the largest in the United States, with a surface area of about 450,000 km² (174,000 miles²). (a) The change in water level from 1950 to 2005, mostly due to withdrawals for irrigation that have exceeded the aquifer’s rate of recharge. (b) The current thickness of the aquifer.

Large-scale use of water from a confined aquifer is unsustainable because the withdrawal of water is not balanced by re-charge. The largest aquifer in the United States is the massive Ogallala aquifer in the Great Plains. Large amounts of water have been withdrawn from this aquifer for household, agricultural, and industrial uses. Unfortunately, the aquifer is recharged slowly, and the rate of recharge is not
keeping pace with the rate of water withdrawal, as FIGURE 9.4 shows. For this reason, the Great Plains region could run out of water during this century.

FIGURE 9.5 Cone of depression. (a) When a deep well is not heavily pumped, the recharge of the water table keeps up with the pumping. (b) In contrast, when a deep well pumps water from an aquifer more rapidly than it can be recharged, it can form a cone of depression in the water table and cause nearby shallow wells to go dry.

FIGURE 9.5 shows what happens when more water is withdrawn from an aquifer than enters the aquifer. As the water table drops farther from the ground surface, springs that once bubbled up to the surface no longer emerge, and springfed streams dry up. In addition, some shallow wells no longer reach the water table. The water table adjacent to a well where water is being rapidly withdrawn is lowered the most, creating a cone of depression: an area where there is no longer any groundwater. In other words, rapid pumping of a deep well can cause adjacent, shallower wells to go dry.

FIGURE 9.6 Saltwater intrusion. (a) When there are few wells along a coastline, the water table remains high and the resulting pressure prevents salt water from intruding. (b) In contrast, rapid pumping of wells drilled in aquifers along a coastline can lower the water table. Lowering the water table reduces water pressure in the aquifer, allowing the nearby salt water to move into the aquifer and contaminate the well water with salt.
In some situations, pumping fresh water out of wells faster than the aquifer can be recharged compromises water quality. **FIGURE 9.6** shows how this can happen when wells are drilled near coastlines. Some coastal regions have an abundance of fresh water underground. This groundwater exerts downward pressure that prevents the adjacent ocean water from flowing into aquifers and mixing with the groundwater. As humans drill thousands of wells along these coastlines, however, rapid pumping draws down the water table, reduces the depth of the groundwater, and thereby lessens that pressure. The adjacent salt water is then able to infiltrate the area of rapid pumping, making the water in the wells salty. This process, called **saltwater intrusion**, is a common problem in coastal areas.

### 9.1.2 Surface Water

Surface water is the fresh water that exists above the ground, including streams, rivers, ponds, lakes, and wetlands. As mentioned in **Chapter 3**, these waters represent ecosystems that perform a number of important functions. The world’s three largest rivers, as measured by the volume of water they carry, are the Amazon in South America, the Congo in Africa, and the Yangtze in China. Early human civilizations typically settled along major rivers not only because these waterways served as important means of transportation, but also because the land surrounding rivers is often highly fertile. Most rivers naturally overflow their banks during periods of spring snowmelt or heavy rainfall. The excess water spreads onto the land adjacent to the river, called the **floodplain**. These floodwaters deposit nutrient-rich sediment on the floodplain, improving the fertility of the soil. The ancient Egyptians built a large and prosperous civilization by using the Nile River for commerce and its fertile floodplains for agriculture. The use of rivers as a means of transport continues today. Many large cities in North America, including Pittsburgh, New Orleans, and St. Louis, developed on the banks of major rivers.
Ponds and lakes typically form in depressions in the landscape that are filled by precipitation, runoff that is not absorbed by the surrounding landscape, and groundwater that flows into the depression. Determining Earth’s largest lakes depends on whether we consider surface area, depth, or volume. **FIGURE 9.7** shows comparisons based on each of these factors. Some lakes, such as Lake Victoria in Africa, have large surface areas but are not especially deep, whereas other lakes, such as Lake Baikal in Asia, do not have especially large surface areas, but are incredibly deep and therefore have a large volume.

Lakes can be created by a variety of processes, including tectonic activity and glaciation. When tectonic activity causes areas of land to rise up, it can isolate a region of the ocean. Because lakes formed in this way are ocean-derived, they have higher
salinities than other lakes. The Caspian Sea in western Asia is an excellent example of a salty lake that was formed by tectonic uplift. Tectonic activity can also cause land to split open into long, deep fissures that subsequently fill with water. Some of the world’s largest lakes have formed this way, including Lake Victoria and Lake Tanganyika in Africa and Lake Baikal in Asia. Another way that lakes are formed is through the movement of glaciers. Over thousands of years, glacial movement scrares large depressions in the land that subsequently fill with water. This process is thought to have played a major role in the creation of the Great Lakes in North America. Lakes are classified by their level of primary productivity. Lakes that have low productivity due to low amounts of nutrients such as phosphorus and nitrogen in the water are called oligotrophic lakes. In contrast, lakes with a moderate level of productivity are called mesotrophic lakes, and lakes with a high level of productivity are called eutrophic lakes.

Freshwater wetlands play important, if sometimes unrecognized, roles in water distribution and regulation, as we saw in Chapter 4. During periods of heavy rainfall that might otherwise lead to flooding, freshwater wetlands—as well as salt marshes and mangrove swamps—can absorb and store the excess water and release it slowly, thereby reducing the likelihood of a flood. Wetlands are measured by surface area. There is some debate about which freshwater wetland is the world’s largest, but most researchers consider the Pantanal in South America to be the largest wetland and the Florida Everglades to be the second largest.

9.1.3 Atmospheric Water

Although the atmosphere contains only a very small percentage of the water on Earth, that atmospheric water is essential to global water distribution. People living in arid regions rely heavily on precipitation, in the form of rain and snow, for their water needs. In certain regions, such as East Africa, annual rainfall follows a fairly regular pattern: April, May, October, and November are normally rainy months. However, even areas with predictable rainfall patterns can experience unexpected droughts. In the fall of 2000, the United Nations Food and Agriculture Organization reported that a succession of droughts had put 16 million people at risk of starvation in eastern Africa. In 2004, the worst drought in more than a decade adversely affected many parts of southern Africa, destroying crops, killing cattle, and causing millions of people to go hungry.

In addition to the direct losses of human lives, livestock, and crops that they cause, droughts have long-term effects on soil. Because the cycling of many nutrients important to ecosystem productivity, such as nitrogen and phosphorus, depends on the movement of water, droughts affect nutrient cycling and thus soil
fertility. Furthermore, prolonged droughts can dry out the soil to such an extent that the fertile upper layer—the topsoil—blows away in the wind. As a result, the land may become useless for agriculture for decades or longer. Finally, soil that has become severely parched may harden and become impermeable. In this case, when the rains finally do arrive, the water runs off over the land surface rather than soaking in, eroding the topsoil in the process.

Human activities can contribute to the negative effects of droughts. In the midwestern United States in the 1920s and 1930s, for example, the amount of conversion of native grasslands into wheat fields increased dramatically. Because wheat fields are more susceptible to soil erosion by wind than native grasslands, this conversion produced many more hectares of erodible land. In the early 1930s, a severe and prolonged drought caused a decade of crop failures. With few crop plants alive to hold the soil in place, the drought led to massive dust storms like the one pictured in FIGURE 9.8, as winds picked up the parched topsoil and blew it away. Indeed, one dust storm, on April 14, 1935, was so severe that the Sun was entirely blocked out in the southern Great Plains, leading to the name “Black Sunday.” Topsoil from these dust storms traveled as far as Washington, D.C., and earned the southern Great Plains the nickname of “the Dust Bowl.” The decade of dust storms and the resulting losses of topsoil led to large-scale human migration out of the region and impacted the economy of the entire nation. Today, improved farming practices have reduced the susceptibility of soil to erosion by wind, making major dust storms in the Great Plains and elsewhere much less likely.
Many drought-prone areas of the world rarely experience high amounts of rainfall, but when it does happen, severe flooding can occur. California, for example, is a relatively dry region of the United States. Occasionally, however, California experiences heavy rainstorms. There is no system in place to capture this water, so the state can have serious flooding problems.

Just as human activities such as farming influence the impact of droughts, human activities can worsen the risk of flooding. Flooding occurs when water input exceeds the ability of an area to absorb that water. In healthy natural areas, porous soil and wetlands soak up excess rainwater. In areas where the soil has been baked hard by drought, however, or in urban and suburban areas with large areas of impermeable surfaces—pavement or buildings that do not allow water penetration—the water from heavy rainfall events cannot soak into the ground. Instead, storm waters run off over impermeable soil or paved surfaces and into storm sewers or nearby streams. Excess water that the ground does not absorb fills streams and rivers, which overflow their banks and may flood lowland areas. Like droughts, floods can lead to crop and property damage as well as losses of animal and human lives.

CHECKPOINT

- What are the primary repositories of fresh water on Earth? Which of these repositories is the largest?
- What is the difference between a confined and an unconfined aquifer? How do their recharge rates differ?
- How do human activities worsen the effects of droughts and floods?

9.2 Humans can alter the availability of water

As we have just seen, the availability of water around the world can be unpredictable, yet water is critical for the survival of living things. Humans have learned to live with variations in water availability in several ways. We can channel the flow of rivers with levees, block the flow of rivers with dams to store water, divert water from rivers and lakes and transport it to distant locations, and even obtain fresh water by removing the salt from salt water. In this section we will look at each of these water distribution methods and examine their costs and benefits.

9.2.1 Levees
Before the intervention of humans, most rivers periodically overflowed their banks. These occasional overflows of nutrient-rich water made their floodplains particularly fertile. We have seen that throughout history, humans have taken advantage of these fertile floodplains for agriculture. In more recent times, humans have sought ways to prevent flooding so they could develop floodplain land for residential and commercial use. One way to prevent flooding is by constructing a **levee**, an enlarged bank built up on each side of the river. The Mississippi River has the largest system of levees in the world. This river is enclosed by more than 2,400 km (1,500 miles) of levees that offer flood protection to more than 6 million hectares (15 million acres) of floodplains.

![Figure 9.9 Levees](image)

Levees are built to prevent rivers from flowing over their banks and onto the floodplain. In 2008, this levee, just north of St. Louis, Missouri, collapsed and allowed the floodwaters to spread over the surrounding fields.

The use of levees has produced several major challenges. First, natural floodwaters can no longer add fertility to flood-plains by depositing sediments there, so the fertility of these lands is reduced. Second, because the sediments do not leave the river, they are carried farther downstream and settle out where the river enters the ocean. Third, levees may prevent flooding at one location, but by doing so, they force floodwater farther downstream, where it can cause even worse flooding in the next city or town. Finally, the building of levees encourages development in floodplains, but these areas still occasionally flood. This practice raises the question of whether development should be allowed in these areas where flooding remains a high risk.

When floodwaters become too high, levees can either collapse due to the tremendous pressure of the water, or water can come over the top and quickly erode a large hole in the levee. Both events result in massive flooding (**FIGURE 9.9**). One of the most famous levee failures occurred in New Orleans in 2005, as the result of Hurricane Katrina. The levees could not contain the storm surge and heavy rainfall associated with
the hurricane. The water overtopped nearly 50 levees, quickly washing out the banks of
dirt and flooding many of the neighborhoods that the levees were built to protect. The
hurricane and the devastating floodwaters caused more than 1,800 deaths and more
than $80 billion in damage to homes and businesses.

9.2.2 Dikes

Dikes are similar to levees, but they are typically built to prevent ocean waters from
flooding adjacent land. Dikes are common in northern Europe, where large areas of
farmland lie below sea level. Perhaps the best-known dikes are those of the
Netherlands, where dikes have been used for nearly 2,000 years. Approximately 27
percent of the land in the Netherlands is below sea level. The dikes, combined with
pumps that move any water that does intrude back out to the ocean, have allowed the
country to develop areas that would otherwise be under water. The original pumps
were powered by windmills, which is why we often associate the Netherlands with wind
energy. Today, however, the water is pumped with electric and diesel pumps.

9.2.3 Dams

A dam is a barrier that runs across a river or stream to control the flow of water. Water
is stored behind the dam in a large body of water called reservoir. Dams hold water
for a wide variety of purposes, including human consumption, generation of
electricity, flood control, and recreation. In 2009, there were 845,000 dams in the world
and 82,642 dams in the United States. The largest reservoir system in the United States
is along the Missouri River. With six dams and reservoirs in Montana, North
Dakota, South Dakota, and Nebraska, this system stores nearly 90 trillion liters (24
trillion gallons) of water.

For centuries, humans have used dams to do work, from turning waterwheels that
operated grain mills to powering modern turbines that generate electricity in
hydroelectric plants. Although hydroelectric dams (discussed further in Chapter
13) are some of the world’s largest, they represent only 3 percent of all dams in the
United States. In contrast, 18 percent of U.S. dams were built with the primary purpose
of flood control—to reduce or prevent flooding farther down the river. Another 38
percent of U.S. dams were constructed primarily for recreation. Dams have also been
built to create scenic lakes for housing developments.

Dams provide substantial benefits to humans, but they come with financial, societal, and
environmental costs. The world’s largest dam, the Three Gorges Dam built across the
Yangtze River in China, illustrates these costs and benefits well. This massive
structure, pictured in FIGURE 9.10, is 2 km (1.3 miles) wide, 185 m (610
feet) high, and has created a reservoir 660 km (410 miles) long behind it. The Three
Gorges Dam took 13 years to construct, from 1993 to 2006, and it took another 2 years for the reservoir to fill with water. Dam building, like other large-scale construction, uses large amounts of energy and materials and displaces people. The Three Gorges Dam and the reservoir it created flooded 13 cities, 140 towns, and 1,350 villages, forcing more than 1.3 million people to be relocated. The benefits of the dam include the large amount of electricity generated through hydroelectric power rather than through the burning of fossil fuels and the reduction of the seasonal flooding that has plagued cities and villages downstream of the dam, killing more than 1 million people during the past 100 years.
Because dams are an impediment to fish such as salmon that migrate upstream to breed, fish ladders like this one in New Brunswick, Canada, have been designed to allow the fish to get around the dam and continue on their traditional path of migration.

One of the most common environmental problems associated with dams is the interruption of the natural flow of water to which many organisms are adapted. For migrating fish such as salmon, dams represent an insurmountable obstacle to breeding. The loss of these fish can have a cascading effect on other organisms that depend on them, such as bears that feed on migrating salmon. To alleviate this problem, fish ladders, which are built like a set of stairs with water flowing over them, have been added to some dams. Migrating fish can swim up the fish ladders and reach their traditional breeding grounds (FIGURE 9.11).

Using dams to prevent seasonal flooding has other consequences for the ecology of an area. Seasonal flooding scours out pools and shorelines, and this disturbance favors their colonization by certain plants and animals. Some of the species that are highly dependent on such disturbances are very rare. In recent years, managers have begun to experiment with releasing large amounts of water from reservoirs to simulate seasonal flooding. The results have been very promising. In some areas where dams are no longer needed, they have been removed to restore the natural flow of water, as
described in this chapter’s opening story. In these cases, much of the natural ecology has been quickly restored.

9.2.4 Aqueducts

Levees, dams, and dikes are designed to hold water back from its normal course. For centuries, however, people have needed not only to store water, but also to move it. Aqueducts are canals or ditches used to carry water from one location to another. Typically, aqueducts remove water from a lake or river and transport this water to where it is needed. Although aqueducts are famously associated with the Roman Empire, their use dates back to at least the seventh century BCE in Greece. The earliest aqueducts were made of limestone, but modern aqueducts include concrete canals and pressurized steel pipes laid above or under the ground. These structures are more efficient water carriers than the ditches and stone-lined canals of historic times. Older aqueducts, many of which are still in use, can lose as much as 55 percent of the water they carry through leakage or evaporation. These losses can be particularly troublesome in water-poor areas such as the arid regions of Israel and Jordan, where water is already scarce.
Aqueducts deliver water from places where it is abundant to places where it is needed. This section of the Colorado River Aqueduct, which diverts water from the Colorado River to Los Angeles, passes through the Mojave Desert.

In the United States, two of the country’s largest cities, New York and Los Angeles, depend on aqueducts for their daily water needs. The Catskill Aqueduct brings clean, fresh water over 200 km (120 miles) from the streams and lakes of the Catskill Mountains to the city of New York. The Colorado River Aqueduct is a canal that carries water 400 km (250 miles) from the Colorado River to Los Angeles (FIGURE 9.12). As with many of our answers to natural resource supply challenges, there are trade-offs and environmental costs associated with aqueducts. Although bringing water to cities from pristine areas may ensure its cleanliness, the construction of aqueducts for this purpose not only requires a great deal of money, but also disturbs and fragments natural habitats. Even if an aqueduct is buried as an underground pipeline, a great deal of disruption occurs during the construction process. Moreover, diverting water from a natural river means that there is less water flowing where water has flowed for millennia. Some major rivers in the United States, including the Colorado River and the Rio Grande, now frequently have periods during which so much water is removed from them, at multiple locations, that they go dry before they reach the ocean. Some water diversion projects have international impacts. India and Bangladesh, for example, share nearly 250 rivers that originate in the Himalayas of India and flow into Bangladesh. In 2009, India proposed a large-scale water diversion project, involving more than 50 rivers, that has caused Bangladesh some major concerns. By diverting water from these rivers, India stands to gain 170 billion liters (55 billion gallons) of water each year for agriculture and household use. However, Bangladesh is situated downstream of these river diversions. Bangladeshi officials worry that the project will end up dramatically reducing the flow of river water into their country, affecting local fish populations and river navigability for commerce. Even farther downstream, the project may reduce the flow of fresh water into estuaries. When less fresh water enters an estuary, ocean water moves farther up into the river. This influx of seawater raises the salinity of the estuary and harms aquatic life that is not adapted to such salty water.
Consequences of river diversion. Diverting river water can have devastating impacts downstream. The Aral Sea, on the border of Kazakhstan and Uzbekistan, was once the world’s fourth largest lake. Since the two rivers that fed the lake were diverted, its surface area has declined by 60 percent, and the lake has become split into two parts: the North and South Aral seas.

The most infamous river diversion project happened in the 1950s, when the Soviet Union diverted two rivers that fed the Aral Sea in Central Asia. Diversion of the rivers dramatically decreased freshwater input into the Aral Sea. The salinity of the remaining lake water increased, destroying the local fish populations. Although the Aral Sea was originally the fourth largest lake in the world in terms of surface area, the diversion project reduced its surface area by more than 60 percent, as shown in FIGURE 9.13. The withdrawals of water caused the Aral Sea to split into two parts: the North Aral Sea and the South Aral Sea. Dust storms have eroded soil, salt, and pesticide residues from the dry lake bed and carried particles of these substances into the atmosphere. The lake’s size reduction has also affected the local climate. Without the climate-moderating effect of a large water body, summers in the region are now hotter, and winters are colder. While efforts are being made to save the North Aral Sea, saving the South Aral Sea has been deemed too expensive, and all efforts have been abandoned. The drying of the South Aral Sea continues today: the shallower eastern half of the South Aral Sea is predicted to be completely dry in 10 years.

9.2.5 Desalination
One of the ways in which some water-poor countries are obtaining fresh water is by removing the salt from salt water, a process called desalination, or desalinization (FIGURE 9.14). The salt water usually comes from the ocean, but it can also come from salty inland lakes. Currently, the countries of the Middle East produce 50 percent of the world’s desalinated water.

The two most common desalination technologies are distillation and reverse osmosis. In distillation (FIGURE 9.14a), heat is used to boil water, which leaves its salts behind as it evaporates. The steam that is produced is captured and condensed, yielding pure water. A great deal of energy is required to boil the water and then condense it, so distillation can be a monetarily and environmentally expensive process.

In reverse osmosis (FIGURE 9.14b), water is forced through a thin semipermeable membrane at high pressure. Water can pass through the membrane, but salt cannot. Reverse osmosis is a newer technology that is more efficient and often less expensive.
costly than distillation. However, the liquid that remains, called brine, has a very high salt concentration. It cannot be deposited on land because its high salt content would contaminate the soil, potentially harming plant and animal life. If dumped into a bay or coastal area, it can harm fish and other aquatic life. Typically, brine is returned to the open ocean, though its high salt concentrations can still cause localized harm to ocean life.

Ultimately, all water management systems require a large investment to build, maintain, and repair. This means that many water-poor countries are not able to implement large-scale methods of water management to provide for their needs. Water availability varies greatly around the world, as FIGURE 9.15 shows. The Middle Eastern and North African countries represent about 5 percent of the world’s population, yet they have less than 1 percent of the fresh water available for drinking. The United Nations estimates that nearly 1.2 billion people live in regions that have a scarcity of water.

CHECKPOINT
• How do levees, dikes, dams, and aqueducts differ from one another? What is the primary purpose of each?
• Why is it necessary to desalinize water?

9.3 Water is used by humans for agriculture, industry, and household needs

Figure 9.16 Total per capita water use per day. The total water use per person for agriculture, industry, and households varies tremendously by country.

A human can survive without food for 3 weeks or more, but cannot survive without water for more than a few days. In addition, water is essential for producing food. In fact, 70 percent of the world's freshwater use is for agriculture. The remaining 30 percent is split between industrial and household uses, the proportion of which varies from country to country. On average, experts estimate that about 20 percent of the world's freshwater use is for industry and about 10 percent is for household uses. As we have seen with so many other resources, the daily use of water per capita varies dramatically among the nations of the world. Figure 9.16 shows total daily per capita use of fresh water for a number of countries.

Previous Section  |  Next Section
9.3.1 Agriculture

As we have just noted, the largest use of water worldwide is for agriculture. During the last 50 years, as agricultural output has kept up with human population growth, the amount of water used for irrigation throughout the world has more than doubled. Indeed, producing a metric ton of grain (1,000 kg, or 2,200 pounds) requires more than 1 million liters of water (264,000 gallons). Together, India, China, the United States, and Pakistan account for more than half the irrigated land in the world. In the United States, approximately one-third of all freshwater use is for irrigation. As we saw in Chapter 8 (see “Measuring Your Impact” on page 233), raising livestock for meat also requires vast quantities of water. For example, producing 1 kg (2.2 pounds) of beef in the United States requires about 11 times more water than producing 1 kg of wheat.

IRRIGATION Since agriculture is the greatest consumer of fresh water throughout the world, agriculture presents the greatest potential for conserving water by changing irrigation practices. There are four major techniques for irrigating crops: furrow irrigation, flood irrigation, spray irrigation, and drip irrigation (FIGURE 9.17).
Several techniques are used for irrigating agricultural crops, each with its own set of costs and benefits.

The oldest technique is *furrow irrigation* (FIGURE 9.17a), which is easy and inexpensive. The farmer digs trenches, or furrows, along the crop rows and fills them with water, which seeps into the ground and provides moisture to plant roots. Furrow irrigation is about 65 percent efficient, meaning that 65 percent of the water is accessible to the plants; the other 35 percent either runs off the field or evaporates.

A second technique is *flood irrigation* (FIGURE 9.17b), which involves flooding an entire field with water and letting the water soak in evenly. This technique is generally more disruptive to plant growth than furrow irrigation, but is also slightly more efficient, ranging from 70 to 80 percent efficiency.

A third technique is *spray irrigation* (FIGURE 9.17c), which is more expensive than furrow or flood irrigation and also uses a fair amount of energy. Water is pumped from a well into an apparatus that contains a series of spray nozzles that spray water across
the field, like giant lawn sprinklers. The advantage of spray irrigation is that it is 75 to 95 percent efficient.

The fourth technique is *drip irrigation* (**FIGURE 9.17d**), which uses a slowly dripping hose that is either laid on the ground or buried beneath the soil. Drip irrigation using buried hoses is over 95 percent efficient. It has the added benefit of reducing weed growth because the surface soil remains dry, which discourages weed germination. Drip irrigation systems are particularly useful in fields containing perennial crops such as orchard trees, where the hoses do not have to be moved for annual plowing of the field.

**Figure 9.18** Hydroponic agriculture. These tomatoes are growing in a greenhouse with their roots immersed in a solution of water and nutrients. By recycling the water, hydroponic operations can use up to 95 percent less water than traditional irrigation techniques.

Efficient irrigation technology benefits the environment by reducing water consumption and by reducing the amount of energy needed to deliver the water. However, as with all human activities, the trade-offs involved in each irrigation technique (water costs, energy costs, and equipment costs) need to be weighed to determine the best solution for each situation.

**HYDROPONIC AGRICULTURE** For some crops, *hydroponic agriculture* is an alternative to traditional irrigation. Hydroponic agriculture is the cultivation of crop plants under greenhouse conditions with their roots immersed in a nutrient-rich solution, but no soil (**FIGURE 9.18**). Water not taken up by the plants can be reused, so this method uses up to 95 percent less water than traditional irrigation techniques. Hydroponic operations can produce more crops per hectare than traditional farms. In addition, they can grow crops under ideal conditions, grow the crops during every season of the year, and often grow the crops with little or no use of pesticides. Hydroponic agriculture is growing in popularity, especially for vegetables; hydroponic tomatoes, for example, have won awards for their flavor. While the costs of growing vegetables hydroponically can be a bit higher, consumers appear to be willing to pay more for
hydroponically grown vegetables. Indeed, one company in Georgia now grows hydroponic vegetables in a huge facility that covers 129 ha (318 acres).

9.3.2 Industry

Water is required for many industrial processes, such as generating electricity, cooling machinery, and refining metals and paper.

In the United States, approximately one-half of all water used goes toward generating electricity. It is important to distinguish between water that is withdrawn from and returned to its source and water that is withdrawn and consumed. For example, water that passes through a turbine at a hydroelectric dam is withdrawn from a reservoir to generate electricity, but that water is not consumed. It passes from the reservoir through the turbine and back to the river flowing away from the dam. That is not to say that this process has no effect on the environment. We discussed the ecological impacts of damming rivers earlier in this chapter. In addition, passing millions of gallons of water through a spinning turbine kills millions of fish each year.

![Figure 9.19 Water consumption by a nuclear power plant.](image)

When nuclear reactors, such as this one in Germany, heat water to make the steam that turns electrical turbines, the steam must be cooled back down. During the cooling of the steam, a great deal of water vapor is released to the atmosphere. This water vapor represents consumption of water by the plant.

Some processes that generate electricity do consume water. This means that some of the water used is not returned to the source from which it was removed, but instead enters the atmosphere as water vapor. Thermoelectric power plants, including the many plants that generate heat using coal or nuclear reactors, are large consumers of water. These plants use heat to convert water into steam, which is then used to turn turbines. The steam needs to be cooled and condensed before it can be returned to the water’s source. In many plants, this cooling is accomplished using massive cooling towers. If you have ever seen a nuclear power plant, even from a distance, you may
have seen the large plumes of water vapor rising up for thousands of meters from the cooling towers. The towers allow much of the steam from the plant to condense and cool into liquid water, but a large fraction of it is lost to the atmosphere. This water vapor represents the water that is consumed by nuclear reactors (FIGURE 9.19). The refining of metals and paper also requires large amounts of water. Copper, used extensively for electrical wiring, requires 440 L (116 gallons) of water per kilogram to refine. Aluminum, used in products as diverse as automobiles and aluminum foil for cooking, requires 410 L (108 gallons) per kilogram. Steel, used to manufacture home appliances, cars, buildings, and other products, requires 260 L (68 gallons) per kilogram. When we use paper, we indirectly use water. A kilogram of paper requires 125 L (33 gallons) of water to manufacture. All of this means that a great deal of water is used in industry. As we will see later in this chapter, there are opportunities to reduce the use of water during these processes.

### 9.3.3 Households

![Figure 9.20](image)

**Figure 9.20** Household per capita water use per day. When only household water use, rather than total water use (as in FIGURE 9.16), is considered, the ranking of many countries changes. [Data from A. K. Chapagain and A. Y. Hoekstra, *Water Footprints of Nations*, Vol. 1, Main Report, UNESCO-IHE. Research Report Series #16, 2004.]

According to the U.S. Geological Survey, approximately 10 percent of all water used in the United States is used in homes. The quantity of water used in households depends greatly on the types of infrastructure available in a country. Households in less developed countries generally do not have the appliances and bathroom fixtures that
are common in more developed countries. As a result, per capita household water use varies dramatically among nations. For example, on average, an individual in the United States uses 595 L (157 gallons) per day, whereas an average individual in Kenya uses only 41 L (11 gallons) per day. FIGURE 9.20 shows per capita daily house-

hold water use for the United States and 10 other countries.

Indoor use of water is quite similar across the United States, as households across the country are typically equipped with bathrooms, washing machines, and cooking appliances. FIGURE 9.21 shows the fraction of indoor water use that goes to each of these functions. Of all household water used indoors, 41 percent is used for flushing toilets, 33 percent for bathing, 21 percent for laundry, and 5 percent for cooking and drinking.

![Figure 9.21 Indoor household water use. Most water used indoors is used in the bathroom. [Data from U.S. Environmental Protection Agency, 2003.http://esa21.kennesaw.edu/activities/water-use/water-use-overview.epa.pdf.]

Outdoor water use—for watering lawns, washing cars, and filling swimming pools—varies tremendously across the United States by region. In California, for example, the typical household uses about six times more water outdoors than the typical Pennsylvania family.

Although drinking water represents a relatively small percentage of household water use, it is a particularly important one. If you live in a developed country, you may not have given much thought to the availability and safety of drinking water. However, more than 1 billion people—nearly 15 percent of the world’s
population—lack access to clean drinking water. Every year, 1.8 million people die of diarrheal diseases related to contaminated water, and 90 percent of those people are children under 5 years old. This means that 5,000 people in the world die each day in large part because they do not have access to clean water. As we will see in Chapter 14, in which we discuss water pollution, developed countries typically have modern sanitation systems, stronger environmental laws, and the technologies to remove harmful contaminants and waterborne pathogens from public water supplies. Poor conditions in many developing countries do not provide safeguards that ensure the availability of clean drinking water.

CHECKPOINT

- What are the dominant uses of water by humans?
- How do different irrigation methods influence water use?
- Why does it require so much more water to produce 1 kg of beef than 1 kg of grain?

9.4 The future of water availability depends on many factors

The future of water availability will depend on many things, including how we resolve issues of water ownership and how we improve water conservation and develop new water-saving technologies as the world’s population grows.

9.4.1 Water Ownership

Water is an essential resource, but who actually owns it? It turns out that this is a complex question. In a particular area, such as the Klamath River region described in this chapter’s opening story, it is clear that multiple interest groups can claim a right to use and consume the water. However, having a right to use the water is not the same as owning it. For example, regional and national governments often set priorities for water distribution, but of course they have no control over whether a particular year will bring an abundance of rain and snow. In California, the state government promises specific amounts of water for cities, suburbs, farmers, and fish, but collectively, these promises far exceed the actual amount of water that is available in many years. Throughout the world, the issues of water rights and ownership have created many conflicts. Earlier in this chapter we discussed India’s plan to divert water from rivers that flow from the Himalayas into Bangladesh (FIGURE 9.22). Since the water originates in India, does India own the water? Does Bangladesh have any legitimate claim to some of this water that its people have relied upon for millennia? In the water-
poor Middle East, water rights have long contributed to political tensions. In both the 1967 Arab-Israeli War and the 1980s Iran-Iraq War, disputes over water use added to the conflict. Water experts predict that as populations in these arid regions continue to grow, conflicts over water will increase.

![A Himalayan river.](image)

The government of India is proposing to divert water from some of the rivers flowing out of the Himalayas to provide more water for its citizens. However, rivers, such as this one flowing down from Mera Peak in Nepal, subsequently flow into Bangladesh, raising interesting questions regarding who owns the water.

One solution that has been proposed by economists is to allow all interested parties to openly compete for water and let market forces determine its price. In this way, they argue, water could be owned, but the true value of water would be realized and paid for. In 1981, a free-market system of water distribution was initiated in Chile. While water is public property, Chile allows individuals and corporations to buy and sell water. The idea behind this approach is that having to buy water will encourage more efficient use. While market forces can be useful in determining the appropriate distribution of water among competing needs, government oversight helps to ensure that the needs of the people and the environment are balanced with the needs of private corporations. As we will see in the Science Applied section that follows this chapter (“Is There a Way to Resolve the California Water Wars?”), this more balanced approach is now being attempted.

**DO THE MATH**

**Selecting the Best Washing Machine**

Suppose you move into a new house and need to purchase a washing machine. You’ve heard that the new front-loading machines use less water, but that they are more
expensive. A traditional washing machine costs $400, whereas the water-efficient washing machine costs $800. So how do you choose?

1. If the average family washes 5 loads of laundry per week, how many loads does the family wash per year?
   
   \[5 \text{ loads/week} \times 52 \text{ weeks/year} = 260 \text{ loads/year}\]

2. The traditional machine uses 150 L of water per load of laundry, and the efficient machine uses 75 L. How many liters would the efficient washing machine save per year?

   \[(150 \text{ L} - 75 \text{ L})/\text{load} \times 260 \text{ loads/year} = 19,500 \text{ L/year}\]

3. The average cost of water in the United States is $0.40 for every 1,000 L. How much money would you save each year by using the more efficient washing machine?

   \[0.40/1,000 \text{ L} \times 19,500 \text{ L/year} = 7.80/\text{year}\]

4. How many years would you have to own the more efficient washing machine before you would save money compared with the traditional machine?

   \[
   \frac{800 - 400}{7.80/\text{year}} = 51.3 \text{ years}
   \]

For simplicity, this problem considers only the dollar cost of water in determining the payback period. However, one must also consider the energy and dollar cost of heating water. If half of the loads are done with hot or warm water, this reduces the payback period to fewer years.

### 9.4.2 Water Conservation

Ultimately, we all have to share a finite amount of water. In some regions, such as much of the northeastern United States, water is abundant. In other regions, where water is scarcer, water conservation is a necessity.

In recent years, many developed countries have begun to find ways to use water more efficiently through technological improvements in water fixtures, faucets, and washing machines. In 1994, new federal standards were issued for toilets and showerheads in the United States. For example, a toilet manufactured before 1994 typically uses 27 L (7 gallons) per flush, but toilets sold after January 1994 must use 6 L (1.6 gallons) or less per flush, representing a 78 percent reduction in water use. Australia and some countries in Europe and Asia have moved to dual-flush toilets. First invented by an Australian company in 1980, this type of toilet allows the user to push one button for a normal 6 L flush to remove solid waste, but another button produces a much more efficient 3 L (0.8-gallon) flush to remove liquid waste. Although dual-flush toilets have not yet been accepted by consumers in the United States, consumers have embraced
improve efficiencies in showerheads and washing machines. For example, a 10-minute shower with an older showerhead might use 150 L (40 gallons) of water, but revised federal standards for new reduced-flow showerheads call for a 10-minute shower to use no more than 95 L (25 gallons)—a 37 percent reduction in water use. Washing machines are not subject to the new federal standards, but newer, more efficient front-loading washing machines are now available to consumers. However, these more efficient machines also cost nearly twice as much to purchase. **Do the Math** “Selecting the Best Washing Machine” looks at the costs and benefits of these newer, more energy-efficient washing machines.

In countries where a percentage of the population is particularly wealthy, household water uses include watering lawns and filling swimming pools, both of which require large amounts of water. In some regions of the United States, homeowners have been encouraged, or even required, to plant vegetation that is appropriate to the local habitat. For example, the city of Las Vegas, Nevada, paid homeowners to remove water-intensive turf grass from their lawns and replace it with more water-efficient native landscaping. Vegetation substitution can result in a savings of 2,000 L of water per square meter (520 gallons per 10 square feet) of lawn per year (**FIGURE 9.23**).

![Figure 9.23 Landscaping in the desert.](image)

By using plants that are adapted to a desert environment, homeowners in Arizona can greatly reduce the need for irrigation, resulting in a considerable reduction in water use compared with growing grass.

One of the best ways to reduce water use and consumption is to produce more efficient manufacturing equipment. In the United States, businesses and factories have achieved more sustainable water use in the last 15 years, mainly through the introduction of equipment that either uses less water or reuses water. Industries that need cooling...
water for machinery, for example, have converted from once-through systems (systems that bring in water for cooling and pump the heated water back into the environment) to recirculating water systems.

There are some simple ways to conserve water that can be used throughout the world. For example, the impervious surfaces of buildings represent a substantial water collecting surface. A simple gutter system can be used to collect rainwater and channel it into rain barrels or, for greater capacity, a large underground water tank. As we will see in Chapter 14, some countries are now using wastewater for irrigation after sending it through a sewage treatment process.

The world’s growing population and the associated expansion of irrigated agriculture have increased global water withdrawals more than fivefold in the last hundred years. Global water use is expected to continue to grow with the human population through the early part of this century. But, as Figure 9.24 shows, despite the United States’ growing population, water withdrawals in the United States have leveled off since they peaked in 1980. This is largely a result of greater water use efficiency in agricultural irrigation, electricity generation, and household use. Reductions in water use are projected to continue until at least 2020, when all the estimated gains from water-saving devices and technologies will begin to level off unless newer, even more efficient technologies are developed.

**CHECKPOINT**

- Why is water ownership a complex issue?
- What are some of the ways that humans can conserve water?
- How does economic development influence water use?
In certain parts of the world, such as the United States, sanitation regulations impose such high standards on household wastewater that we classify relatively clean water from bathtubs and washing machines as contaminated. This water must then be treated as sewage. We also use clean, drinkable water to flush our toilets and water our lawns. Can we combine these two observations to come up with a way to save water? One idea that is gaining popularity throughout the developed world is to reuse some of the water we normally discard as waste.

This idea has led creative homeowners and plumbers to identify two categories of wastewater in the home: gray water and contaminated water. Gray water is defined as the wastewater from baths, showers, bathroom sinks, and washing machines. Although no one would want to drink it, gray water is perfectly suitable for watering lawns and plants, washing cars, and flushing toilets. In contrast, water from toilets, kitchen sinks, and dishwashers contains a good deal of waste and contaminants and should therefore be disposed of in the usual fashion.
Figure 9.25 Reusing gray water. A Turkish inventor has designed a washing machine that pipes the relatively clean water left over from a washing machine, termed gray water, to a toilet, where it can be reused for flushing. Such technologies can reduce the amount of drinkable water used and the volume of water going into sewage treatment plants.

Around the world, there are a growing number of commercial and homemade systems in use for storing gray water to flush toilets and water lawns or gardens. For example, a Turkish inventor has designed a household system allowing the homeowner to pipe wastewater from the washing machine to a storage tank that dispenses this gray water into the toilet bowl with each flush (FIGURE 9.25).

Many cities in Australia have considered the use of gray water as a way to reduce withdrawals of fresh water and reduce the volume of contaminated water that requires treatment. The city of Sydney estimates that 70 percent of the water withdrawn in the greater metropolitan area is used in households, and that perhaps 60 percent of that water becomes gray water. The Sydney Water utility company estimates that the use of gray water for out-door purposes could save up to 50,000 L (13,000 gallons) per household per year.
Unfortunately, many local and state regulations in the United States and around the world do not allow use of gray water. Some localities allow the use of gray water only if it is treated, filtered, or delivered to lawns and gardens through underground drip irrigation systems to avoid potential bacterial contamination. Arizona, a state in the arid Southwest, has some of the least restrictive regulations. As long as a number of guidelines are followed, homeowners are permitted to reuse gray water. In 2009, in the face of a severe water shortage, California reversed earlier restrictions on gray water use and agreed to allow gray water to be used for irrigating lawns and trees. Given that the typical household produces 227,000 L (60,000 gallons) of gray water per year, using gray water for irrigation presents a major opportunity for water conservation throughout the world.

References


**Key Ideas Revisited**

- **Identify Earth’s natural sources of water.**
  Most water on Earth resides in the oceans. Of the relatively small proportion that is fresh water, nearly three-fourths is tied up as ice and glaciers, leaving a small amount remaining in groundwater, streams, rivers, lakes, and wetlands. All of these sources of fresh water can be used by humans. Atmospheric water is an additional source of water, but its availability may vary seasonally as well as from year to year. Human activities can contribute to the negative effects of drought and flooding.

- **Discuss the ways in which humans manage water distribution.**
  Humans have created a variety of ways to store and divert water, including levees, dikes, dams, and aqueducts. Each of these water distribution technologies has important benefits, but can also have negative environmental impacts. Humans have also developed technologies for the desalination of salt water.

- **Describe the major human uses of water.**
  Water is used in agriculture, industry, and households. Agricultural uses of water include several different methods of irrigation as well as the developing field of hydroponic agriculture. Industrial uses of water include the generation of electricity, the refining of metals and paper, and the cooling of machinery. In households, water is used primarily in bathrooms and for washing clothes. Per capita water use varies tremendously by country. Developed countries tend to use more water than developing countries, where many people have access to only a few liters of water per day.

- **Identify the factors that will affect the future availability of water.**
The future of water availability depends on water ownership, water conservation, economic development, and global change. Water ownership is a highly complex issue that involves the market value of water and our need to ensure that adequate supplies are available. Water conservation efforts include improvements in agricultural irrigation techniques, the increased use of recycled water in industrial processes, more efficient household appliances, planting less water-demanding landscapes, and simple water collection devices that collect rainwater and allow recovery and reuse of gray water.

PREPARING FOR THE AP EXAM

MULTIPLE-CHOICE QUESTIONS

1. What percentage of Earth’s water is fresh water?
   - (a) 3 percent
   - (b) 10 percent
   - (c) 50 percent
   - (d) 90 percent
   - (e) 97 percent

2. Which of the following contrasts between confined and unconfined aquifers is correct?
   - (a) Confined aquifers are more rapidly recharged.
   - (b) Only confined aquifers can produce artesian wells.
   - (c) Only unconfined aquifers are overlain by a layer of impermeable rock.
   - (d) Only unconfined aquifers have a water table above them.
   - (e) Only unconfined aquifers can be drilled for wells to extract water.

3. Which of the following statements about surface waters is not correct?
   - (a) Historically, most rivers regularly spilled over their banks.
   - (b) The largest river in the world is the Amazon River.
   - (c) Levees are used to make reservoirs.
   - (d) Dikes are human-made structures that keep ocean water from moving inland.
   - (e) Wetlands play an important role in reducing the likelihood of flooding.

4. Which of the following statements about dams is not correct?
   - (a) Dams are used to reduce the risk of flooding.
   - (b) Dams can cause increased water temperatures.
   - (c) The water held back by a dam is called a reservoir.
Fish ladders allow migrating fish to move past dams.
Most dams are built to generate electricity.

5. Which of the following statements about aqueducts is correct?
- (a) Aqueducts designed as open canals can lose a lot of water via evaporation.
- (b) Aqueducts are a modern invention.
- (c) Aqueducts do not divert water from lakes.
- (d) Aqueducts do not affect the amount of water remaining in rivers.
- (e) Aqueducts move water from locations where the demand for water is high.

6. Which of the following statements about desalination is correct?
- (a) Distillation requires more energy than reverse osmosis.
- (b) The brine left over from desalination is not harmful when returned to the ocean.
- (c) Large-scale desalination of water is affordable to all nations.
- (d) Desalination of ocean water is not yet a feasible endeavor.
- (e) Most desalination occurs in the Middle East.

7. Which of the following lists of household water uses is in the correct order, from highest to lowest?
- (a) Toilet > laundry > cooking and drinking > bathing
- (b) Toilet > bathing > laundry > cooking and drinking
- (c) Laundry > bathing > toilet > cooking and drinking
- (d) Bathing > toilet > laundry > cooking and drinking
- (e) Bathing > toilet > cooking and drinking > laundry

8. Which of the following lists of agricultural irrigation techniques is in the correct order, from least efficient to most efficient?
- (a) Drip irrigation, furrow irrigation, flood irrigation, spray irrigation
- (b) Spray irrigation, furrow irrigation, flood irrigation, drip irrigation
- (c) Furrow irrigation, flood irrigation, spray irrigation, drip irrigation
- (d) Furrow irrigation, spray irrigation, drip irrigation, flood irrigation
- (e) Furrow irrigation, flood irrigation, drip irrigation, spray irrigation

9. Which of the following statements about the industrial use of water is not correct?
- (a) It is used to refine metals.
- (b) It is used to create steam.
- (c) It is important in generating electricity.
- (d) It plays a role in making paper products.
- (e) Its use is becoming less efficient.
10. Which of the following is *not* a water conservation technique?
- (a) Flood irrigation
- (b) Reduced-flow showerheads
- (c) Recycling of industrial water
- (d) Dual-flush toilets
- (e) Front-loading washing machines

**FREE-RESPONSE QUESTIONS**

**[Notes/Highlighting]**

1. An important source of fresh water is groundwater. Answer the following questions about human use of groundwater.
- (a) Using a cross section of the ground, draw the water table, an unconfined aquifer, and a confined aquifer. (4 points)
- (b) Explain the factors that create an artesian well. (2 points)
- (c) Describe the concerns that scientists have regarding the pumping of water from confined aquifers. (2 points)
- (d) Explain how cones of depression near the coasts of continents can lead to saltwater intrusion of water wells. (2 points)

**[Answer Field]**

2. Answer the following questions about the world’s approximately 845,000 dams.
- (a) What are the benefits that dams provide to humans? (4 points)
- (b) What are the costs of dams to human society? (2 points)
- (c) What are the negative impacts of dams on the environment? (2 points)
- (d) If dams have both costs and benefits, how should we decide when a dam should be built? (2 points)

**1. Saving Water** The need to conserve water is widespread throughout the world. People who live in developed countries such as the United States can make some simple changes to conserve water.
- (a) An older showerhead uses 150 L for a 10-minute shower, whereas a reduced-flow showerhead uses only 95 L. If you take one shower per day, how many liters of water would you save in 1 year if you replaced your older showerhead?
- (b) An older toilet uses 27 L per flush, whereas a replacement toilet uses only 6 L per flush. If you flush the toilet four times per day, how many liters of water would you save in 1 year if you replaced your older toilet?
- (c) Now let’s assume that you have a newer toilet that uses 6 L per flush, but you are considering upgrading to a dual-flush toilet. If you flush the toilet four times per day, but three of those times you could use the 3 L flush, how many liters of water would you save in 1 year?
• (d) If you made all three of the changes described in questions a–c, how much water, in total, would you save from going down the drain?
• (e) If you lived in a family of four people, and you paid $1 for every 1,000 L of water your family used, how much money, in total, could your family save in 1 year with these water conservation improvements?

[Answer Field]

Is There a Way to Resolve the California Water Wars?

Pick up any tomato, broccoli spear, or carrot in the grocery store, and chances are it came from California. California’s $37 billion agricultural industry is more than twice the size of the agricultural industry of any other state, and it accounts for nearly one-half of all the fruits, nuts, and vegetables grown in the United States. California’s temperatures are ideal for many crops, and its mild climate permits a long growing season. But water is a scarce resource there. Most of California’s growing regions lack the necessary water for farming. To remedy this situation, the state has developed an extensive irrigation system that moves water from areas where it is abundant to other areas where it is scarce.
Although agriculture in California has been an economic success, it has increased competition among the state’s residents for water. Nearly two-thirds of those residents live in southern California, where residential and business demand for water has long exceeded the locally available supply. Los Angeles, for example, has been importing water from other areas of the state for more than 100 years. As the state’s population continues to grow at about 1 percent per year, demand for water will also grow.

Wildlife also depends on a readily available supply of fresh water. In many regions of California, diverting water away from streams and rivers threatens the habitats of fish and other aquatic organisms, including several endangered species. Salmon, for instance, depend on the presence of cold, clean water for laying their eggs. In the delta region where the San Joaquin and Sacramento rivers come together just east of San Francisco, so much water has been pumped out to be sent to southern California that the fish have experienced dramatic declines.

**What historical factors have led to California’s water wars?**

At 144 trillion liters (38 trillion gallons) of fresh water per day, California’s water use is more than twice that of any other state. The vast majority of that water is used in the Central Valley region, which produces more than 80 percent of California’s farm income. In 1935, the U.S. Department of Reclamation began an immense endeavor called the Central Valley Project, which diverts 8.6 trillion liters (2.3 trillion gallons) of water per year from rivers and lakes throughout the state for both agricultural and municipal uses (**FIGURE SA4.1**).
Figure SA4.1 Water distribution in California. To supply water to the agricultural areas in the Central Valley and to supply drinking water to municipalities, the state has developed an elaborate system of aqueducts. These aqueducts can be open canals or pipes laid above or below the ground. While the project made agriculture possible in many of southern California’s desert regions, it also locked into place long-term contracts that have subsidized several decades of cheap water for farmers, who pay rates that are only 5 to 10 percent of those paid by southern California towns and cities. Interestingly, northern California also has farms, but much of its abundant water is sent to southern California farms and municipalities.

In 2005, the federal government renewed nearly 200 large water supply contracts with farmers. These contracts were for 25 years of water, with an option available to extend them another 25 years, at prices so low that the payments did not even cover the cost of the electricity used to transport the water. Organizations ranging from the Cato Institute to the Natural Resources Defense Council protested this decision. The controversy raised the question of whether farmers should be given cheap access to
water to protect the existing agricultural industry, given that agriculture consumes the majority of water used in the state, or be required to pay the same price for water as everyone else.

**How might farmers respond to increased water prices?**

What would happen if the federal government raised the price of water for California farmers? If water were more expensive, farmers would face four choices: raise the prices of their crops, switch to less water-intensive crops, use more efficient irrigation methods, or sell their farms. Each of these options would have different effects on the state’s environment and economy.

One obvious way to offset higher water prices would be for farmers to charge more for the produce they grow. For example, if California broccoli growers had to pay the same price for water as municipalities, that cost would add about 13 cents to the price of broccoli per pound—an increase of less than 10 percent. This action would not change
the environmental threat of water depletion, but would have a small negative effect on the consumer’s wallet.

Other farmers faced with higher water prices might decide to switch to crops that require less water. For example, alfalfa, which uses 25 percent of California’s irrigation water and has a low resale value compared with other crops, would no longer be a profitable crop. A farm using 296 million liters (78 million gallons) of water can produce about $60,000 worth of alfalfa per year, according to the Natural Resources Defense Council. If farmers had to purchase water at the unsubsidized rate, that water would cost them $168,000; if the alfalfa continued to sell for only $60,000, the farmers would lose more than $100,000 a year growing alfalfa. Tomatoes, broccoli, and potatoes use about half as much water per acre as alfalfa and have a higher resale value (FIGURE SA4.2). Just by replacing alfalfa with these crops, California would reduce its statewide water use by 20 percent. This action would have a positive environmental impact, since less overall water would be needed for agriculture in the state.

Investment in new irrigation technology that uses less water would also reduce a farmer’s costs. As we saw in Chapter 8, the four major irrigation techniques differ in cost and efficiency. If farmers had to purchase water at the unsubsidized rate, converting to more efficient irrigation techniques could rapidly pay for itself, as the initial investment in equipment would be offset by savings on water. As long as the cost of water continues to be subsidized by the government, farmers have little incentive to upgrade their irrigation technology.

If water prices rise, not all farmers will be able to manage the new costs. This recognition brings us to the final option: some farmers could be driven out of business and sell their land. This outcome would probably reduce the amount of food grown in the region. Whether conversion from farming to other uses would reduce water demand would depend on how the land was used. For example, if it became a housing development in which residents practiced water conservation, then the residents would use much less water per acre than the farmers had. However, if the residents chose to plant and water large lawns and were not careful about their indoor use of water, they could use even more water than the farmers.

Because charging more for water could force some farmers out of business, many politicians are reluctant to support this change. In response, some economists argue that farmers who possess long-term subsidized water contracts should be allowed to sell their water allotment to the highest bidder, something that is not allowed under the current law. In this scenario, a farmer could buy water from the government at the contracted low cost and then sell that water to a city at a substantial profit rather than using it on the farm. Farmers would increase their income, cities would get the water
they need without taking additional water from natural systems, and the government agencies that sell the water would get the same amount of money that they do today. Many critics argue, however, that the government should not be giving preferential water rates to a few users who can then make money on the water. **How have the water wars played out in the political arena?**

The California water wars have developed because of the large number of competing interests involved, including northern California farmers and municipalities that are losing water, southern California farmers and municipalities that need more water, endangered species that are declining due to the diversion of water, and beautiful natural areas that have experienced reduced water capacity, increased salinity, or gone completely dry.

Competition for California’s water has been marked by political maneuvering and numerous lawsuits. In the 1960s, for example, there was a large push to build dams that would create reservoirs to collect water. Today there are about 1,200 dams in the state. Because of the money and time needed to construct new dams, many Californians do not consider more dams to be a viable solution to today’s water problems.

The past few years have witnessed a number of lawsuits that have produced very interesting court decisions. For example, the Natural Resources Defense Council won a lawsuit regarding the 2005 water contracts for farmers in the eastern San Joaquin Valley, who use water diverted from the San Joaquin River. The judge ruled that the contracts were illegal because they did not consider the potential impact of diverting water on the endangered species that rely on the river.

In 2007, a federal court was asked to consider the impact that the large, powerful pumps used to divert water from the San Joaquin and Sacramento delta region were having on local fish populations—particularly on the delta smelt (*Hypomesus transpacificus*), a federally protected fish whose population in the delta region was declining. The court ruled that pumping from the delta region—the source of much of the state’s fresh water—must be reduced. This decision came during a multi-year drought, which made its impact on southern California even larger than it would have been otherwise. A number of California congressmen accused the state and federal governments of caring more about fish than people.

The problem of water scarcity in California rose to a crisis level in June 2008, when Governor Arnold Schwarzenegger declared that the state was officially in a drought. As a result of a lack of rain and a reduced amount of snow in the Sierra Nevada, the spring of 2008 was the driest in 88 years. The California legislature passed a bill to cut water use by 20 percent. But the legislature put most of the responsibility for reducing water
use on residential users, despite the fact that agriculture uses a much larger portion of the state’s water. Some municipalities started rationing water, and a number of municipalities began enforcing a 2001 state law that requires new building developments to show plans that ensure a 20-year water supply.

As the drought continued into 2009, additional ideas to promote water conservation were proposed. In June 2009, for example, the Los Angeles Department of Water and Power announced that it would credit customers with $11 per square meter of turfgrass replaced with drought-resistant plants or mulch.

In November 2009, the California legislature passed a series of bills to address the water crisis. The $40 billion package called for the restoration of the San Joaquin and Sacramento delta ecosystem as well as the building of new dams and a series of water conservation efforts to reduce water demand. A few days later, the governor signed the bill into law.

**What can be done?**

Given the scarcity of water in California, it stands to reason that its sustainable use is an important topic with many environmental, economic, and even political implications. Economists generally argue that all users should be charged the same amount for a resource so that only those who value it most will use it. Doing so would provide increased motivation for more efficient water use by farms, residences, and businesses. Increased water costs could be helpful in reducing the demand for water, but we cannot forget the simultaneous need for all users to better conserve water.

Scenarios similar to the California water wars are being played out in many other parts of the world. Competition for water exists not only among farmers and municipalities, but also among neighboring countries. Indeed, disagreements over water have turned into real wars between nations. If the competing interests in California can devise creative solutions to the state’s water problems, those solutions can serve as a model for the rest of the world so that we can continue to have economic prosperity without severely harming the environment.