Many existing sources of water are being stressed by withdrawals from aquifers and diversions from rivers and reservoirs to meet the needs of homes, cities, farms, and industries. Increasing requirements to leave water in streams and rivers to meet environmental, fish and wildlife, and recreational needs further complicate the matter.


FOCAL POINTS

- Water is a most vital mineral resource because it is essential for human survival.
- 97.2 percent of the water of Earth’s hydrosphere is contained in the oceans; this water is saline, containing 3.5 percent salts, and is unusable for most purposes.
- Most of the world’s fresh water—2.15 percent of Earth’s total water—is held in ice caps and glaciers and is unavailable for human use.
- The largest store of fresh water available for human use occurs as groundwater.
- The hydrologic cycle describes the constant movement of water from the oceans to the atmosphere by evapotranspiration, and back to the oceans, often via the land surface, as precipitation.
- The world’s principal rainfall belt lies along the equator, whereas the main desert regions lie 25–30° north and south of the equator and in the polar regions.
- Flooding occurs as a natural consequence of heavy rainfall but is aggravated by human construction on floodplains and by human activities that increase surface runoff.
- Attempts to control flooding usually involve the construction of dams to hold back water, and channelization to promote rapid water flow away from an area.
- Supply systems to provide potable water for communities date from prehistory and are used on a massive scale today.
- The United States has the highest per capita water usage, averaging about 5070 liters (1340 gallons) of fresh water per day.
- In the United States, thermoelectric generating plants use the greatest amounts of water, most of which is recovered, but irrigation consumes the greatest amount of water.
- Extraction of groundwater can lead to a lowering of the water table, ground surface subsidence, and even saltwater intrusion into aquifers in coastal areas.
- The importance of water as a resource will inevitably grow as world population increases.

INTRODUCTION

Seen from outer space, the blue oceans and white clouds make it obvious why planet Earth is called the water planet (Figure 11.1). Indeed, no resource is more abundant or more necessary to us than the water that covers three quarters of Earth's surface, and that moves constantly about us in both seen and unseen forms. From the dawn of history, the oceans, rivers, lakes, and springs have served us in many ways—as gathering points, as routes of transportation, and as either the means of, or barriers to, our migrations. Indeed, the availability of clean water is as important for the development and maintenance of our modern cities as it was for the most primitive of early gatherings.

Yet despite the global abundance of water, there is an uneven distribution of water that constantly creates local problems; around the world the problems are too much or too little of it to satisfy our needs. These problems are often compounded by our desires to use ever increasing amounts of water, by our modification of natural waterways, and by our contamination of surface and groundwaters. These factors highlight our need for a thorough knowledge of the distribution of water, an understanding of the effects of our activities on water availability and purity, and for long-range planning of water requirements. Indeed, water is viewed by many experts as the most critical of the resources on which we rely. The rising world population, especially in areas of limited fresh water, will strain the capabilities of supply systems; this is occurring at the same time that there is an increasing awareness of the need to use huge quantities of water for preservation of the environment. Consequently, there is an increasing political importance given to fresh water, and that importance will only grow in the years to come.

THE GLOBAL DISTRIBUTION OF WATER

The total amount of water available in Earth's hydrosphere is approximately $1.36 \times 10^{21}$ cubic kilometers, or $1.36 \times 10^{18}$ liters, that is distributed in all of its forms and locations (Figure 11.2). Most of the surface water, 97.2 percent, resides in the oceans; an additional 2.15 percent is frozen in polar ice caps and in glaciers. The oceans are saline and not directly usable for most human needs; the glacial and polar ice is fresh but is inaccessible. Consequently, the vast majority of our requirements must be met by the remaining 0.65 percent of fresh water. Distribution of this small proportion of Earth's water at any given time is a function of the hydrologic cycle and the natural storage capacity of the rocks and surface landforms. Thus, the problems of water supply are more complex than the mere total abundance; they also include local distribution patterns, the rates of recharge and natural loss, and, increasingly, the cleanliness of water. The availability of potable water (i.e., water suitable for drinking), more than any other factor in the future, will determine the number of people who can live in any geographic

FIGURE 11.1 Earth, the water planet, as seen from the Apollo 17 spacecraft. The abundance of water in the oceans, clouds, and ice caps gives Earth an appearance that is unique among the planets. (Photograph from NASA.)
province as well as their use of natural resources and their overall lifestyles.

The Hydrologic Cycle

The free water on Earth's surface, although unchanging in quantity, is constantly in motion through the hydrologic cycle (Figure 11.3). The atmosphere is a great solar-powered heat engine that draws up water by evaporation, transports vapor water, condenses it as clouds, and then discharges water as rain or snow. The precipitated water completes the hydrologic cycle by flowing via the rivers and streams and groundwater systems back to the oceans, or by evaporation back into the atmosphere from the land surface, and by transpiration from plants. Each region of the world has a natural water budget in terms of precipitation, evapotranspiration, and runoff; the effects of human alteration of the water budgets in many areas are discussed later in this chapter.

Water has the highest heat capacity—or ability to absorb and hold heat with minimal temperature change—of any substance known. Consequently, the movement of massive amounts of water in the atmosphere and in ocean currents involves the movement of large quantities of thermal energy that play very direct roles in the control of the world's climates. This effect is probably best seen in the North Atlantic Ocean where the Gulf Stream, warmed by the Sun in the Caribbean, flows northeastward as the North Atlantic Current, releasing heat to provide the mild climate of northern Europe. Without the Gulf Stream to transport this heat, England and Scandinavia would be as cold as northern Canada or Siberia, regions which lie at the same latitude.

The evaporation of water from any wetted surface requires the input of 540 calories for every gram of water that is changed from a liquid to a vapor state. Because this heat comes from the surrounding environment such as the remaining water, soil, or air, evaporation is a very effective cooling process. The condensation of water vapor to liquid water reverses the heat flow and liberates 540 calories per gram of liquid water condensed. The melting of ice to water also requires energy—80 calories per gram—and hence is also effective in cooling.

Precipitation and Evaporation Patterns

Precipitation is very unevenly distributed around the world (Figure 11.4). The highest precipitation zone is the equatorial belt where annual precipitation generally exceeds 100 centimeters (40 inches), and commonly exceeds 200 centimeters (80 inches). The wettest place on Earth is close to the equator in the mountains of Colombia where 1320 cm (524 inches) of rain falls annually. The wet equatorial zone

![Figure 11.2 Distribution of water in various forms and locations on Earth in terms of cubic kilometers and percentages. (From the U.S. Geological Survey.)](image-url)
is flanked by two zones, at approximately 25 to 30 north and south latitude, that contain many of the world’s major deserts and in which precipitation is commonly less than 25 centimeters (10 inches). Precipitation generally increases in the temperate regions of 35 to 60 north and south latitude and then decreases to less than 20 centimeters in the polar regions. These zones result from Earth’s reception of solar energy and the convection of air through the major atmospheric cells (Hadley cells) (Figure 11.5). The high-precipitation equatorial zone results from the rising of warm, damp air into the upper atmosphere where cooling reduces its capacity to hold water and thus produces torrential rains. The arid regions that flank the equatorial zone result from the descent of the cooler and much drier air from the upper atmosphere. As the air descends, it is warmed by Earth’s surface, and the ability of the sinking air to hold water rapidly increases. Thus, instead of releasing water, it is absorbing water and creating arid regions.

The world’s precipitation patterns are also affected by major ocean currents—for example, the Humboldt Current, which results in the extension of desert conditions up the west coast of South America, and by major mountain chains, such as the desert regions of the western United States that lie on the eastern flank of the Rocky Mountains. The driest place on Earth is in northern Chile where the dual effects of atmospheric convection cells and the adjacent cold ocean current yield an average precipitation value less than 1 millimeter (0.03 inches) per year!

The United States is, in general, an example of a blessed country in terms of water resources because it receives an average of about 75 centimeters (30 inches) of rainfall annually. This rainfall is, however, quite irregularly distributed, with annual values ranging from more than 250 centimeters in some mountainous areas of Washington, Oregon, and North Carolina, to less than 10 centimeters (4 inches) in some desert regions of the Southwest (Figure 11.6(a)). The actual amounts of precipitation vary significantly about the average, with the greatest variations occurring in areas of lowest average precipitation. The eastern United States, thanks largely to the Gulf of Mexico, enjoys an abundant

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**Figure 11.3** The general hydrologic cycle for Earth. Water is constantly moving from one reservoir (atmosphere, ocean, rivers, groundwater, etc.) in the processes of evaporation, precipitation, runoff and infiltration.
FIGURE 11.4 Worldwide precipitation patterns. Note that a zone of high rainfall lies along the equator and that more arid zones lie along belts that are 25°-30° north and south of the equator. (From B.J. Skinner, Earth Resources, 3rd ed., Prentice-Hall, 1986.)

supply of water and receives 65 percent of the total precipitation in the continental states, whereas the western part of the country, due largely to high mountains, is subject to a deficiency of water. This geographic variation is compounded by temporal variations tied to long-term weather fluctuations such as are created by the episodic appearance of the El Niño and La Niña phenomena in the Pacific Ocean. Thus, although water is a renewable resource, the rate of renewal is neither uniform nor totally predictable. Accordingly, the long-term availability of water to satisfy national needs requires both efficient storage systems and effective distribution systems.

Water is returned to the atmosphere from land or standing water by evaporation and by transpiration—the loss of water by plants directly to the atmosphere. The average annual evaporation rate for a site is calculable on the basis of weather conditions, is readily tested by simple experiments, and is well established for many areas (Figure 11.6b). The rates are highest where solar insolation (radiation) and winds are greatest, and especially where humidity is least, and rates are lowest where temperatures are lowest. Transpiration is a function of the type of plants involved as well as weather conditions and can vary markedly, depending upon the vegetation cover of an area. Nevertheless, the effects of both temperature and evaporation combine to return water into the atmosphere; to cool the surface, and to reduce the availability of free water for agricultural, domestic, or industrial use. Worldwide, the combined evapotranspiration rate is about 62 percent (see Figure 11.3), and for the United States it is about 70 percent. The percentages are much greater in areas of low rainfall and high temperature, and much lower in areas of high rainfall and cooler climate. In arid countries, such as Australia, the fraction of water lost to evapotranspiration is very large; in humid climates such as that in Great Britain the fraction lost to this process is relatively small.

The type and density of natural vegetation commonly reflect the availability of water in a region. In areas of low rainfall, plant cover will develop to a point where all precipitation is used in evapotranspiration and none is left for stream flow; additional plant growth can only occur if there is groundwater to support it. Ephemeral (or temporary) streams may, of course, flow during periods of high rainfall. In several parts of the southwestern United States, introduced pest plants, such as mesquite, have become such major consumers of both surface water and groundwater that they threaten the meager supplies available and are the objects of major eradication programs.

Evapotranspiration is a significant contributor to problems of surface water and soil quality in many arid parts of the globe, including the desert Southwest of the United States. There, the very high evaporation rates, exceeding
Precipitation may be seasonal but can occur at any hour of the day, whereas evaporation increases sharply during summer months and during afternoon hours. Furthermore, in periods of high rainfall much of the water may flow out of an area before there is time for it to evaporate, or it may percolate into the groundwater system and reemerge later in springs or streams.

The Water Resources Council has found, on the basis of available surface water and water demand, that the eastern portion of the United States is an area of water surplus, whereas the western (and geographically larger) region is generally an area of water deficiency [Figure 11.6(d)]. The pattern of water availability has played, and will continue to play, an important role in population distribution, and in the pattern of land use and resource exploitation in the country. To permit accurate assessment of the regional water supply and demand, the continental United States has been subdivided into 18 Water Resources Regions by the U.S. Water Resources Council, primarily on the basis of major surface water drainage systems. The 30 percent of precipitated water shown as flowing in rivers and streams into the oceans in Figure 11.3 is a bit misleading because it does not show that a considerable amount of water, ultimately lost to evapotranspiration, actually first travels long distances as stream flow. Much of this water has, in fact, already been used in domestic water supplies and in industry before it returns to the atmosphere.

**Groundwater**

Near-surface rocks and soils serve as storage sites for quantities of water estimated to be 3000 times larger than the volume of water in all rivers at any given time, and 35 times larger than the volume of all inland lakes and seas. Although this underground water is, by far, the largest quantity of accessible fresh water, it is commonly a nonrenewable resource because the natural rates of movement and recharge are so slow relative to the rapid rates at which it is withdrawn (Figure 11.7). Deep groundwater commonly is water that was trapped and isolated in sediments some time in the geologic past. In contrast, shallow groundwater supplies are usually intimately related to surface water flow as shown in Figure 11.8. Depending upon the land surface slope, vegetation, soil depth, and rock-type, widely varying amounts of precipitated and runoff water may percolate into the intergranular pore spaces and fractures. Water percolates downward until it reaches the **water table**, the surface below which the pores and fractures are water-filled. The water table is not flat but usually has a shape that is similar to, but smoother than, the topography of the land surface.

Above the water table is an unsaturated or vadose region of the soil. The upper part of this zone is filled with water when it rains, but then drains relatively quickly except for water adhering to mineral surfaces. However, even this small amount of adhering water is very important because it is the principal water supply for most plants. During periods
FIGURE 11.6 (cont.)
FIGURE 11.7 Cross section of a typical soil zone showing the relationship of the water table to the ground surface, streams, and lakes.

The rapid growth of Florida's population, from fewer than 3 million in 1950 to more than 15 million in 2000, has resulted in a variety of problems in terms of water resources. The Kissimmee River, which flows from the Orlando area southward to Lake Okeechobee (Figures 11.1A and 11.1B), is a prime example that provides insight to water issues, not just in Florida, but in many parts of the world. Prior to the 1960s, the Kissimmee flowed slowly in a meandering channel bordered by more than 20,200 hectares (50,000 acres) of marshy wetlands. Episodic rains, some resulting from hurricanes, created large fluctuations in the water flow of the Kissimmee and would turn the river’s floodplain into a broad sheet of shallow water. To control the flooding, between 1961 and 1971, the Army Corps of Engineers converted the original 163-kilometer (102-mile-long) meandering river into a 93-kilometer (58-mile-long) 10-meter (30-foot)-deep channel with a series of dams, water control structures, drainage canals, and navigation locks. The elimination of the flooding problem and the construction of drainage devices to divert water for use by farmers, orchards, and the growing cities served to convert 18,200 hectares (45,000 acres) of natural marshlands into pasturage land. The value of the land rose from $400/acre to more than $4000/acre. At the time of completion, the cost of $32 million was considered a reasonable price for the benefits returned.

However, by the mid-1970s it became apparent that the channelization of the Kissimmee had many other effects. The wetlands had served as an important water filter to remove nitrogen and phosphorus from sewage and fertilizers. In addition, the wetlands had played a key role in supplying much of the water that evaporated into the atmosphere to provide frequent rainstorms. With the removal of the wetlands, rainfall decreased, water levels fell, water purity decreased, and the water flow in the Kissimmee and the productivity of Lake Okeechobee declined. The spawning sites for bass and other fish along the river were lost, and 90 percent of the migratory and resident bird population disappeared. Through studies of the hydrology of Florida also revealed that the Kissimmee River and Lake Okeechobee were integral parts of a broad flow of water that created and supported the Everglades. With the decrease in the flow of water, the Everglades rapidly began to deteriorate.

It became clear that the only way to restore the quality of the water in Lake Okeechobee, and perhaps to save the Everglades, was to return the Kissimmee River to its original condition. Although the state authorized such action as early as 1976, lack of funding and the view by the Army Corps of Engineers that restoration was not a high priority resulted in little action until 1985 when the state

of drought the upper soil zone can lose much water directly to evaporation; under such conditions moisture actually moves upward, possibly even from the water table, by means of capillary action. Somewhat deeper than the upper soil zone is a zone in which the flow of water through the unsaturated soil or rock is usually downward toward the water table. The soil and vadose water zones do not constitute direct resources of water, but they are essential for the replenishment of the groundwater zones.

It is important to realize that most streams and lakes that are in equilibrium with their surroundings represent the intersection of the groundwater table with the surface topography. It is the slow lateral seepage of groundwater that provides the water for stream flow when there has been no rain and there is no surface runoff. In humid areas, streams continue to flow, perhaps with reduced volumes of flow, even in long periods of drought. In arid regions, where the groundwater table may lie far below the land surface, streams will often flow after rainstorms only until the water has either evaporated or percolated into the subsurface. In these areas, the high rate of evapotranspiration commonly result in the return of most water to the atmosphere. The
sponsored a demonstration project. The project blocked a portion of the artificial channel and forced water back into the original river bed. The test had dramatic and rapid effects—water quality improved and natural plant and animal life returned to the flood plain.

The final 1945-page report and plan approved by the Army Corps of Engineers in December 1994 calls for restoring the entire Kissimme River system and could become the most ambitious environmental restoration project ever attempted. The plan calls for filling in 47 kilometers (29 miles) of the newer river channel, rebuilding 19 kilometers (11.6 miles) of original river channel, moving more than 38 million cubic meters (50 million cubic yards) of soil to fill in up to 3200 kilometers (2000 miles) of canals, and return 14,000 hectares (35,000 acres) of original floodplain wetlands to their natural condition. The cost is high because some 30 percent of the drained pastureland was sold into private hands and had risen a great deal in value. Unfortunately the price tag to complete the restoration keeps rising with each year of delay; the original cost estimate of about $100 million had risen to $300 million by the 1980s, to $2 billion by 1993, and to $7.8 billion by 2000. Consequently, when the project is completed in about 2015 there will have been the expenditure of perhaps $8 billion to $10 billion in order to regain what was originally free.

shallow penetration of the rainfall before being evaporated often allows the water to pick up dissolved salts that are then left as a near-surface soil cement (referred to as caliche or "hard pan") that makes the soil less permeable and reduces the value of the soil for agriculture (see Chapter 12).

Aquifers, geologic formations that possess sufficient porosity and permeability to allow for movement of the water contained within them, underlie large areas of the United States (Figure 11.9). In fact, more than 50 percent of the population of the United States are presently supplied by groundwater from aquifers for their domestic supplies. In many arid parts of the world, aquifers constitute the only significant source of water. Even in more humid parts of the world where surface water is present, aquifers are commonly utilized as major water sources because they provide a relatively constant flow of good quality water.

The major problems in the utilization of groundwater are the rate of water withdrawal, the rate of recharge, and the water quality. The surfaces of many parts of the continents are underlain by metamorphic or igneous rocks in which the only available quantities of groundwater are the meager quantities that lie in the fractures and joint systems or along
faults. Interconnectedness of the joints allows ready movement of the water, but the quantities stored in such rocks are often very limited. Even in many areas underlain by sedimentary rocks, porosity or permeability is too low to allow for a worthwhile rate of water flow. If an aquifer is to have a sustained yield, there must be a constant replenishment from surface water through the generally slow process of percolation. It has been estimated that, in the United States, if all groundwater were removed to a depth of 750 meters (2460 feet), 150 years would be required to totally recharge the system.

The problem of the slow recharge of aquifers has become evident in several parts of the world, including the western United States, where withdrawal rates up to 100 times the recharge rates are rapidly lowering the water tables (see p. 446). In areas where withdrawal exceeds recharge, water is being mined and is being extracted like any other nonrenewable mineral commodity. The effect of the loss of water on land value is being recognized, so that the farmers who own the land are permitted to depreciate it as the water table falls. Even in humid regions where there is abundant rainfall, the withdrawal of water from aquifers at rates exceeding those of recharge creates problems such as the draining of wells by depression of the water table, and the movement of salt water into previously freshwater beds.

The third problem of aquifers is water quality. As groundwater moves through the rocks it dissolves the more soluble constituents. The problem varies with rock type and with flow rate, and has been greatly aggravated in recent years by the introduction of contaminants from agricultural, industrial, and domestic sources. In general, water with less than 0.05 percent (500 parts per million) total dissolved solids is considered suitable for human consumption (specific requirements for potable water are listed in Table 11.1); however, water with up to 1 percent dissolved solids can be used for some industrial and agricultural purposes.

Bacteria present within the soil may cleanse slow-moving water of harmful natural biological contaminants. Unfortunately, complex synthetic chemical contaminants have seriously limited the usefulness of some aquifers, particularly where there is a rapid rate of water movement that spreads contaminants much more rapidly than they can be filtered or decomposed by bacteria.

Another problem resulting from the withdrawal of water from aquifers is land subsidence. This is a local, but increasingly observed, phenomenon that can have serious consequences. This is discussed in greater detail on page 447.

**Ice Caps and Glaciers**

About 2.15 percent of the world's total surface water, but more than 70 percent of the nonsaline water, is held as ice in ice caps and glaciers. This water is primarily contained within the ice cap and glaciers of Antarctica and for all practical purposes is essentially unavailable for human use (Figure 11.10). Proposals to tow large icebergs to water-deficient areas such as the Middle East have been proposed in the past but have not yet resulted in any significant financial backing or serious efforts to carry out the proposals. In the short term, the amount of water held in glaciers and ice caps may be considered constant, but in the not-too-distant geologic past—during the Pleistocene or the Ice Age—the amount of water held as ice in these regions was as much as 50 percent greater than at present. During the major glacial advances, more of the snowfall over polar and cold temperate landmasses built up and persisted, with the result that glaciers advanced and sea level dropped as much as 100 meters (330 feet) below its present level. In contrast, during warmer interglacial periods, sea level rose significantly about present levels. One of the greatest concerns about global warming, if human activities were to bring it about, is

![Figure 11.9](image-url) - The rates of groundwater flow are very much less than the rates of surface flow because the water must percolate through the very small openings between soil particles or along the thin fractures in rocks. Consequently, water movement that may take only a few hours on the surface can take years to hundreds of years in the subsurface.
### TABLE 11.1
National drinking-water regulations*

#### Primary and enforceable standards

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Concentration, ppm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>0.005 (proposed)</td>
</tr>
<tr>
<td>Barium</td>
<td>2</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.005</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.1</td>
</tr>
<tr>
<td>Lead</td>
<td>0.015</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.002</td>
</tr>
<tr>
<td>Nitrate (as N)</td>
<td>10</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.05</td>
</tr>
<tr>
<td>Copper</td>
<td>1.3</td>
</tr>
<tr>
<td>Fluoride</td>
<td>4</td>
</tr>
<tr>
<td>Cyanide</td>
<td>0.2</td>
</tr>
<tr>
<td>Coliform bacteria</td>
<td>in no more than 5% of samples</td>
</tr>
<tr>
<td>Endrin</td>
<td>0.002</td>
</tr>
<tr>
<td>Lindane</td>
<td>0.0002</td>
</tr>
<tr>
<td>Methoxychlor</td>
<td>0.04</td>
</tr>
<tr>
<td>Toxaphene</td>
<td>0.003</td>
</tr>
<tr>
<td>2,4-D</td>
<td>0.07</td>
</tr>
<tr>
<td>Total trihalomethanes</td>
<td>the sum of the</td>
</tr>
<tr>
<td></td>
<td>concentration bromodichloromethane,</td>
</tr>
<tr>
<td></td>
<td>dibromochloromethane, tribromomethane</td>
</tr>
<tr>
<td></td>
<td>(bromoform) and trichloromethane</td>
</tr>
<tr>
<td></td>
<td>(chloroform)]</td>
</tr>
<tr>
<td>Radionuclides; (for units, see p. 36)</td>
<td>0.10</td>
</tr>
<tr>
<td>Radium 226 and 228 (combined)</td>
<td>5 pCi/L</td>
</tr>
<tr>
<td>Gross alpha particle activity</td>
<td>15 pCi/L</td>
</tr>
<tr>
<td>Gross beta particle activity</td>
<td>4 mrem/yr</td>
</tr>
</tbody>
</table>

#### Secondary and nonenforceable standards

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Maximum Level, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride</td>
<td>250</td>
</tr>
<tr>
<td>Color</td>
<td>15 color units</td>
</tr>
<tr>
<td>Silver</td>
<td>0.1</td>
</tr>
<tr>
<td>Dissolved solids</td>
<td>500</td>
</tr>
<tr>
<td>Foaming agents</td>
<td>0.5</td>
</tr>
<tr>
<td>Iron</td>
<td>0.3</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.05</td>
</tr>
<tr>
<td>Odor</td>
<td>3 (threshold odor number)</td>
</tr>
<tr>
<td>pH</td>
<td>6.5–8.5</td>
</tr>
<tr>
<td>Sulfate</td>
<td>250</td>
</tr>
<tr>
<td>Zinc</td>
<td>5</td>
</tr>
</tbody>
</table>

Data from the U.S. Environmental Protection Agency, 2000.

*The U.S. Environmental Protection Agency's National Interim Primary Drinking-Water Regulations and National Secondary Drinking-Water Regulations are summarized here. The primary regulations, which specify the maximum permissible level of a contaminant in water at the tap, are health-related and are legally enforceable. If these concentrations are exceeded or if required monitoring is not performed, the public must be notified. The secondary drinking-water regulations control contaminants in drinking water that affect the aesthetic qualities related to public acceptance of drinking water. These secondary regulations are intended to be guidelines for the states and are not federally enforceable.
the potential for a sea-level rise that would inundate many of the world's major coastal cities, as well as much prime agricultural land.

Surface Runoff, Floods, and Flood Control

Most rainfall produces some surface runoff. The amount of this runoff is a function of the amount of rainfall, the slope and length of the drainage basin, the rock and soil type of the drainage basin, the vegetation cover, and the extent of any impermeable areas in the basin. The runoff can range from zero to more than 90 percent of total rainfall in a given basin; the remainder evaporates and returns into the atmosphere, percolates into the groundwater system, or is held back in storage facilities.

Surface runoff can be characterized in terms of a hydrograph or lag-time diagram [Figure 11.11(a)]. This depicts both the quantity and time of rainfall and the subsequent runoff from a drainage basin. Small drainage basins have lag times measurable in minutes or hours, whereas large ones may have lag times of hours to days or even weeks. Once the runoff characteristics have been determined for a basin, it is possible to predict water-flow levels and to estimate potential flood conditions.

Activities such as mining, timbering, farming, and construction frequently promote an increase in the amount and rate of surface runoff, as shown in Figure 11.11(b). Consider, for example, the effects of urbanization of a previously tree-covered or grass-covered area. Construction of a typical suburban community makes 10–30 percent of the area impermeable because of streets, driveways, houses, and sidewalks, and construction of a city environment or large shopping mall, can make 50 to 100 percent of an area impermeable. Most of the water from an impermeable area runs off onto permeable areas, thereby subjecting the permeable sections to water conditions equivalent to added rainfall.

The result of natural rainfall plus the effect of the added water is then the equivalent rainfall. Much of the added runoff water does not actually drain onto adjacent land but is carried by storm drains into streams or rivers; nevertheless, that extra water will appear in some part of a drainage basin. Unfortunately, as more water runs off more rapidly, less of it is able to percolate into the soil to be added to the groundwater system, as shown in Figure 11.12. Assuming uniform rain distribution in a basin and 100 percent runoff of water from impermeable areas, something that is never quite true, but that suffices for a demonstration, converting 25 percent of a basin to an impermeable condition results in a 33 percent increase in equivalent rainfall for the permeable portion; conversion of 33 percent to an impermeable condition raises equivalent rainfall by 50 percent, and 50 percent impermeability raises equivalent rainfall by 100 percent. In
The Global Distribution of Water

Specific area, soil permeability, the duration and intensity of the rain, and the type of vegetation will play important roles in the actual runoff.

The increase in runoff that inevitably results from increases in impermeable areas due to urbanization can either be permitted to contribute to normal streamflow or be controlled. An example of such control is found on Long Island, New York, where the runoff from impermeable areas enters into shallow catchment basins from which the water seeps downward in order to enrich the ground water supply. The system provides another environmental benefit because excessive amounts of fresh water do not pour into brackish estuaries where its dilution effects are detrimental to marine life.

Flooding occurs when surface runoff exceeds a stream channel's capacity and the water spreads out the floodplain or beyond. Flooding is a natural phenomenon triggered by intense or prolonged rainfall or the melting of snow cover. It is of little, or no consequence, in undeveloped areas, but our tendency to build homes, businesses, and factories on floodplains brings civilization into conflict with nature, and all too often into peril. Floodplains are widely used as farmland because they are well watered, and fertile as a result of the soil deposited by episodic flooding. Relatively short-duration flooding of farm fields, except at planting and harvest time, are usually not a great problem because plants are tolerant of brief submersion. More intensive flooding can result in extensive erosion, burial of crops by too much new silt, or the rotting of the crops owing to extended inundation. Although the extent to which human activities actually cause flooding is not entirely understood, it is evident from the previous discussion that the removal of vegetation from large parts of the drainage basins and the subsequent expansion of impermeable surfaces must increase runoff and must contribute to the potential for flooding. Once hydrographs (Figure 11.11) have been defined they can serve as valuable aids in predicting floods and to the timing of their rising, cresting, and falling.

The United States, like many nations, suffers some local flooding every year. Usually, the flooding is the result of intense but brief storms that drop large quantities of rain where cool and warm air masses meet, or around the center of a low-pressure zone. Whether the flooding is brief and local, or extended and extensive, the energy of the flowing water (with a mass more than 800 times greater than the flowing air) often causes great damage to human structures (Figure 11.13). Widespread flooding often results from the

**Figure 11.12** General relationship between equivalent rainfall and infiltration. As the amount of a natural soil-covered land surface is converted into impermeable area (usually by building houses and by paving streets and parking lots), the amount of rainwater that infiltrates the ground decreases. The increased runoff is like extra rainfall (referred to as equivalent rainfall) for the remaining portion of the area. The two curves illustrate, in a very general way, the effects of increasing impermeable area. The amount of infiltration decreases as the amount of impermeable area increases. The equivalent rainfall for the remaining permeable area increases as the amount of impermeable increases. Hence, if 25 percent of an area is paved, the infiltration decreases by about 25 percent, but the equivalent rainfall for the remaining permeable area increases 33 percent. If 50 percent of an area is paved, the infiltration decreases by about 50 percent and the equivalent rainfall for the remaining permeable area increases 100 percent.
hurricanes that strike the southeastern United States from July to November. In late October 1998, Hurricane Mitch dumped up to 180 centimeters (6 feet) of rain in part of Central America in five days. The normal flooding expected from this much rainfall was intensified because deforestation and farming practices resulted in large increases in the runoff. In Southeast Asia, the seasonal monsoon rains create massive flooding of low-lying areas annually.

In the spring and summer of 1993 the central United States suffered some of the most massive and extended flooding in the country's history. The "Flood of 1993," as it has become known, resulted from the persistence of a stationary front that allowed for the convergence of warm, moist air moving northward from the Gulf of Mexico and cooler air from the northwest along a band extending from Colorado to Michigan (Figure 11.14). This type of weather phenomenon is common for brief periods, but in 1993 it persisted for approximately five months. Many areas received rain virtually every day, and total rainfall through the period exceeded 200 percent of normal. The humidity was commonly 100 percent so there was little evaporation. Because soils were saturated, runoff was nearly 100 percent, and the dams that had been built to control flooding were full. Consequently, the river banks over an area of greater than 1700 square miles overflowed onto floodplains and hundreds of communities and more than 10 million acres of farmland were under water (Plates 61 and 62). Barge traffic along the Mississippi River had to be halted, railway lines were blocked, interstate highways were under water, and still the rain kept falling.

Over the years, the U.S. Army Corps of Engineers had constructed levees along many stretches of the Mississippi and other rivers to prevent flooding of towns and farmland, but the flooding in 1993 was so extensive, and the water levels were so high, that many levees were topped and some breached. This resulted in flooding of areas previously viewed as safe and that were unprepared for flooding. In some areas, homes as far as 11 kilometers (7 miles) from the major rivers were flooded. There was significant loss of crops in the flooded area, at least 48 deaths, and damages estimated to be at least $10 billion to $12 billion.

The rains finally ended in August 1993 and floodwaters gradually subsided, but some of the effects will be permanent. Many families moved, fearing they might face similar flooding again, and in a few instances entire towns had to be relocated to higher ground. The effectiveness of
The Global Distribution of Water

FIGURE 11.14 The dominant weather patterns in the spring and early summer of 1993 brought warm, moist air from the Gulf of Mexico into convergence with unseasonably cool, dry air along the jet stream over the American Midwest. The area of convergence (heavier shading) experienced much heavier than normal rainfall and extensive flooding (see Plate 61) beyond levels ever previously recorded. At the same time a portion of the Southeast (lighter shading) experienced severe drought. Human activities can intensify flooding or water shortage, but natural weather changes can often bring about intense variations in water availability.

Levees and the value of the dams as flood-control devices have now been questioned. It has been recognized that the levees of many areas held the water in the main channels and thus allowed it to flow more rapidly downstream where, in several cases, the flooding became worse. Consequently, it was decided not to rebuild all of the levees, because the absence of the levees upstream would have allowed the floodwaters to spread laterally. This would have reduced the highest water flows in the major river channels and made the flooding downstream significantly less. Such decisions are not easy because minimizing flood damage downstream requires increasing the flood damage upstream. The entire situation highlights the problems encountered when human activities come into conflict with natural environmental processes.

In an effort to reduce the vast amounts of damage and the scores of deaths and injuries that occur annually as a result of flooding, the two procedures now most widely used are the construction of dams and the channelization of rivers. The two processes operate on different principles, but both seek to achieve the same result. Dams serve as temporary water barriers to hold back high flow before it reaches a vulnerable area, and hence prevent it from flooding (Figures 11.15 and 11.16). Channelization, by contrast, provides an efficient means by which water can be carried out of an area so quickly that it does not rise to flood levels. The construction of levees, as noted in the discussion of the Flood of 1993, serves to dam waters from lateral movement while also serving as a formal channel for downstream movement. Several of the consequences of building dams and channels are summarized in Figures 11.16 and 11.17, respectively.

Dams, of course, serve many other purposes, such as water storage for irrigation, electric-power generation, recreation, and livestock watering, but in the United States a
significant proportion of the more than 58,000 dams are used, at least in part, for flood control. The dams range from earthen barriers used for farm ponds, to the 250-meter (770-foot)-high Oroville Dam in California, and to the 23-kilometer (14.5-mile)-long Watkin Dam in Utah. Dams have been effective in the reduction of flooding and have provided the added benefit of generating large amounts of electricity. They have also provided many new lakes for recreational purposes. Unfortunately, the water requirements for these activities are often incompatible. Flood control calls for the emptying of reservoirs, at least before anticipated heavy precipitation, in order for there to be ample storage capacity during the period of high runoff; power generation requires a steady water flow, or one cycled to match electricity demand; and recreation calls for lakes to remain at a constant high level. A contribution frequently overlooked is enrichment in the quantity of groundwater around dam sites; as dams fill, groundwater tables generally rise as more water percolates into the subsurface.

Against the advantages of dam construction must be weighed some disadvantages, such as sediment catchment, increased evaporation, loss of inundated land, interruption of river transport, disruption of fish migration, and environmental alteration. Construction of the Aswan High Dam in Egypt on the Nile River in the 1960s ended the annual flooding of the Nile Valley and has provided electricity generation facilities, but the reservoir that formed is now filling with the sediment that for thousands of years served as a natural fertilizer for agriculture in the Lower Nile Valley. The Aswan High Dam has markedly reduced soil fertility along the Lower Nile and is rapidly leading to eutrophication of the reservoir behind the dam. In all arid regions, the
Dams to Stop Flooding

Loss of riparian land

Recreation

More water for irrigation or municipal use

Higher groundwater levels

Hydroelectricity generation

Alteration of fish migration

Reduced flooding

Lowered ground water table

Loss of wetlands

Reduced evapotranspiration

FIGURE 11.16 Construction of dams to reduce flooding has many consequences, as noted on this schematic diagram of a dam and the lake formed behind it.

damming of rivers provides water for many uses but at the same time promotes evaporative water loss and the buildup of salts in the remaining waters.

For example, it is estimated that the combined natural and dam-induced evaporation of the Colorado River removes 10 percent of its total water flow. The construction of nearly every new dam meets with opposition from those whose land will be inundated and from those who do not want to see further change of the natural environment. In the 1970s the concern for endangered species of both fish and plants in the United States nearly prevented the completion of massive dams in Tennessee and Maine. The discovery of the snail darter, a 3-inch minnow-like fish found only in the area to be flooded by the $116 million Tellico Dam in Tennessee, provided the basis for halting construction for more than a year until it was determined that these fish could and do live in other rivers of the area. The Furibish lousewart, a wild snapdragon-like plant that was thought to be extinct, was discovered in the valley to be flooded by the $600 million Dickey-Lincoln Dam in Maine; the discovery provided grounds to delay the construction for many months until it was determined that additional colonies of the plants existed elsewhere.

The U.S. governmental agencies responsible for major dam construction and supervision have now determined that few, if any, major power or flood-control dams will ever again be constructed in this country. In fact, by the late 1990s, plans were underway to tear down existing dams in states from Maine to the West Coast in order to restore original river environments and to promote salmon migration. Other countries, especially developing ones, are, however, considering new projects to provide electrical power for economic development and to control common flooding problems. Thus, Brazil is weighing construction of major dams on the Amazon, and China broke ground in late 1994 for the Three Gorges Dam on the Yangtze River in central China. This dam, scheduled to require more than twenty years for completion, will be the world's largest hydroelectric facility and will alleviate nearly annual flooding downstream. It has met with widespread opposition ever
Channelization

Channelization is the conversion of a sinuous channel, flowing from A to B, into a straight channel connecting the same points. Channelization has commonly been used to reduce flooding and is designed to allow for the very rapid movement of water away from an area so that flooding does not develop. The upper portion of the diagram notes the variety of consequences that result from channelization. The lower portion of the diagram is a profile showing that straightening and shortening the channel results in a steeper gradient; this results in more rapid flow of the water.

since it was first suggested in 1919, because it will alter the river ecology, flood hundreds of square miles of farmland, and displace more than 1 million people from their homes. In Canada, Quebec Hydro developed plans for major hydroelectric dams on the rivers that drain the sparsely inhabited area east of Hudson Bay. Even here, environmental concerns raised by potential customers in Canada and New York, as well as pressure from Native American tribes, brought about cancellation of major parts of the project.

Channelization has provided an expedient means of flood control in many areas. The principle (illustrated in Figure 11.17) is straightforward: replacement of a natural sinuous channel by a shorter and straighter one that allows for more rapid water flow out of a flood-prone area. The rate of water flow is increased because a straighter channel offers less resistance and because the gradient of the new shorter channel is steeper than a long winding one. Frequent secondary effects have included the lowering of the water table and drainage of swamplands adjacent to the river; such lands then have considerable real estate value.

Although often effective, and carried out in hundreds of areas, channelization has also been found to have significant drawbacks, such as increased erosion, transfer of flooding, reduced natural filtering of groundwater, and the loss of wetlands habitat. Unless the channelization extends to a flood-control reservoir, or to the ocean, the rapid transport of water from one part of a river basin to another, only to dump the water back into its original channel farther downstream, merely transfers the problem of flooding to another area, namely downstream. An example of this in the United States is the Blackwater River in Johnson County, Missouri, where channelization did reduce local flooding but created extra flooding in adjacent counties downstream. The decrease in channel length from 53.6 to 29 kilometers (33.5 to 18 miles) nearly doubled the gradient and increased the water velocity, which, in turn, increased stream channel erosion. The original channel was 15 to 30 meters (45 to 90 feet) wide, but erosion broadened the channel up to 70 meters (200 feet) and resulted in the collapse of several bridges. The much greater rate of water flow tended to scour the channel and reduced the total amount of biomass production.
OUR USE OF WATER

Water Usage and Consumption

Water is more widely used and more essential than any other resource. The amount consumed per capita, however, varies widely as a function of each society’s lifestyle and standard of living. In discussing water usage, it is important to distinguish between withdrawal (sometimes called usage), which is the water physically extracted from its sources, and consumption, which is the withdrawn water that is no longer available because it has been evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise held from returning to its source.

Withdrawal uses of water are generally subdivided into (1) domestic-commercial, (2) industrial-mining; (3) thermoelectric power; and (4) irrigation-livestock, as illustrated in Figures 11.18(a) and (b). Hydroelectric power generation, in which water is actually withdrawn only to the extent that it is diverted through turbines to generate electricity, is considered a special category and is discussed separately. The amount of water withdrawn and its division between surface sources and groundwater varies according to the population, the type of society, and the climatic conditions in an area. In the United States, approximately three-quarters of water usage is supplied by surface sources [Fig. 11.19] but major agricultural states such as Nebraska and Kansas, and the arid state of Arizona, draw most of their water from underground sources. Not surprisingly, California, by virtue of size, population and agricultural production, uses the most water, and Alaska, with its small population and very small agricultural production, uses the least.

Total water usage in the United States currently amounts to about 6130 liters (1620 gallons) per person per day when all of the usages are considered. If only the domestic household water supply that is delivered by public supply systems is considered, the figure is about 460 liters (105 gallons) per person per day. The use of water by our society is largely taken for granted, and we often overlook the large quantities required to support our modern lifestyle. Table 11.2 presents some data on the water usage required for particular purposes by modern Western society.

Rural water withdrawn from private wells constitutes only about 1 percent of United States water usage, but in many sparsely populated areas this represents the dominant water supply. The use at any one site varies from the small amounts withdrawn for a single house to very large quantities used to supply large herds of livestock. In many lesser developed parts of the world, the rural water supply is the major water source for large segments of the population (Figure 11.20). Because rural water is used for many agricultural purposes as well as for household needs, a somewhat larger proportion of the rural water is consumed.

Domestic and Commercial—Supplying Our Cities

Domestic and commercial water usage includes that needed by normal households and for the water for motels, hotels, restaurants, offices, stores, and businesses, as well as government and military establishments. Although it is only about 11.5 percent of total usage, domestic water is what most of us see directly each day. More than 80 percent of what we use is returned to the water systems, and most of that is through public water-treatment plants.

The growth of cities has always required the availability of continuous supplies of fresh water. Virtually all ancient, and most modern, cities were established along rivers or in places where there were ample springs. As cities grew, so did their needs for water. When needs exceeded local supplies, it became necessary to find additional water and to develop ways to transport it to urban distribution centers.

The earliest water transportation systems, or aqueducts, were probably stream channels that were altered or extended so that they flowed into more accessible areas. Biblical Jerusalem was served by an aqueduct consisting of limestone blocks through which a 38-centimeter hole had been drilled by hand. The Greeks bored tunnels, up to 1280 meters long at Athens, and built masonry structures to carry water. The ancient masters of the construction of aqueducts were the Romans, who built nine major aqueducts that brought 322 million liters (85 million gallons) of water a day to Rome in A.D. 97. All told, the Romans constructed aqueducts (Figure 11.21) to service nearly 200 of their cities and many of their mining efforts throughout their empire. After the fall of the Roman Empire, few additional aqueducts were built until the late 1500s, when Sir Francis Drake, then mayor of Plymouth, England, constructed one that was 39 kilometers (24 miles) long. In 1609 a 61-kilometer (38-mile) aqueduct called the New River was built to bring water to London.

In the era of modern cities, even though the demand for water has increased, the large scenic aqueducts of the past have been nearly completely replaced by buried steel pipes and pumping stations. A prime example is New York City, where a complex system of aqueducts links 15 major reservoirs containing more than 1860 x 10⁹ liters of water (approximately 490 x 10⁶ gallons), some of the reservoirs
FIGURE 11.18  (a) Schematic presentation of water in the United States in 1995 showing the source, type of use, and disposition. (From U.S. Geological Survey Circular 1200). (b) Water use and availability in the United States in 1995. Groundwater withdrawal is shown by the lowest-curve; surface water withdrawals are represented by the area between the lower two curves. In-stream hydroelectric power usage of water is actually about 2.5 times greater than the average flow of all rivers because much water flows through several closely spaced dams each day and is counted each time. For comparison, the change in U.S. population from 1950 to 2000 is also shown (right-hand scale).
are as much as 200 kilometers (125 miles) from the city (Fig. 11.22). Despite the vastness of the system used to supply New York City, there is little problem because the abundance of rainfall in the northeastern United States provides more than adequate water for all other users as well as those in New York. However, New York, like many long-established cities, faces critical problems with its aging infrastructure, as described in the discussion on page 430 (see also Figure 11.1 C, Figure 11.1 D, and Plate 64).

Some of the water problems of the western United States are also being addressed by means of aqueducts. Thus, the Central Arizona Project (Figure 11.23) is a major supplier of water for cities such as Phoenix and Tucson, and California has constructed a complex system to supply its major cities. One of these extends more than 1100 kilometers (685 miles) in California to bring water from many parts of the state to Los Angeles; it is discussed later in this chapter under the heading “Water for Drinking—The Los Angeles Aqueduct System” (p. 457).

Irrigation

Irrigation has become an essential requirement for farming in large areas of the world where soils are sufficiently fertile, but rainfall is too low or too irregular to support the types of crops being grown. Water demand for this purpose has been rising rapidly and is now approximately 42 percent of total U.S. usage and as much as 80–90 percent of usage in India and Mexico (Figure 11.20). In the United States as in many countries, the withdrawal of water for irrigation takes place on a very irregular geographic distribution pattern depending upon rainfall. Thus, the eastern part of the United States uses only approximately 5 percent of its water withdrawal for irrigation, whereas the western portion uses 90 percent of its water for this purpose. Irrigation systems range from simple siphons (Figure 11.24) in which gravity carries water from a main water course into the furrows to large mechanized walking systems (Figure 11.25(a)) that can systematically distribute water in a circular pattern up to
1.6 kilometers (1 mile) from a central well [Figure 11.25(b)]. Depending upon the weather conditions and the crops raised, irrigation can consume vast quantities of water. For example, whereas irrigation constitutes only 42 percent of total U.S. water use, it accounts for 84 percent of water consumed. The demand for irrigation water has resulted in the building of elaborate surface water catchment and transport systems, as seen in the Lower Colorado River region (p. 443). Irrigation demand has also resulted in severe drainage of groundwater from parts of some aquifers, such as the Ogallala where 150,000 wells now draw water (p. 446) for farms along the eastern flank of the Rocky Mountains.

**Water for Industry and Mining**

Industrial water use includes water for processing, washing and cooling, with some of the major users being the steel, chemical, paper, and petroleum industries. Environmental concerns about industrial water usage usually do not center upon the quantities of water used because about 85 percent of the water is returned; rather, the focus is on the cleanliness of the returned water. Prior to the 1970s, industrial pollution was widespread, but the increasingly stringent water quality regulations in most Western nations and especially the United States and countries of the European Union now
### TABLE 11.2
Water requirements for modern Western society

<table>
<thead>
<tr>
<th>Activity or Product</th>
<th>Water Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(liters)</td>
</tr>
<tr>
<td>Home use:</td>
<td></td>
</tr>
<tr>
<td>Shower (per minute)</td>
<td>19</td>
</tr>
<tr>
<td>Bath</td>
<td>114</td>
</tr>
<tr>
<td>Toilet flush</td>
<td>15</td>
</tr>
<tr>
<td>Automatic washing machine</td>
<td>114</td>
</tr>
<tr>
<td>Hose flow per hour</td>
<td></td>
</tr>
<tr>
<td>of lawn watering or car washing</td>
<td>1,136</td>
</tr>
<tr>
<td>Food production:</td>
<td></td>
</tr>
<tr>
<td>Sugar per ton</td>
<td>946,000</td>
</tr>
<tr>
<td>Corn per ton</td>
<td>946,000</td>
</tr>
<tr>
<td>Rice per ton</td>
<td>9,460,000</td>
</tr>
<tr>
<td>Milk per gallon</td>
<td>61,000</td>
</tr>
<tr>
<td>Beef per pound</td>
<td>14,000</td>
</tr>
<tr>
<td>Nitrate fertilizer per ton</td>
<td>568,000</td>
</tr>
<tr>
<td>Industrial:</td>
<td></td>
</tr>
<tr>
<td>Paper</td>
<td>23,700</td>
</tr>
<tr>
<td>Bricks per ton</td>
<td>950–1,900</td>
</tr>
<tr>
<td>Oil refining per 42-gal barrel</td>
<td>1,770</td>
</tr>
<tr>
<td>Synthetic rubber per ton</td>
<td>2,500,000</td>
</tr>
<tr>
<td>Aluminum per ton</td>
<td>1,325,000</td>
</tr>
<tr>
<td>Iron per ton</td>
<td>113,600</td>
</tr>
<tr>
<td>Human survival:</td>
<td></td>
</tr>
<tr>
<td>70 kg (154 lb) person per year</td>
<td>720</td>
</tr>
</tbody>
</table>


![Domestic sector & rural](Bulgaria_Czechoslovakia_France_Hungary_India_Israel.png)

**FIGURE 11.20** Differences in water usage in several different countries reflect different types of economies. (From The Global Report 2000.)
How do you supply more than 1.5 billion gallons (5.7 billion liters) of clean water to more than 8 million people who live over an area of 300 square miles (780 km²) including two major islands (Manhattan and Staten Island)? The answer is with an incredible system of reservoirs, aqueducts, tunnels, and pump stations with an aggregate value of more than $8 billion. The situation is similar for every major city in the developed world and is going to grow even larger and more complex as world population continues to increase.

Our story began in a relatively simple manner when the first Dutch immigrants founded New Amsterdam on Manhattan Island in the early 1600s. They met their water needs by relying on ponds, springs, and a few private wells. In 1667, shortly after the British seized the city and changed the name to New York, the first well was dug to serve as a public water supply. By the early 1700s, the combined effects of a growing population, contamination by sewage and garbage, and saltwater intrusion into the wells forced the inhabitants to begin to haul in fresh water from unspoiled springs in Brooklyn. Continued growth made these supplies inadequate and contributed to the city’s inability to control major fires like the one that destroyed one-quarter of the buildings in 1776. Limited supplies of clean water also contributed to a cholera epidemic that killed 3500 people in 1832.

Citywide efforts to provide an adequate water supply really began in 1799 when the State Legislature gave water delivery rights to a company that sunk new wells, built new storage ponds, and installed a distribution systems of wooden pipes. The company was headed by the American patriot Aaron Burr and used its excess funds to start the Chase Manhattan Bank. More and more water was needed, so 4000 immigrants were set to work in 1837 to develop drains, reservoirs, and a 66-kilometer (41-mile) aqueduct to bring water from the Croton River north of the city. The aqueduct, carrying water largely by gravity, delivered its first water to New York City during a celebration on July 4, 1842. The new water system seemed large enough for many years to come, but more people meant more demand and the population soon outgrew the supply. By the 1880s, it was necessary to build newer, larger dams and reservoirs, and to construct the first large underground supply tunnel.

More clean water allowed the population to continue to grow. That growth, combined with the new flush toilets and household fixtures, demanded yet more water. The city then looked outward again and purchased large watershed areas in the Catskill Mountains more than 100 miles to the northwest. This vastly enlarged the total capacity of reservoirs and the daily supply, but it required the construction of two large tunnel systems, 65 to 225 meters (200 to 700 feet) beneath the city streets, that were placed in service in 1917 and then in 1936.

Today New York City is looking ahead again with the construction of another tunnel, No. 3, to improve the required industry and mining figure and, hence, only about 1 percent of total United States water usage.

**Thermoelectric Power**

Thermoelectric power plants use water in the generation of electricity from fossil fuel, nuclear, and geothermal sources. Most of the water goes for condenser and reactor cooling, and about 98 percent of the fresh water withdrawn is returned to the rivers from which it comes. Thermoelectric power generation actually uses approximately 50 percent more water than is shown in Figure 11.18 (the total being about 740 million liters or 195 million gallons per day) with that extra water being saltwater withdrawn from coastal estuaries. The large water requirements of thermoelectric plants necessitate that they be located where abundant water supplies exist—nearly always on large rivers or along the coast.

The water used in thermoelectric plants passes rapidly through the cooling systems; hence, there is almost never
BOX 11.2 Water for New York City (continued)

adequacy and dependability of the entire system. The new
tunnel ranks as one of the world’s great engineering feats
being 100 kilometers (60 miles) long, 8 meters (24 feet) in
diameter, and, in places, lying 140 to 250 meters (450 to
800 feet) below the ground surface in solid rock (see Fig-
early in the twenty-first century, this tunnel will not only
help in water delivery but will permit maintenance and re-
pair of some of the older tunnels and pipe systems for the
first time in more than a century years, and the first testing
of some vital valve systems that have not been closed for
more than fifty years. No resource is more vital than water,
but most of us take the incredible infrastructure required
for its delivery totally for granted.

FIGURE 11.C One of the pump stations required to
supply 1.5 billion gallons (5.68 billion liters) of water
per day to New York City.

FIGURE 11.D A portion of the new 24-foot (8-meter)-
diameter Tunnel No. 3 being constructed to carry water
under New York City. (Photographs by Carl Ambrose;
courtesy Department of Environmental Protection of
the City of New York.)

FIGURE 11.21 Supplying water
to cities has been a major concern
since the Romans built aqueducts,
such as the Pont du Gard at
Nimes, France, to transport water
to nearly 200 cities. This was built
in the first century A.D. and car-
rried water from two springs to
Nimes. It is one of the best pre-
served of Roman structures. (Pho-
tograph courtesy of the French
Government Tourist Office.)
any problem of contamination. The main environmental impact results from the return of the heated discharge water into rivers and estuaries. Unless carefully monitored and remixed with sufficient quantities of cool water, the warmer water can adversely affect normal aquatic life.

Hydroelectric Power

The amount of water used to generate hydroelectric power in the United States dwarfs all other usage, with the total of about 12.5 trillion liters per day (3.3 trillion gallons) being about 2.6 times as much as all of the runoff water in all the nation's rivers and streams. This apparent impossibility results from the repeated reuse of water within pumped-storage power plants (where excess electricity generation capacity is used to pump back into a reservoir so that it can be used another time), from the repeated reuse that occurs in successive hydroelectric plants along the same river, and from the use of some water before it is evaporated or consumed in irrigation. Shown schematically in Figure 6.27, the process of hydroelectric power generation itself consumes very little water, but the ponding of large reservoirs behind power dams, especially in arid regions, does result in the evaporative loss of significant quantities of water.

Hydroelectric power is generated in all parts of the United States; but by far the largest producing area is the Pacific Northwest, where the tremendous flow of the Columbia and Snake Rivers passes through several dams. Hydroelectric power generation has long been promoted as a nonpolluting alternative to fossil fuel and nuclear plants. This statement is only partly true, because the dams do have a large environmental impact on the areas they flood, and in the modification of fish habitats and migration paths. There has been much concern expressed about major dams playing a significant role in the decline of salmon in the Columbia River and its tributaries. In attempts to increase the numbers of salmon moving upstream, special lock systems, fish ladders, and other novel techniques have been employed. However, it is clear that as long as major dams block the flow of rivers containing migratory fish, there will be conflicts between the needs of power generation and various environmental concerns.

The potential for hydroelectric power generation in a country like the United States has been largely developed. Although the potential generating capacity for the world is approximately seven times that presently generated, the development of additional hydroelectric capacity will be hampered by the remoteness of suitable areas from population centers (see also Chapter 6).

The United States is a relatively water-rich nation, but because of its size and variable climate it has an irregularly distributed water supply. Differences in supply and con-

![FIGURE 11.22](a) The water supply system for the city of New York links 15 major reservoirs—some as much as 200 kilometers (125 miles) away—to meet the needs of approximately 10 million people. (After a map courtesy of the City of New York Department of Water Resources.) (b) Existing and projected New York City water supply tunnels. (Courtesy of Department of Environmental Protection of the City of New York.)
umption of the various water regions are considerable, but it is apparent that the nation is withdrawing only about one-third of available runoff and consuming only about one-third of that withdrawn. Despite the remaining large capacity for development, local supply problems are becoming increasingly apparent, and careful decisions will be needed in future years to ensure a constant high quality supply.

The Global 2000 Report to the President (1978) summarized the world’s water supply situation and noted that there would be adequate water available on Earth to satisfy aggregate totals of projected water withdrawals in the year 2000. However, because of the regional and temporal nature of water resources, and the local demands that do not always correspond to the abundances, shortages will probably be more frequent and more severe than those experienced today. The year 2000 has now passed and many of the water problems foreseen in 1978 are coming to pass.

**Water Composition and Quality**

Earth’s waters range widely in composition and in suitability for human usage. The most pure spring or rainwaters may have as little as 30 parts per million (ppm) (0.003 percent) of
dissolved minerals, whereas the most saline waters, such as found in the Dead Sea or Great Salt Lake, may have nearly 300,000 ppm (30 percent) dissolved substances (Table 11.3). Seawater, which constitutes more than 97 percent of the planet's water, is remarkably homogeneous, with about 35,000 ppm (3.5 percent) dissolved salts. In general, waters with more than 500 ppm (0.05 percent) dissolved salts are unsuitable for human consumption, whereas, waters with more than 2000 ppm (0.2 percent) dissolved solids are unsuitable for most other human uses.

The dissolved constituents in surface and groundwater are derived from the atmosphere and from the soils and rocks with which they come in contact (see Chapter 12). Rainwater and snow generally contain a predominance of bicarbonate (from the solution of atmospheric carbon dioxide), but only a few parts per million of salts, dominantly sodium chloride carried in the winds from ocean spray. Other natural sources of atmospheric salts are volcanic eruptions that can release significant amounts of sulfates and chlorides into the atmosphere, wind blown dust from continental areas, and organic aerosols released by vegetation. In recent years there has been a growing concern about the effects of fossil fuel combustion and the release of industrial gases and particulate matter on the quality of rainwater. Numerous studies have demonstrated an increase in the acidity of rainfall in certain areas (so called acid rain; see also Box on p. 84 and Figure 4.4). This has been found to be harmful to vegetation, fish, and many terrestrial organisms, and to increase the rate of weathering of building materials and natural rocks. In recent years, the pH of rainfall has dropped to 4.5-4.2 over large parts of southern Norway, southern Sweden, and the eastern United States; the most extreme case was a rainfall of pH 2.4, equivalent to the acidity of vinegar, in Scotland in 1974. Two primary causes of acid rain appear to be sulfur dioxide (SO₂) and nitrogen oxides (NOₓ) generated by the burning of fossil fuels in power plants, industries, and motor vehicles.

Most of the dissolved substances in terrestrial waters are derived from the associated rocks, but the degree of concentration varies not only with rock type but also with the duration of contact and the amount of evaporative concentration. Compositions of waters in several American rivers that are typical of waters worldwide are listed in Table 11.3. The differences demonstrate the effects of evaporative concentration (higher salt levels in rivers from Kansas, Arizona, and New Mexico) that occur in arid parts of the world. The
difficulty, both in maintaining old supplies and in developing new clean-water supplies in future years, as population pressures mount and the number and complexity of possible chemical contaminants continue to grow.

A tragic case of natural water poisoning has occurred in Bangladesh in Southeast Asia. In an attempt to help provide clean drinking water to millions of citizens who were ingesting surface water tainted by bacteria and water-borne diseases, the WHO helped drill more than 1 million shallow wells. The effort seemed a success until it was revealed, in the mid-1990s, that a large percentage of the wells were contaminated by naturally occurring arsenic derived from the underlying sediments, and that as many as 65 million people were at risk. Because the arsenic poisoning develops slowly, and because the water from the wells tastes and appears better than contaminated surface water, many of the people have continued its use despite warnings. There have been many deaths, and thousands have lesions caused by the slowly accumulating arsenic poisoning.

**Water Ownership**

Ownership of most mineral resources is relatively straightforward because they are static materials lying on or below the land surface in some relatively easily definable form. In most areas of private land ownership, the resources are considered a part of the land that can be exploited at the discretion of the owner, subject to state and local regulations. Frequently, however, mineral rights have been separated from land ownership or have been sold or leased by the landowners to companies; the companies can exercise these rights to extract mineral resources if they comply with state and local laws regarding disturbance to overlying or adjacent properties.

The U.S. Public Health Service and the World Health Organization (WHO) have established recommended maximum limits for the concentrations of many mineral, organic, and synthetic substances in public water supplies (Table 11.1). Of particular concern is the accidental introduction of synthetic organic chemicals into water supplies because they may have toxic effects even in extremely low concentrations. The maximum total dissolved solids should not exceed 500 ppm, but numerous public and private supplies, especially in arid regions and in many developing countries, exceed this limit (usually excess sodium chloride), because better water is not available or because costs to produce it are prohibitive. There will be increased

**Riparian Rights in the Eastern United States.**

Basic riparian law may be summarized as the right of every landowner to make reasonable use of a lake or stream that flows through, or borders on, his or her property as long as the use does not damage the similar rights of other landowners. Although now locally much modified by regulatory statutes to provide for cities or public utilities, the riparian principle still basically governs the use of surface water in most of the eastern states. The rights have generally

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**FIGURE 11.24 Simple gravity siphon irrigation system in which the water flows from a feed canal into furrows across the field. (Courtesy of R. B. Rose.)**
FIGURE 11.25  (a) Walking irrigation system used to disperse water over large fields. (b) Aerial view of a large center well walking irrigation system, in which a central well supplies water sprinklers that continuously proceed in circular paths up to 1 mile (1.6 kilometers) in diameter. (Photographs courtesy of Valmont Industries, Inc.)
TABLE 11.3
Compositions of some typical river waters in the United States and ocean water

<table>
<thead>
<tr>
<th>Substance (ppm)</th>
<th>Kootenai River, Rexford, MO</th>
<th>Mississippi River, Cape Girardeau, MO</th>
<th>Arkansas River, Derby, KS</th>
<th>Chickasaw Creek, Handson, MS</th>
<th>Colorado River, Hoover Dam, AZ</th>
<th>Delaware River, Philadelphia, PA</th>
<th>Ocean Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica (SiO₂)</td>
<td>6.9</td>
<td>6.8</td>
<td>13</td>
<td>11</td>
<td>8.7</td>
<td>45</td>
<td>–</td>
</tr>
<tr>
<td>Iron (Fe²⁺)</td>
<td>0.06</td>
<td>0.18</td>
<td>–</td>
<td>–</td>
<td>0.01</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Calcium (Ca²⁺)</td>
<td>46</td>
<td>47</td>
<td>107</td>
<td>225</td>
<td>92</td>
<td>18</td>
<td>413</td>
</tr>
<tr>
<td>Magnesium (Mg²⁺)</td>
<td>14</td>
<td>14</td>
<td>26</td>
<td>129</td>
<td>106</td>
<td>13</td>
<td>10,717</td>
</tr>
<tr>
<td>Sodium (Na⁺)</td>
<td>3.8</td>
<td>11</td>
<td>355</td>
<td>3.2</td>
<td>5.3</td>
<td>2.1</td>
<td>385</td>
</tr>
<tr>
<td>Potassium (K⁺)</td>
<td>1.0</td>
<td>4.0</td>
<td>13</td>
<td>3.2</td>
<td>5.3</td>
<td>2.1</td>
<td>385</td>
</tr>
<tr>
<td>Bicarbonate (HCO₃⁻)</td>
<td>160</td>
<td>138</td>
<td>249</td>
<td>380</td>
<td>159</td>
<td>28</td>
<td>–</td>
</tr>
<tr>
<td>Carbonate (CO₃²⁻)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>–</td>
</tr>
<tr>
<td>Sulfate (SO₄⁻)</td>
<td>45</td>
<td>64</td>
<td>217</td>
<td>1300</td>
<td>322</td>
<td>39</td>
<td>2863</td>
</tr>
<tr>
<td>Chloride (Cl⁻)</td>
<td>2.0</td>
<td>12</td>
<td>505</td>
<td>46</td>
<td>104</td>
<td>104</td>
<td>19</td>
</tr>
<tr>
<td>Fluoride (F⁻)</td>
<td>1.2</td>
<td>0.4</td>
<td>1.0</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td>–</td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>0</td>
<td>7.9</td>
<td>9.3</td>
<td>17</td>
<td>2.0</td>
<td>2.0</td>
<td>–</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>215</td>
<td>254</td>
<td>1275</td>
<td>2220</td>
<td>763</td>
<td>128</td>
<td>35,000</td>
</tr>
<tr>
<td>pH</td>
<td>7.9</td>
<td>7.5</td>
<td>8.0</td>
<td>7.4</td>
<td>8.0</td>
<td>7.3</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Data from "Quality of Surface Waters at the U.S.," Geological Survey Water Supply Paper 2141–2150, 1999

functioned in a proportional manner, with the understanding that when water is plentiful all have plenty, and when water is scarce, all share the hardship. The major exception to this is that municipal water supplies are now usually given protection of the right of eminent domain; hence, in times of shortage, cities get their quantities of water first, and riparians share what remains. The sale of riparian rights to those who do not border on streams has been allowed in some states but is not common. Because the eastern United States generally has large and continuous water supplies, the riparian system has worked well.

Prior Appropriation in the Western United States. The law of prior appropriation grew out of the California Gold Rush when the forty-niners staked claims for placer gold and for the water to wash the gold from the gravel. The rights to both the gold and the water were, "First come, first served." This concept grew into the formalized laws that allowed the settlers in an area to make an appropriation of a specific quantity of water for any beneficial use, and that protected the appropriations on the basis that the oldest are honored first and newer appropriations are only honored as long as there is sufficient water. Thus, in times of shortage the more recent appropriations would be denied water, whereas the earliest appropriations would always have some water unless there was none at all.

In contrast to the riparian rights, which are generally held only by the landowner adjacent to a stream, appropriation rights have generally been available for sale to all those who would pay, even if they were long distances from the stream. The consequences of this are seen in California where cities such as Los Angeles were very farsighted in the early 1900s and bought up water rights in areas hundreds of miles away in anticipation of their needs decades later. Today, Los Angeles exercises its appropriation right to secure water that is transported by a complex series of aqueducts. Protests over the removal of water from the source regions such as the Owens Valley east of San Francisco to Los Angeles has led to numerous lawsuits, small pitched battles, and even bombings of the aqueducts. Nevertheless, Los Angeles bought the water appropriations and will have the rights to use them until or unless the courts rule otherwise.

Just as many riparian principles have been altered, appropriation rights have now been modified or encumbered by various compacts, agreements, or legislation decrees in many areas to allow for either more equitable or more economical use to be made of the water. Nevertheless, the original stamp of the appropriative right is still clearly visible in the water laws of many states of the American West.

Groundwater

However difficult or arbitrary the decisions on surface water rights have been, the decisions on groundwater rights have been even more difficult, because the source of the water, its quantity, and its movement have generally been unknown. Clarification of groundwater rights are extremely important as this is the source of the water used in more than 50 per-
cent of American homes. Most courts in the past, and some still today, follow what has been termed the “English rule of absolute ownership,” which states that groundwater, like the rocks, belongs to the property and thus is the possession of the owner of the surface, who can extract as much as he or she desires for any purpose. As long as wells were widely spaced and pumping was relatively limited, there were few problems; however, the advent of modern high-capacity pumps and the turning of many large cities to groundwater for portions of their water supplies resulted in the drying up of many shallow wells. This led to widespread application of what is now called the “American rule of reasonable use,” which permits unlimited extraction of groundwater for use on a plot of overlying land, but not the removal of water to distant places for sale (e.g., to cities), without the compensation of farmers whose wells go dry as a result of the sale. In the western United States, many states have simply applied the law of prior appropriation to both groundwater and surface water. However, increasingly the western states have placed groundwater usage under the control of water commissions so that this valuable resource is not subject to excessive or wasteful withdrawals. Fortunately, in recent years, courts have begun to considered our growing knowledge of the limits of groundwater resources, as well as the manner in which groundwater moves, and have recognized the “conjunctive” relationship between surface and groundwater as shown in Figure 11.26a. This does not solve all problems, but it is certainly better than relying solely upon previous rulings that assumed the presence of unlimited quantities.

There are widespread misunderstands about the amounts and the flow of groundwater. Studies usually report the saturated thickness of an aquifer, the specific yield, and the safe yield. The groundwater in aquifers actually only occupies the cracks or pores of the sediment or rock unit; only in the underground caves of some karst limestones are there actual underground rivers. Most aquifers in sedimentary rocks actually only contain 15–30 percent open pores, and the fractures in igneous or metamorphic rocks usually constitute only a few percent of the volume. Furthermore, much of the water does not drain out but is retained as films between grains or along fractures by capillary action (this is called “specific retention”); the retained water may ultimately evaporate but it will not drain out by gravity. As a result, an aquifer that may have a reported thickness of 100 meters might contain only the equivalent of 25 meters, of water, of which only 12 to 15 meters can be extracted.

The withdrawal of groundwater depends not only on how much is present but also on how fast it can move through the pores. Surface rivers and streams commonly flow at rates of 3 to 6 kilometers (2 to 4 miles) per hour but groundwater movement is typically only centimeters or millimeters or less per hour. Thus, well water is often many years old when extracted, and the rate of groundwater recharge is very slow compared to that of a surface reservoir. The specific yield is the maximum rate at which one can continuously pump water from an aquifer; the safe yield, usually a much lower value, is the maximum rate at which water can be pumped without lowering the water table. Fractured igneous or metamorphic rocks usually contain much less water because the volume of the fractures is small, but the water will often flow more quickly because the fractures are larger, more continuous, and more intersecting. Furthermore, if they intersect areas of flowing streams they may be more rapidly recharged than typical sedimentary aquifers.

Mining can lower groundwater tables locally to regionally when water is pumped out to permit the operations beneath the level of the original water table, as shown in Figure 11.26b. The extent of the effect depends upon the mine depth and the rate of groundwater flow. After mining has been completed, groundwater tables commonly return to their original levels, filling underground mine workings and turning open pits into lakes (see Plate 18).

Environmental Water Rights

Over the past twenty years or more there has been an increasing awareness and an emphasis on the water needs of wildlife, with the result that in the United States many new regulations regarding environmental water rights have been developed. Whereas many policies, even into the 1950s, actively sought to drain wetlands to make them into farmland, and diversionary canals were built to move water to farms and cities, today the situation is almost the reverse. The federal Endangered Species Act and the Wetlands Act are specifically aimed at preserving populations of animals and the habitats necessary for their survival. The effects of withdrawing surface waters are reasonably obvious, and the effects on wildlife, such as fewer fish, beavers, or water birds, can be clearly linked with water loss. Conversely, groundwater withdrawal has less immediate and less obvious effects, but may be equally important as stream levels begin to drop, springs dry up, and marshy wetlands are gradually converted to meadows. The combined effects of surface drainage and groundwater withdrawal were especially evident along the Mississippi migratory flyway, the migratory path for water birds, where duck populations dropped dramatically from the 1950s to the 1980s. The restoration of wetlands, beginning in the 1980s, had beneficial effects as breeding and feeding areas reappeared. The population of ducks has risen steadily through the 1990s.

Effects such as those discussed above have introduced environmental water rights into the complicated factors governing water use throughout the United States, and into many other countries. No longer is it sufficient to merely point to increased needs or desires for water to grow crops or serve cities. Every new major use, and every transfer of water from surface or subsurface sources, must be considered in terms of environmental impact as well its need. The result is a much more careful consideration of water needs.
Conjunctive water relationships are those demonstrating the connection of ground and surface waters in an area. (a) Intense pumping of a well adjacent to a small stream can lower the groundwater table sufficiently so that the stream water begins to infiltrate the ground, lowering the stream flow, and actually be drawn into the well. (b) Shown here are the effects of mining on the groundwater table as the mine pit is deepened and water is pumped out of the pit to permit continued mining. The first stage of mining only has a minor effect on the groundwater table in the immediate vicinity of the mine. The third stage of mining has lowered the groundwater table so much that the stream has gone dry. After mining has been completed and the groundwater table returned to its normal level, the stream again flows and the mine's open pit has become a lake.
much better conservation practices, and frequently, higher water prices.

**Desalinization Of Water**

Samuel Taylor Coleridge in his poem “Rime of the Ancient Mariner” identified a problem faced by large numbers of coastal cities and islands when he wrote, “Water, water everywhere nor any drop to drink.” Coastal localities have access to vast quantities of water that cannot be used because it is saline. In fact, four principal methods have been developed to permit the use of the seawater, or other brines, for human consumption. The general process, called desalinization or desalting, can be accomplished by any one or combination of the following: (1) distillation, (2) electrodialysis, (3) reverse osmosis, or (4) freezing. These processes are shown in very simple schematic form in Figure 11.27.

Distillation of a brine for potable water is identical to the process long used in school chemistry labs to produce high-purity water. Salty water is boiled and the evolved steam is condensed into fresh water. The dissolved salt is left behind, making the remaining brine even saltier.

Electrodialysis uses two special membranes that selectively allow for the passing of sodium (Na⁺) or chloride (Cl⁻). As salty water passes between the membranes, the sodium ions are drawn through one membrane to the cathode, and the chloride ions are drawn through the other membrane to the anode. The result is a flow of fresh water from the cathode to the anode.

Reverse osmosis uses a membrane to force the water to pass through, while the salts are retained on the other side. The resulting flow is fresh water.

Freezing is a simple process that can be used to prepare freshwater by freezing seawater or other brines. The ice is then melted to produce freshwater.

**FIGURE 11.27** Fresh water can be prepared from seawater or other brines by many processes. The four most commonly used today are (a) distillation (b) electrodialysis (c) reverse osmosis, and (d) freezing.
BOX 11.3  Water in the Middle East

When one thinks of critical resources and the Middle East, the thought generally focuses on petroleum. After all, this is the area of the world's greatest petroleum reserves, the site of several OPEC countries, and the place where the Persian Gulf War of 1991 was fought. But it is another resource, one that is often taken for granted, that has emerged as critical to development and to peace in the region—water. The need for water in this arid and semiarid region has been apparent since Biblical times and its truth is clear in the recent Israeli comment, "Water is like blood; you can't live without it."

The dual problems of water availability, and agreement on its equitable distribution, have grown more acute in the past fifty years because of large population increases resulting from immigration into some areas (especially Israel), high birth rates in other areas (for example, among the Palestinian Population), the need for intensive irrigation, and the desire to develop hydroelectricity. Solutions to the finding and distribution of water have been made even more difficult by a series of Arab-Israeli conflicts and several border and resource disputes between Arab neighbors. The water resource problems of the Middle East are but briefly described here, but, in many ways, they reflect the problems of water availability in several parts of the world.

Water was early recognized as a vital resource for Israel, and by the early 1950s a regional agreement was being planned with Jordan to share the waters of the Yarmouk River and the Sea of Galilee (Figure 11.5). The 1956 Suez War, followed by the 1964 damming of the southern outlet of the Sea of Galilee, and finally the 1967 war, effectively killed the plans. The Israeli annexation of the West Bank and the Golan Heights provided not only a military position, but also control of the runoff areas that now supply two-thirds of Israel’s water. The Israelis control most of the Yarmouk River flow while the Jordanians contend that they have never been provided with 100 million cubic meters of water annually from the Sea of Galilee as promised. Drought combined with the extraction of water, primarily for irrigation to water-intensive crops, has lowered the level of the Sea of Galilee to its lowest point in history and raised its salinity to concentrations that threaten its aquatic life. Jordan has been forced to rely more than ever on groundwater but anticipates exhaustion of those supplies by 2011. Attempts to broker peace agreements between Israel and its Arab neighbors in the 1990s and the early part of the twenty-first century have always included discussions on water rights as well as on borders and security.

Slightly north and east, another water resource drama is unfolding. Turkey, which controls the headwaters of both the Tigris and Euphrates Rivers, began an ambitious plan in the mid-1980s that could ultimately include some 20 dams and 15 hydroelectric power plants. The biggest dam, the Atatürk Dam on the Euphrates, would be the fifth largest in the world and would reduce downstream flow to Syria and Iraq by half. The total project is designed to generate sufficient electricity to modernize Turkey and to provide irrigation water to transform more than 16,200 square kilometers (4 million acres) of semiarid land into a Middle Eastern breadbasket.

At the center of the cell and a saltier brine from the lateral parts remain the electrodes. 

*Reverse osmosis* produces fresh water from salty water by forcing water molecules through a semipermeable membrane when high pressure is placed on the salty water. The membrane has pores that allow for the relatively small water molecules to pass through but will not allow the larger hydrated salt ions (Na⁺ and Cl⁻) to pass through. In a continuous process, about 30 percent of the original salty water passes through the membrane to produce fresh water, while the remainder, now saltier, is discharged.

The freezing process takes advantage of the fact that sea salty water freezes, the ice that forms is fresh water and the salt is concentrated in the remaining brine. In a sim-
BOX 11.3 Water in the Middle East (continued)

Turkey has said it will return flow back to the Euphrates, but the Syrians fear pollution of the river—their main source of drinking water—by salts, fertilizers, pesticides, and other pollutants. Predictably, tensions are high but solutions are few. Water has no rival as a resource in an arid region.

![Map of the Middle East showing the locations of the Sea of Galilee, the Dead Sea, and the Tigris and Euphrates Rivers.](image)

**FIGURE 11.E** Map of the Middle East showing the locations of the Sea of Galilee, the Dead Sea, and the Tigris and Euphrates Rivers.

Sian Gulf where oil for energy is plentiful and inexpensive, but water is scarce. During the Gulf war of 1990–1991, much effort was made to protect some of the world’s largest desalting plants from oil spilled in the gulf. In the United States, coastal cities in Florida and California are looking to the ocean, or to subsurface brines, to provide increasing proportions of their future water supplies. Catalina Island off the coast of southern California has turned to desalting because of an increased population, but now the community faces the problem of even more people wanting to live on the island because of the success of the desalting plant.

**POTENTIAL WATER PROBLEMS**

Water, like most other mineral resources, is irregularly distributed over Earth’s surface. Unfortunately, this distribution often does not correspond to our needs or desires for water at a given place and time. These inconsistencies have frequently led to problems of supply and quality and clearly suggest that such problems will increase in the years to come. In general, humid regions with more than about 75 centimeters (30 inches) of annual precipitation have sufficient surface water available in the forms of lakes, rivers, and permanent streams to meet water needs. However, in areas of intense population concentration, especially those without neighboring large rivers, the local demand can easily exceed supplies. Furthermore, normally well-watered areas can suffer periods of drought, which result in depletion of usual water supplies (Figure 11.28). Arid regions are constantly plagued by inadequate surface water supplies, with the deterioration of water quality due to the evaporative concentration of salts, and in some areas, with dwindling groundwater supplies. In some regions, water has become as important politically as it is important economically because the control of water
governs many other activities (see Box on p. 441 for an 
example).

It is not possible to chronicle here examples of all cur-
rent and potential water problems, but the following dis-
cussion does attempt to examine some of the major problems
with which we must contend in the near future.

Limited Surface Water Supplies—The Colorado
River Project

Deserts, by virtue of the paucity of life-sustaining water,
have always been some of the most inhospitable areas of the
world for humankind (Figure 11.29). We have partly over-
come the aridity of deserts by diverting rivers into them, and
by pumping up groundwater that occurs in underlying
aquifers. Ancient irrigation systems brought about the
spread of civilization from the Fertile Crescent—the valleys
of the Tigris and the Euphrates Rivers in what is now Iraq—
across Iran, Afghanistan, Pakistan, and India. More modern
systems have allowed the spread of agriculture through arid
regions of many lands and have converted parts of deserts in
Israel and in California into some of the most productive re-
regions in the world. The introduction of additional water sup-
plies has allowed for the development of large population
centers where naturally available surface water would not
have permitted such populations.

The low-latitude desert regions of the world have of-
fered good sites for large scale agriculture and development

FIGURE 11.28 Even in the generally well-water Central Atlantic
states, prolonged periods of lower than normal rainfall can
have dramatic effects on water supplies. The water lever in
Carvin's Cove reservoir, the principal water supply for Roanoke,
Virginia, dropped to nearly 30 feet below the spillway of its dam in
1999, forcing the city to restrict water usage by residents and to
purchase water from surrounding municipalities. The pier normally
extends far out into the water but was nearly a hundred meters
from the water's edge when this photograph was taken. (Photo-
graph by J.R. Craig.)

FIGURE 11.29 The droughts that have been experienced in several
parts of Africa in the past twenty years have killed large numbers
of cattle and severely limited the capabilities of many people to
raise crops. (Photograph from the United Nations.)
because many of them permit year-round growth of crops. The extensive agricultural development of these areas does, however, call for the consumption of vast quantities of water. High evaporation rates in low latitude deserts mean that water becomes a nonrenewable resource because there can be little recycling, and there must be a constant influx of the water to maintain these activities. The sources of the massive amounts of water needed to develop and sustain our activities in arid regions have been twofold—water imported from rivers in more humid adjacent areas, and groundwater. Water provision schemes for arid regions have met with considerable success as evidenced by the creation of millions of hectares of agriculturally productive land. Unfortunately, even some of the largest and most carefully planned projects have the potential for major problems.

An example of this is the well-known Colorado River Project, which supplies water to seven western states and Mexico [Figure 11.30 (a), and Plate 65]. Since the late 1800s, farmers have tapped the Colorado for its water. By the 1920s, it became apparent that the water of the Colorado was too valuable a resource to allow uncontrolled exploitation. Therefore, in 1922 the Colorado River Compact [Figure 11.30 (b)], signed by the states in its drainage basin, decreed that the Upper Basin states of Wyoming, Colorado, New Mexico, and Utah should forever get 7.5 million acre feet ($9 \times 10^{12}$ liter; one acre foot of water is equivalent to about $1.2 \times 10^6$ liters or $3.26 \times 10^5$ gallons) of water to share annually. The Lower Basin states of Arizona, California, and Nevada would draw the same amount. In 1944, a treaty guaranteed Mexico 1.5 million acre feet.

**FIGURE 11.30** (a) The Colorado River Basin, showing the location of the major dams and lakes and the areas of the upper and lower basins. (b) The top curve represents the total flow of the Colorado River—measured at Yuma, Arizona—before Hoover Dam was constructed in the 1930s and calculated as the flow at Hoover Dam plus the Gila and Bill Williams Rivers after that. The actual flow reaching Yuma since 1934 is the lower curve; the rest of the water has been diverted for irrigation and municipal water supplies. The dashed lines indicate the total amounts of water promised to the Colorado River Basin states and Mexico. (Data from U.S. Geological Survey, Yuma, Arizona.)
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FIGURE 11.30 (cont.)

acre feet (1.8 \times 10^{12} \text{ liters}) of water annually; although the original treaty did not specify the quality of the water reaching Mexico, a subsequent agreement established that it should not contain more than about 900 ppm dissolved solids.

The problems that have arisen are threefold. The Colorado River does not generally carry as much as 15 million acre feet of water [Figure 11.30(b)]; the water reaching Mexico sometimes contains as much as 1500 ppm of salt; and the Navajo Indian reservation, never considered in allotment schemes, has proposed a project that would claim a significant part of the Colorado River to irrigate its crops.

The original allocations of water between the Upper and Lower Basin states of the Colorado River were based upon water flow estimates done between 1896 and 1922. Unfortunately, these estimates were made during a wet period, when the average annual flow was about 16.8 \times 10^6 \text{ acre feet} (20.6 \times 10^{12} \text{ liters}). Since 1931, however, the flow has only averaged about 13.1 \times 10^6 \text{ acre feet} (16.1 \times 10^{12} \text{ liters}), and in 1934 the flow was only 5.6 \times 10^6 \text{ acre feet} (6.9 \times 10^{12} \text{ liters}).

To smooth annual and seasonal fluctuations and to retain waters, an elaborate scheme has been built for trapping and tapping the Colorado River, as is shown in Figure 11.30(a). The dams store water for usage but also bring about an increase in the salinity by allowing extra evaporation. The problem of supply has not yet been fully felt because some states have not demanded their total allocation, and the Navajo Indians have not pressed their demands. However, the completion of the Central Arizona Project (Figure 11.23) in the 1980s resulted in Arizona's using its allocation, and in California's having to give up an extra million acre feet over its allocation that it had been taking to satisfy the water needs of San Diego and Los Angeles. Furthermore, projections for future water demand for agriculture and for the processing in the Colorado Basin of energy resources of coal, oil, and, perhaps some day, oil shale, far exceed the river's flow.

The solution to the problem of the quality of water being passed on to Mexico has been the construction of a large desalination plant at Yuma, Arizona. This $350 million facility, operating by reverse osmosis, delivers 1.5 million acre feet (1.8 \times 10^{12} \text{ liters}) of water (with only about 800 ppm impurities) to Mexico for its irrigation needs. The saline by-product water from the plant, with about 8200 parts per million dissolved salts, is channeled in a diversionary canal into the Gulf of California. The cost of the desalinated water to be delivered to Mexico to meet treaty obligations has been estimated at thirty times the cost of irrigation water in California.

Additional conflicts have arisen along the Colorado River Basin over the function of the dams that hold back the large reservoirs. The dams have eliminated the problems of flooding that had previously occurred periodically along the lower Colorado; however, the dams are now often so filled with water being held for irrigation that they no longer have the excess capacity necessary to stop floodwaters. Furthermore, the floodplains below the dams are now heavily pop-
ulated; population issues limit the rapid release of water, which is sometimes needed to create the excess capacity needed for flood control. Compounding these problems is the need to be able to generate hydroelectric power to meet the increasing energy demands to pump water to the various areas served by the basin.

Groundwater Depletion and the Problem of the High Plains Aquifer

Under normal conditions, the quantity of groundwater and the level of the water table exist in a long-term equilibrium in which the recharge is balanced by the discharge. When pumping begins, the equilibrium is disrupted and, in general, groundwater levels fall. If pumping is only of small quantities, the decline may be local, as a cone-of-depression around a single well; in contrast, if pumping is of large quantities from many wells, the fall may be widespread. Pumping may also bring about decreases in the natural discharge to streams, to the sea, or in the rates of evapotranspiration.

A safe or sustained yield is the amount of groundwater withdrawal that can be pumped for long periods of time without a continuing drop in the water table. Withdrawals in excess of a safe yield result in water mining and a progressive drop of the water table and, at some point, a decrease in the rate at which water can be pumped. Water mining is thus much like the mining of any other mineral resource except that there is often at least some replenishing of supplies by natural recharge.

As noted above, commonly only 15–25 percent of the thickness of an aquifer is actually extractable water. Furthermore, as the water table drops and the saturated thickness decreases owing to pumping, the rate of additional extraction also decreases because more of the water movement is lateral instead of flowing directly downward by the pull of gravity.

The pumping of groundwater has increased rapidly in this century in response to burgeoning populations, increased industrial demands, the expansion of irrigation into semiarid regions, and the development of high-capacity pumps. An example of this increase in the United States since 1950 is shown in Figure 11.31; the present rate of pumping (>80 × 10^9 gallons per day; 300 × 10^9 liters per day) approaches 10 percent of the estimated 10^12 gallons per day (3.8 × 10^12 liters per day) of water estimated to be present through the aquifers. Unfortunately, the demand for groundwater is very unevenly distributed and often does not correspond to the rates of recharge. Hence, groundwater mining with a resultant fall in the water table has indeed occurred in many parts of the United States, as shown in Figures 11.32 and 11.33.

The aquifers of the Atlantic and Gulf coastal plains are recharged by relatively high rainfall (>92 centimeters; 40 inches per year), but the heavy demand of dense popula-

tion and industry has resulted in a falling water table in every coastal plain state. An example of the decline is the area near Houston, Texas, where the water table dropped nearly 100 meters between 1940 and 1970, when stabilizing measures were taken. Groundwater levels in the upper Midwest and the western parts of the United States display marked declines in many areas because the lower rates of precipitation have been unable to recharge the aquifers as rapidly as pumping for irrigation withdraws water. This problem is especially prevalent in California, the nation’s principal user of groundwater. The California Department of Water Resources has determined that large declines in the groundwater are occurring in eleven basins, eight of which are in the San Joaquin Valley, where agricultural irrigation is greatest. In the mid-1980s, the water table was declining as much as 2 meters (6 feet) annually and averaged about 0.8 meters (2.5 feet) per year. The coastal basins, serving cities as well as irrigation schemes, experienced water table drops of as much as 65 meters (200 feet) from 1950 to 1983. Another prime example of water table decline is in Arizona, southeast of Phoenix, where water has been withdrawn for agricultural and municipal use since 1930. The average annual drop is now about 2.7 meters (8 feet) each year, and the total decline is nearly 130 meters (400 feet).

The southern High Plains of the United States, although commonly dry, hot, and windswept on the surface, is the location of one of the country’s major groundwater accumulations—the Ogallala aquifer [Figure 11.34]. This Miocene deposit contains more than 24,000 cubic kilometers of gravel, much of which is saturated with high-quality groundwater. The southern High Plains, with an annual rainfall of 50 to 75 centimeters (20 to 30 inches) and an evaporation rate of 150 to 250 centimeters (60 to 100 inches), was the site of poor dry land farming until the water of the Ogallala was discovered in the 1930s. Since that time, some 150,000 wells have penetrated the aquifer to draw out millions of acre feet per year for use in irrigation. By the late 1960s, it became apparent that the water table in several parts of the aquifer was being depressed at rates as great as 1.5 to 2 meters each year. A few portions of the aquifer have actually registered a rise in the water table due to the addition of irrigation water, but large areas in the Texas Panhandle and in western Kansas have seen a drop in the water table of 30 meters or more in a span of a half century. Accurate records only exist for about the past thirty-five years, so the predevelopment levels are often estimates. After 1980 the records are very detailed, and it is apparent that the areas estimated to have suffered the greatest drop in water table to 1980 have continued to suffer in this way. The mining of this water at present rates, in an area where recharge is effectively nil, will leave many parts of the Ogallala dry within a few years. At stake are some 5 million acres in six Great Plains states, an area as large as Massachusetts; this region has been a major agricultural producer. The inevitability of the draining of the Ogallala and the nearly valueless nature of the land when the water is gone is a sobering thought.

If the land when there is no more water has even led the Internal Revenue Service to grant Texas High Plains farmers a depreciation on their land as the water table drops.

The examples of groundwater depletion discussed here are representative of a problem that is growing in magnitude both in the United States and worldwide. We shall either have to find ways to live with the amounts of continuously available water in each area or be willing to pay for massive water transport systems; we shall never find a way to live without water.

**Land Subsidence Due to Groundwater Withdrawal**

The removal of large quantities of groundwater in some areas has resulted not only in the lowering of water tables but also in the local and significant subsidence of the land surface, as shown in Figure 11.35(a). Extraction of groundwater from most aquifers has little or no effect on the land surface because the water is only interstitial to the grains of the rock that support the entire rock column. However, in some confined or semiconfined aquifers containing fine-grained sediments, the trapped water actually partially supports the rocks. Hence, when the water is pumped out there is a slow and generally irreversible subsidence of the land surface. Occasionally, there are even sudden collapses, as depicted in Figure 11.35(b).

Although subsidence rates are rarely dramatic, the effects and damages can be considerable and include: (1) damage to well casings; (2) structural damage to buildings, roads, and bridges; (3) damage to buried cables, pipes, and sewers; (4) changes in the grades and efficiencies of canal and irrigation systems; and (5) increased susceptibility of flooding in low-lying coastal areas. There was great fear that
New Orleans, much of which lies 2 to 3 meters below sea level as a result of subsidence, could suffer catastrophic inundation when Hurricane Andrew hit the Gulf Coast in 1992. Fortunately, the worst part of the storm passed west of New Orleans, but most informed scientists and officials believe that sooner or later a large hurricane with a strong tidal surge could swamp New Orleans with tremendous damage and loss of life. At this point, it is impossible to raise the level of New Orleans, so the only realistic protection is the construction of massive sea walls and levees. Subsidence in the Santa Clara Valley of California has lowered the land surface below sea level with resulting costs estimated at more than $30 million. In the Central Valley of California, subsidence began in the 1920s as groundwater was utilized for irrigation. By 1964, annual groundwater withdrawals had exceeded 20 million acre feet ($24 \times 10^6$ liters) and subsidence had affected about 13,500 square kilometers ($5200$ square miles). By 1970, the water table had dropped as much as 110 meters ($350$ feet) and the land surface had subsided about 8 meters ($26$ feet) (Figure 11.36); the combined effect even reversed the direction of water flow in the aquifer.

Extraction of groundwater to meet the growing needs of the Houston–Galveston area since 1915 has resulted in subsidence of 2.5 meters (8 feet) in the Brownwood subdivision of Baytown. As a consequence, most of the 450 houses of this coastal subdivision have become permanently inundated by seawater (see Plate 58).

**Saltwater Intrusion Into Aquifers**

Under normal conditions, the slow but steady percolation of groundwater in response to the pull of gravity is sufficient along most coastal areas to keep marine saline waters from seeping inland into the aquifers. The location of the boundary—the fresh water–saltwater interface (Figure 11.37)—varies from one shoreline to another depending upon the rainfall and the permeability of the rocks and sediments, and it changes slightly in any given area as a function of annual or longer-term climatic conditions.

Since the 1960s, it has become apparent that the extraction of large quantities of water from many aquifers to serve growing metropolitan areas has altered the natural hydrologic balance. The consequence of removing vast quantities of water that previously held back the saline waters is the landward movement of the fresh water–saltwater interface, resulting in saltwater intrusion into the previously freshwater aquifers. This phenomenon has been observed in many places but is especially well documented along the coastal areas of the United States. Thus, freshwater wells have been abandoned near Atlantic City, New Jersey, Savannah, Georgia, New York City, and Los Angeles, and in creating saltwater ponds.
It is apparent that the movement of saline water, especially when promoted by human activities, poses a threat to many important water supplies. Our increasing demands on groundwater supplies are likely to intensify the problems and hence require careful consideration of the most efficient uses of this valuable resource.

Water for Sale From The Great Lakes and Alaska?

Humans have commonly constructed or modified water transportation systems to provide water to areas where demand exceeded natural supplies. Some early efforts were aqueducts, as built by the Romans to supply cities, and others were irrigation canal systems, as constructed by the Incas and the ancient Persians. The 1990s saw many new proposals, which, although not yet in place, may offer a glimpse of the future and which attest to the value of water as a resource. One of the most serious has been the transport of water from Alaska or northern Canada to thirsty...
southern California. As California’s water needs have risen as a result of its booming population, access to regionwide water has declined. Accordingly, several entrepreneurs have considered the possibility of large-scale transport of water from rivers in Alaska or Canada to southern California. The proposed means of transport include huge water tankers, similar to oil tankers, submarine pipelines, and large plastic bags up to 300 meters (1000 feet) long. The bags would be filled in Alaska and floated (because fresh water is less dense than saltwater) to California. The technical aspects of each system are quite manageable and costs would be kept reasonable by economy of scale. Spillage of fresh water would not constitute much of an environmental threat, but there are ecological concerns about the changes that might occur in the rivers and bays where the water is removed. None of these systems have yet been approved, but there are increasing numbers of discussions about them.

At the same time, petitions have been made to transport water in large tankers from the Great Lakes to arid or drought-striken parts of the world. The Great Lakes span the international boundary of the United States and Canada;
ence, any action requires the approval of both nations. Small-scale extraction of lake water for local irrigation has always been allowed, but both countries are concerned about any precedent that might be established if large-scale water sales were permitted. Therefore, for at least the early years of the twenty-first century, water taken from the Great Lakes will not occur; special exemptions for humanitarian needs might still be considered.

**FIGURE 11.35 (a) Areas of significant land surface subsidence caused by the withdrawal of groundwater. (From U.S. Geological Survey Water Supply Paper 2250, p. 56, 1984.) (b) The Giant Sinkhole, which collapsed in December 1972, left a crater 130 meters (425 feet) across and 45 meters (150 feet) deep. This and about 1000 other sinkholes in Shelby County, Alabama, are believed to have resulted in part from natural and human-induced groundwater table lowering. (Photograph from the U.S. Geological Survey.)**

**Soil Deterioration Due to Water Logging, Salinization, Alkalinization**

Irrigation in arid regions, although intended to bring unused or low productivity land into full agricultural production, has unfortunately also caused the deterioration or loss to production of an estimated 125,000 hectares of land every year. The problems arise in arid regions where irrigation
systems supply water to soils faster than drainage can remove it. The excess water raises the water table near the soil surface, causing water logging, and permits evaporation to concentrate dissolved salts. Water logging is a problem by itself because most crop plants are not able to survive if their roots are under water; rice is the major exception. The buildup of mineral crusts (Figure 11.39) of the halide (salinization) or alkali salts (alkalinization) impairs plant growth; furthermore, runoff of salt-laden waters into streams reduces the usefulness of that water for irrigation elsewhere.

The deterioration of soils by salt buildup as early as 2400 to 1700 B.C.E. is believed to have caused the collapse of ancient civilizations in Mesopotamia and in the Upper Nile Valley in Egypt. In 1959, it was estimated that 60 percent of Iraq’s agricultural land was seriously affected by salinity. In the 1960s, the same problem arose in the Sind, one of Pakistan’s major provinces, when 49 percent of all agricultural land was waterlogged. Furthermore, 50 percent of the irrigated land of the Sind was highly saline, and 25 percent was moderately saline. Argentina has 2 million hectares of irrigated land affected in this way, Peru 300,000

FIGURE 11.36 An example of land surface subsidence as much as 8 meters (26 feet) in the Los Banos–Kettleman City area of California between 1920 and 1966 as a result of groundwater withdrawal. Further subsidence has been prevented by reinjection of groundwater and the use of alternative sources. However, after subsidence, reinjection of groundwater usually does not result in any rise in elevation. (From U.S. Geological Survey Professional Paper 437-F.)
hectares, and the United States potentially faces the same problem in more than 1 million hectares of the rich San Joaquin Valley in California. In the west central San Joaquin Valley, selenium weathering out of the adjacent formations has been concentrated by evaporation of water on the farmland soils. The selenium, mobilized by irrigation drainage, has accumulated in wetland ponds of the Kesterson National Wildlife Refuge, where closed basins have further concentrated the selenium to the point that it is causing very high rates of deformation of waterfowl (see discussion in Chapter 12).

Salinized land can be reclaimed by the installation of expensive subsurface drainage systems that allow the irrigation water to percolate downward through the soil. This downward movement is similar to the natural water movement in soils in humid areas and eliminates the buildup of the soluble salts at the soil surface. Such reclamation, however, has only been carried out in local areas because it is very expensive to install the drainage systems, because it requires even larger amounts of water to flush out the salt-rich soils, and because the salts that have been washed out may reach groundwater supplies or merely be deposited in downstream areas.

**Desertification** is a relatively recently used term to describe the deterioration of previously useful land adjacent to a desert region, at least partly in response to human activities such as farming and grazing. It frequently occurs in semi-arid regions as a consequence to changes in precipitation patterns, but it remains primarily a problem of soil usage and hence is discussed in greater detail in Chapter 12.

**LARGE-SCALE TRANSPORTATION AND DIVERSION SYSTEMS**

Although we live on a planet 70 percent covered by water, we continually find that, in many areas, either the quantity or the quality of water is not sufficient for our needs. Consequently, we have deepened, dammed, and diverted rivers and streams so that they deliver the water to more useful places, or so that they provide better avenues for transportation. Schemes that alter or divert the flow of rivers have, in this age of environmental awareness, also become emotional issues that commonly bring those who de-
sire to keep the status quo into opposition with those who see benefit from change. Because water, as a measurable and often limited resource, is considered in terms of municipal service, industrial production, power generation, or crop growth, its availability has broad economic implications.

It is, of course, not possible to begin to evaluate all of the types of water transportation and diversion schemes that have been constructed. The following discussion treats only three major examples.

**Water for Transportation—The Tennessee-Tombigbee Waterway**

When we think of water as a resource, we generally consider only that which is actually used or consumed in daily life, in industry or in irrigation. Water is no less an important resource when it serves as an avenue for transportation. Thus, the world’s oceans and rivers have served as trade routes since before recorded history. In Italy, coastal rivers and estuaries were modified into canals for commerce; in England, a far-reaching canal system was built to facilitate transport of the coal and iron ore needed to fuel the Industrial Revolution. In the United States, the famed Erie Canal and many other waterways like it were built to provide efficient and inexpensive means of large-volume transport. In a similar manner, the great St. Lawrence Seaway, a channel with a series of locks, was constructed to permit the direct movement of commodities from the Great Lakes to the Atlantic along an otherwise non-navigable river.

Perhaps the two most famous water transport systems are the Suez Canal and the Panama Canal. The Suez, opened in 1869, provided a short sea route to the Far East from southern European ports. The Panama Canal, complet-
FIGURE 11.39 Salts can build up in soils as a result of water brought in for irrigation. Ultimately, the soils can become so salt-rich that they can no longer be used to grow food crops.

FIGURE 11.40 The Tennessee-Tombigbee Waterways, the largest project ever undertaken by the U.S. Army Corps of Engineers, has been both praised as an aid to economic development and criticized as a major waste of money. (From K.D. Underwood and F.D. Imsand, "Hydrology, Hydraulic and sediment considerations of the Tennessee-Tombigbee Waterway," Environmental Geology, vol. 7, 1985. Used with permission.)
ed in 1914, reduced the length of the route from Atlantic ports to Pacific ports by more than 15,000 kilometers (9400 miles).

Within the United States the construction of canals, dams, and diversions has, in the twentieth century, commonly been referred to as “pork barrel” politics and has been the purview of the U.S. Army Corps of Engineers. The latest, largest, most expensive, and most controversial of these projects is the Tennessee-Tombigbee Waterway (Figure 11.40). First discussed in the early 1800s, a plan was formulated in 1874 and finally authorized by Congress in 1946. Construction began in 1971; in January 1985 the 433-kilometer (234-mile) waterway with 10 locks that can lift ships 104 meters (341 feet) was completed and opened to traffic at a cost of nearly $2 billion. The Tennessee-Tombigbee, as it is called, greatly reduces the distance and time of river transport from the Ohio Valley to the Gulf Coast and has been heralded as one of the nation’s great achievements. It has also been considered an environmental disaster and an economic dilemma. The great canals noted above have had both political and economic impact; the effects of the Tennessee-Tombigbee remain to be seen.
BOX 11.4  The Death of a Lake—The Aral Sea

The Aral Sea, located astride the border between Kazakhstan and Uzbekistan in the Central Asian part of the former Soviet Union, has been referred to as “one of the planet’s most serious environmental and human tragedies.” In 1960 the Aral Sea was the world’s fourth largest lake—a beautiful body of water with a surface area of about 67,000 square kilometers (26,000 square miles) that supported a commercial shipping and thriving fishing industry. By 1993, the sea level had dropped more than 13 meters (40 feet), the surface area had decreased by about 50 percent, the volume fell by 73 percent, salinity tripled, shipping had ended, the fish had died, and the sea had been split in two much smaller bodies (Figure 11.F and Plate 59). What happened and why?

![Figure 11.F](image)

**Figure 11.F**  The surface area of the Aral Sea (black) has shrunk dramatically since 1960 and is projected to continue shrinking because of the diversion of the water from the Amudarya and Syrdarya Rivers for irrigation. See also Plate 59, which shows how the drop in the level has stranded ships many kilometers from the water. (From “The Shrinking Aral Sea,” P. Mckinlin, Geotimes, April 1994. Used with permission.)

Water for Drinking—The Los Angeles Aqueduct System

Out of the desert with its rocks, barren and awe-inspiring, its cactus-like sentinels of solitude, rose this Los Angeles—your city and mine. The magic touch of water quickened the desert into its flowering life—our city. And lest our city shrivel and die, we must have more water, we must build a great new aqueduct to the Colorado.

This statement by William Mulholland, the long-time water czar for Los Angeles, succinctly summarized the recurring plight of that city, this time in 1925, when it was re-
BOX 11.4  The Death of a Lake–The Aral Sea (continued)

For time immemorial, the Aral Sea had been fed by the waters of the Syr Darya and Amudarya Rivers. However, in the 1950s and 1960s, the Soviet Union decided to dramatically increase cotton production by expanding the area of Central Asia under irrigation and cultivation. The first step was to build a 1280 kilometers (800-mile-long) canal to divert large quantities of water from the Amudarya River to the southern part of the Kara Kum Desert. This was subsequently expanded into a complex network of 20 reservoirs and 60 canals that fed the water of the Amudarya and Syr Darya Rivers into (7.7 million hectares; 19 million acres) of cropland in one of the driest regions of Asia. The rivers that sustained the Aral Sea by feeding it 50 to 60 cubic kilometers (12 to 14 cubic miles) of fresh water per year had, by 1985, become totally dry. Subsequently, small amounts of inflow have occurred, but they have not been sufficient to reverse the effects of the diminished supplies.

The devastating effects of the diversion of the inflow are most visible in the change in the size and shape of the Aral Sea, as shown in Figure 11.4. Former ports, with now useless ships (Plate 59), lie as much as 32 kilometers (20 miles) from the shrinking shoreline. The rich schools of fish that once yielded 160 metric tons per day and supplied 10 to 15 percent of the Soviet Union’s freshwater catch are now totally gone because the salinity is nearly equal to that of ocean water. The volume has decreased approximately 75 percent as the water level has dropped more than 16 meters (50 feet) in the main body. The now-dry seafloor, subject to strong winds, has been the source of vast clouds of dust and salt that have blown onto and damaged the irrigated crops. Table 11.4 summarizes several of the data from 1960 extrapolated through 2000.

The devastation of the Aral Sea was completely predictable and demonstrates how easily and rapidly human activities can disrupt the environment in the pursuit of a resource. The hope of many scientists is that the lessons learned in the shrinking of the Aral Sea will mean that the same mistakes will not be repeated in other areas. In the United States, diversion of water from Mono Lake in eastern California to supply growing cities resulted in many of the same effects. However, in the mid-1990s, the water supplies began to be returned to Mono Lake in order to restore the lake to its previous conditions.

<table>
<thead>
<tr>
<th>Year</th>
<th>Surface level (meters)</th>
<th>Area (sq. km)</th>
<th>Volume (cu. Km)</th>
<th>Annual inflow Ave of previous 5 yrs. (cu. km)</th>
<th>Salinity (grams/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>53.41</td>
<td>66,900</td>
<td>1090</td>
<td>56.8</td>
<td>10</td>
</tr>
<tr>
<td>1971</td>
<td>51.05</td>
<td>60,200</td>
<td>925</td>
<td>45.0</td>
<td>11</td>
</tr>
<tr>
<td>1976</td>
<td>48.28</td>
<td>55,700</td>
<td>763</td>
<td>25.3</td>
<td>14</td>
</tr>
<tr>
<td>1993</td>
<td>36.89</td>
<td>30,953</td>
<td>279</td>
<td>5.0</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>small sea</td>
<td>39.91</td>
<td>2689</td>
<td>21</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>large sea</td>
<td>32.38</td>
<td>24,154</td>
<td>185</td>
<td>65-70</td>
</tr>
<tr>
<td></td>
<td>small sea</td>
<td>40.97</td>
<td>3,152</td>
<td>24</td>
<td>25</td>
</tr>
</tbody>
</table>

(250 miles) to the east. Land and water rights were acquired, sometimes by subterfuge, and construction began; by 1913 the $25 million aqueduct was completed and Owens Valley water flowed into Los Angeles.

By 1923 the growth of the population to more than one-half million brought the realization that still more water was needed. This time the Colorado River aqueduct system reached east and began to tap water dammed in Lake Havasu; the project was completed in 1941. Because Arizona did not use its full share of water as authorized by the Colorado River Compact (see p. 444), Los Angeles was allowed to temporarily take Arizona’s unused portion. With continued growth, more water was needed, and a second Owens Valley aqueduct was added in 1970.

Two circumstances have forced Los Angeles, in the 1980s, to again seek more water, this time to the north where there are plans for a $5 billion Peripheral Canal that would take water from the Sacramento River and pass it south via the California aqueduct. First, population has continued to grow and to require increased amounts of water; second, in 1985, Arizona completed the first part of the Central Arizona Project to supply Colorado River water from Lake Havasu to Phoenix and Tucson. Consequently, Arizona is reclaiming the Colorado River water it had allowed Los Angeles to use since 1941; its right to do so was upheld by the U.S. Supreme Court.

The water supply system for Los Angeles has some similarities with that for New York City (described on p. 431), but the legal and emotional ramifications of the former are far greater. Because of the abundance of water in the northeastern United States, New York’s use of water has negligible impact on the availability of water for others. In contrast, Los Angeles’s needs and claims on water supersede the availability of water for many others, including those who live where the surface waters originate. This has resulted in scores of lawsuits, bombings of aqueducts,
and, in recent years, concern about severe environmental effects. The continued growth of major cities such as Los Angeles in relatively water-poor areas will place greater demands on scarce or distant water supplies in the years ahead.

**Water for Irrigation — The Russian Water Diversion Scheme**

The steppes of Central Asia are similar to the Great Plains of North America in that they represent a great agricultural belt that in large areas receive insufficient water to produce to their full potential. This, coupled with constantly falling water levels and increasing salinities in the Caspian and Aral Seas in the 1980s, has led to renewed consideration of a Soviet-era water diversion scheme that would have been the largest engineering project of all time. The diversion would have reversed the flow of a dozen or more rivers that now flow north into the Arctic Ocean and deliver approximately 38 billion liters (9.1 billion gallons) of water to Southern European Russia and 60 billion liters (14 billion gallons) to southern Siberia. Such a plan (Figure 11.43) would require at least fifty years or so to complete and would displace tens of thousands of people from farms and towns along flooded valleys. The environmental effects of diverting so much water into arid areas and away from the Arctic Ocean are not known and are strongly debated; subsequently, the Russian government is reconsidering the diversion plan. Nevertheless, the Aral Sea continues to decline and will soon be reduced to a series of shallow hypersaline lakes.

**INTERNET INFORMATION SOURCES**

The listing given below is intended to provide some Internet sources to find more information on some of the topics covered in this chapter. These are merely starting points and will lead the reader to many other information sources. In addition, several key words are listed that can be used by search engines to find additional sites.

- [http://www.und.nodak.edu/instruct/eng/fkarner/pages/cycle.htm](http://www.und.nodak.edu/instruct/eng/fkarner/pages/cycle.htm)
- [http://www.epa.gov/seahome/groundwater/src/cycle.html#human](http://www.epa.gov/seahome/groundwater/src/cycle.html#human)
- Drinking water standards: [http://www.epa.gov/ogwdw/standards.html](http://www.epa.gov/ogwdw/standards.html)
- [http://www.epa.gov/OGWDW/mcl.html](http://www.epa.gov/OGWDW/mcl.html)
- Arsenic in Bangladesh: [http://bicn.com/acic](http://bicn.com/acic)
- Flooding: [http://www.fema.gov/library/floodf.htm](http://www.fema.gov/library/floodf.htm)
- Channelization: [http://www.ies.wisc.edu/research/ies900/kimchannelization.htm#introduction](http://www.ies.wisc.edu/research/ies900/kimchannelization.htm#introduction)
Kissimmee River:  http://riverwoods.ces.fau.edu/
                      Kissimmee/
http://www.sfwmdd.gov/erdc/krr/index.html
Drought:  http://enso.unl.edu/ndmc/index.html
http://enso.unl.edu/ndmc/watch/watch.htm
Colorado River system:  http://waterknowledge.colostate.edu/1948_uerc.htm
http://waterknowledge.colostate.edu/int_comp.htm
http://www.primenet.com/~alewis/ydp5.htm
http://www.yao.lc.usbr.gov/ydp5.htm
Desalination:  http://www.ida.bm/
Salt water intrusion:  http://water.usgs.gov/ogw/gwrf/saltwater/
http://www.ce.utexas.edu/crwr/watermarks/fall95/articleone.html

Search terms:

FIGURE 11.43  Russia has proposed a major water-diversion scheme that would reverse the direction of flow of water in rivers now flowing into the Arctic Ocean and take it into the drier steppe region and the Caspian Sea. The scheme, which has been much criticized because of the potential for environmental harm, exemplifies the large-scale types of diversions that are being more commonly considered for the redistribution of vital water resources.