10 Water: Process, Supply, and Use

Las Vegas, Nevada, a desert city, is a human-made oasis. (*Edward A. Keller*)

Availability of water is necessary for desert cities to flourish. Egyptian dynasties prospered when water from the Nile River was abundant and suffered famine during droughts. Shown here is a more modern pyramid and monument in one of America's newest playgrounds, also located near a mighty river, which in this case is the Colorado. The pyramid is a luxury hotel, and the city of Las Vegas, one of the most rapidly growing cities in the country, is growing, thanks in part to an abundance of nearby water that allows the development of casinos, water parks, and extravagant shows and outdoor fountains and gardens.

A major question facing people in many parts of the world today is how long will apparent abundant water supplies last as population continues to increase into the new millennium. It is feared that scarcity of fresh water that is safe from disease is a greatly underestimated resource issue that will face the world in coming decades. On a global basis, 70 percent of the world's fresh water that is derived from groundwater and surface water sources is used for agriculture, while another 20 percent is used for industry and 10 percent for residences. The two most populous countries in the world are China and India, and in these countries groundwater resources used to produce food are being used and degraded rapidly. Groundwaters are commonly mined, and levels of groundwater are receding in many locations at the rate of a meter or so per year. As water resources diminish, harvests of crops nourished by irrigation will diminish, perhaps producing food shortages. Undoubtedly, as we go into the twenty-first century, demand for water will increase and competition for limited water resources will likely become apparent.*

*Source: Brown, L. R., and Flavin, C. 1999. A new economy for a new century. In *State of the world 1999*, ed. L. Stark, pp. 3–21. New York: W. W. Norton.

LEARNING OBJECTIVES

Water is one of our most basic and important resources. Ensuring that we maintain an adequate safe supply of water is one of our most important environmental objectives. The lack of a pollution-free and disease-free water supply constitutes a continued serious environmental problem for billions of people in many regions of the world. In this chapter we will consider the topics of hydrology, water supply and use, water management, and water and ecosystems. Learning objectives of this chapter are:

- *To gain a modest appreciation for the global water resource.*
- *To understand why water is a unique fluid in our environment.*
- *To know the major storage compartments for water in the water cycle.*
- *To become familiar with the main factors that control surface runoff and sediment yield.*
- *To understand the basics of groundwater geology, including movement of groundwater and Darcy's law.*
- *To gain a modest acquaintance with the water budget of the United States.*
- *To understand the main types of water use.*
- *To be familiar with some of the major trends in water uses during the past 40 years.*
- *To be able to discuss some of the ways we can conserve our water resources.*
- *To be able to discuss some of the major principles associated with water management.*
- *To understand some of the environmental consequences of water resources development, including construction of dams and canals.*
- *To know the criteria for identifying a wetlands and to understand the environmental significance of wetlands and wetland loss.*

Web Resources

Visit the "Environmental Geology" Web site at www.prenhall.com/keller to find additional resources for this chapter, including:

- Web Destinations
- On-line Quizzes
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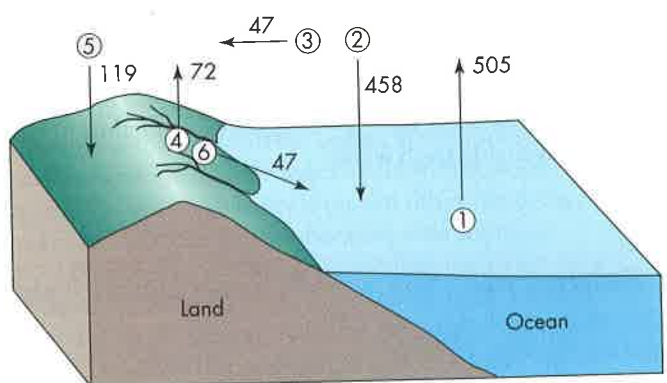
10.1 Water: A Brief Global Perspective

The global water cycle involves the movement of water from one of the earth's storage compartments to another. In its simplest form (diagrammed in Figure 10.1), the water cycle can be viewed as water moving from the oceans to the atmosphere, falling from the atmosphere as rain, and then returning to the oceans as surface runoff and subsurface flow or to the atmosphere by evaporation. The annual cyclic nature of this global movement of water is illustrated in Figure 10.1. Note that:

1. Where the annual volume of water transferred from the ocean (from evaporation) to the land (47,000 km^3) is balanced by the same volume returning by river and groundwater flow to the ocean (1).
2. The 505,000 km^3 per year of water evaporated from the oceans of the world is balanced by the sum of the water that falls as precipitation in the ocean (458,000 km^3) and the 47,000 km^3 of water that is transferred from the atmosphere to the land.
3. Evaporation of water from the land is 72,000 km^3 per year, and the sum of this and that transferred from the



▲ **FIGURE 10.1** Movement of water in the global water cycle. (Data from P. H. Gleick, 1993. *An introduction to global fresh water issues.* In Water in Crisis, *ed.* P. H. Gleick, 1993, *pp.* 3–12. New York: Oxford University Press.)

atmosphere (47,000 km^3 per year) is 119,000 km^3 per year that falls as precipitation on the land.

4. The 119,000 km^3 per year that falls as precipitation on the land, 60 percent (72,000 km^3 per year) evaporates, and 40 percent (47,000 km^3 per year) returns to the oceans as surface or groundwater runoff.

But the water that returns is changed because it carries with it sediment (gravel, sand, silt, clay) eroded from the land. The return flow also carries many chemicals (most of which are natural) but also includes many human-made and human-induced compounds, such as organic waste, nutrients, and thousands of chemicals used in our agricultural, industrial, and urban processes. In this chapter we will be particularly concerned with surface runoff and subsurface flow as they relate to human use.

On a global scale, water abundance is not a problem—the problem is water's availability in the right place at the right time in the right form. Water is a heterogeneous resource that can be found in liquid, solid, or gaseous form at a number of locations at or near the earth's surface. Depending upon the specific location of water, the residence time may vary from a few days to many thousands of years (Table 10.1). Furthermore, more than 99 percent of the earth's water is unavailable or unsuitable for beneficial human use because of its salinity (seawater) or its form and location (ice caps and glaciers). Thus, the water for which all the people on earth compete is much less than 1 percent of the total.

As the world's population and the industrial production of many goods increase, the use of water will also accelerate. Today, world per capita use of water is about 700 m^3/yr, and the total human use of water is 3850 km^3/yr. The per capita use in the United States is about 1850 m^3/yr, or more than 2.5 times the world per capita use. It is estimated that by the year 2000, total world use of water (with a decrease in per capita use due to better conservation) will nevertheless increase to 6000 km^3/yr—a significant fraction of the naturally available fresh water.

The total average annual water yield (runoff) from the earth's rivers and groundwater is approximately 47,000 km^3 (Table 10.2), but its distribution is far from uniform. Some runoff occurs in almost uninhabited regions, such as Antarctica, which produces 2310 km^3, or about 5 percent of the earth's total runoff. South America, which includes the largely uninhabited Amazon Basin, provides 12,200 km^3, or about one-fourth of the total runoff. The total runoff from North America is about two-thirds of that for South America, or 8180 km^3. Unfortunately, much of the North American runoff occurs in sparsely settled or uninhabited regions, particularly in the northern parts of Canada and Alaska.

Compared with other resources, water is used in tremendous quantities. In recent years the total amount of water by volume used on the earth annually has been approximately 1000 times the world's total production of minerals, including petroleum, coal, metal ores, and nonmetals (2). Because of its great abundance, water is generally a very inexpensive resource. But because the quantity and the quality of water available at any particular time are highly variable, statistical statements about the cost of water on a global basis are not particularly useful. Shortages of water have occurred and will continue to occur with increasing frequency, leading to serious economic disruption and human suffering (3).

The U.S. Water Resources Council has estimated that water use in the United States by the year 2020 may exceed surface water resources by 13 percent. As early as 1965, 100 million people in the United States used water that had already been used once before, and by the end of the century most of us will be using recycled water. How can we manage our water supply, use, and treatment to maintain adequate supplies?

10.2 Water as a Unique Liquid

To understand water in terms of supply, use, pollution, and management, we first need a modest acquaintance with some of water's characteristics. Water is a unique liquid;

Table 10.1 The world's water supply (selected examples)

Location	Surface Area (km^2)	Water Volume (km^3)	Percentage of Total Water	Water: Estimated Average Residence Time
Oceans	361,000,000	1,230,000,000	97.2	Thousands of years
Atmosphere	510,000,000	12,700	0.001	9 days
Rivers and streams	—	1,200	0.0001	2 weeks
Groundwater: shallow, to depth of 0.8 km	130,000,000	4,000,000	0.31	Hundreds to many thousands of years
Lakes (fresh water)	855,000	123,000	0.009	Tens of years
Ice caps and glaciers	28,200,000	28,600,000	2.15	Up to tens of thousands of years and longer

Source: Data from U.S. Geological Survey.

Table 10.2 Water budgets for the continents

Continent	Precipitation mm/yr (km³)		Evaporation mm/yr (km³)		Runoff k³/yr
North America	756	(18,300)	418	(10,000)	8,180
South America	1,600	(28,400)	910	(16,200)	12,200
Europe	790	(8,290)	507	(5,320)	2,970
Asia	740	(32,200)	416	(18,100)	14,100
Africa	740	(22,300)	587	(17,700)	4,600
Australia and Oceania	791	(7,080)	511	(4,570)	2,510
Antarctica	165	(2,310)	0	(0)	2,310
Earth (entire land area)	800	(119,000)	485	(72,000)	47,000*

*Surface runoff is 44,800; groundwater runoff is 2,200.

Source: Data from I.A. Shiklomanov, 1993. World fresh water resources. In *Water in Crisis*, ed. P. H. Gleick, 1993, pp. 3–12. New York: Oxford University Press.)

without it, life as we know it would be impossible. Every water molecule contains two atoms of hydrogen and one of oxygen. The chemical bonds that hold the molecule together are *covalent*, meaning that each hydrogen atom shares its single electron with the oxygen atom, and the oxygen atom shares its outermost electrons with the hydrogen atom. Although the molecule is electrically neutral (having no net positive or negative charge), the hydrogen end of the molecule is more positively charged, and the oxygen end is more negatively charged, because the electrons, which are negatively charged, are somewhat closer to the oxygen than to the hydrogen. A molecule with one end more negative and the other more positive is called *dipolar*.

The fact that water is dipolar accounts for many of its important properties and for how it reacts in the environment. For example, water molecules are attracted to each other (more positive ends to more negative ends), so they produce thin films, or layers of water molecules, between and around particles important in the movement of water in the unsaturated (vadose) zone above the groundwater table. This process is one of *cohesion*. Water molecules may also be attracted to solid surfaces *(adhesion)*; in particular, the more negative (oxygen) ends of the water molecule are attracted to positive ions such as sodium, calcium, magnesium, and potassium. Because clay particles tend to have a negative charge, they attract the more positive (hydrogen) end of water molecules and so become hydrated. Finally, the dipolar nature of the water molecule is responsible for producing surface tension: Water molecules are more attracted to each other than they are to molecules of air. Surface tension is extremely important in many physical and biological processes involving water moving through small openings and pore spaces (4).

Water is often referred to as the universal solvent. Its ability to dissolve a wide variety of substances (from simple salts to minerals and rocks) makes it an essential and major component of living matter. Water is particularly important in the chemical weathering of rocks and minerals that, along with physical and biochemical processes, initiates soil formation.

Among common substances, water is the only one with a solid form lighter than its liquid form, which explains why ice floats. If ice were heavier than liquid water, it would sink. Although this would be safer for ships traveling in the vicinity of icebergs, properties of the biosphere would be much different from what they are. Rivers, lakes, and the ocean would freeze from the bottom up.

Another important feature of water is its *triple point*, the temperature and pressure at which its three phases—solid (ice), liquid (water), and gas (water vapor)—can exist together. The triple point of water occurs naturally at or near the surface of the earth. This has important implications for transfer of water from the ocean to the atmosphere and biosphere via the **water cycle.** The world would be a much different place if water couldn't evaporate from the oceans to the atmosphere at near-surface conditions (the water cycle would stop). The triple point for some substances, on the other hand, can only be achieved on earth under laboratory conditions.

Water has a tremendous moderating effect on the environment because of its high *specific heat*. Specific heat is defined as the amount of heat (measured in calories) required to raise the temperature of one gram (g) of a substance one Celsius degree. The specific heat of water is 1.0 calorie/g, as compared to the specific heats of most other solvents, which are about 0.5 calories/g. Thus, compared to other common liquids, water has the greatest capacity to absorb and store heat. This storage of heat helps moderate the environment, particularly near large bodies of water.

10.3 Surface Runoff and Sediment Yield

Surface runoff has important effects on erosion and the transport of materials. Water moves materials either in a dissolved state or as suspended particles, and surface water

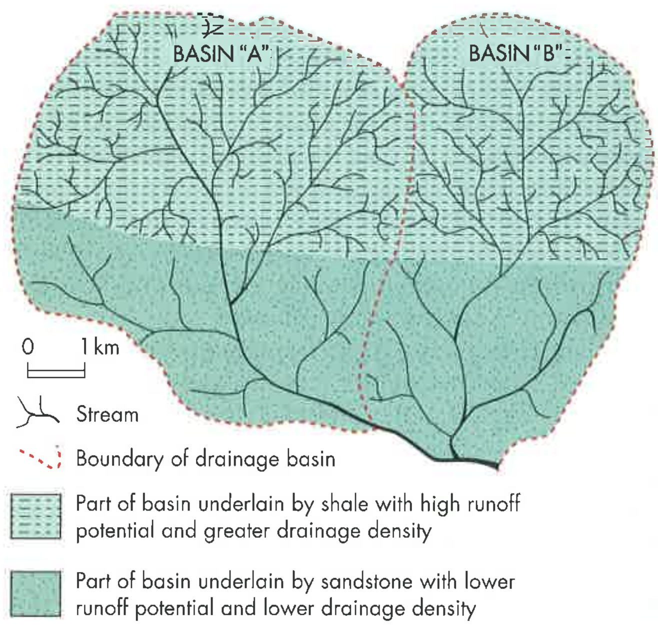
(a)

(b)

▲ **FIGURE 10.2** (a) Raindrop falling in a cornfield causes soil particles to be lifted into the air, initiating the erosion process; (b) surface runoff often causes the formation of small gulleys such as those shown there. (*(a) Runk-Schoenberger/Grant Heilman Photography, Inc.; (b) courtesy of U.S. Department of Agriculture*)

can dislodge soil and rock particles on impact (Figure 10.2). The number and size of the suspended particles moved by surface waters depend in part on the volume and depth of the water and the velocity of flow. The faster a stream or river flows, the larger the particles it can move and the more material is transported. Therefore, the factors that affect runoff also affect sediment erosion, transport, and deposition.

The flow of water on land is divided by watersheds. A **watershed,** or **drainage basin** (Figure 10.3), is an area of ground in which any drop of water falling anywhere in it will leave in the same stream or river. (This definition assumes that the drop is not consumed by the biosphere, evaporated, stored, or transported out of the watershed by subsurface flow.) Large drainage basins can be subdivided into smaller ones. For example, the Mississippi River drainage basin drains about 40 percent of the United States but contains many subbasins such as the Ohio, Missouri, and many others. Drainage basins such as the Ohio may be further divided into smaller basins. Figure 10.3 shows two drainage basins (A and B) that are side by side. Two drops of rain separated by only centimeters along the boundary of a major continental divide may end up a few weeks later in different oceans thousands of kilometers apart. We may also think of a drainage basin as the land area that contributes its runoff to a specific drainage net, the set of channels that makes up a drainage basin. Thus, the drainage basin refers to an area of land, whereas the drainage net refers to the actual river and stream channels in the drainage basin.



▲ **FIGURE 10.3** Two drainage basins. Water falling on one side of the central boundary will drain into Basin A; on the other side, water will drain into Basin B. In this case, the streams from both basins eventually converge.

Factors Affecting Runoff

The amount of surface-water runoff and the amount of sediment carried by the runoff vary significantly from one drainage basin and river to another. The variation results from geologic, physiographic, climatic, biologic, and land-use characteristics of a particular drainage basin and variations of these factors with time. Even the most casual observer can see the difference in the amount of sediment carried by the same river in flood state and at low flow, since floodwaters are usually more muddy.

Geologic Factors The principal geologic factors affecting surface-water runoff and sedimentation include rock and soil type, mineralogy, degree of weathering, and structural characteristics of the soil and rock. Fine-grained, dense, clay soils and exposed rock types with few fractures generally allow little water to move downward and become part of the subsurface flows. The runoff from precipitation falling on such materials is comparatively rapid. Conversely, sandy and gravelly soils, well-fractured rocks, and soluble rocks absorb a larger amount of precipitation and have less surface runoff. These principles are illustrated in Figure 10.3. The upper parts of basins A and B are underlain by shale, and the lower parts are underlain by sandstone. Because the shale has a greater potential to produce runoff than the more porous sandstone, the *drainage density* (length of channel per unit area) is much greater in the shale areas than in the sandstone areas.

Physiographic Factors Physiographic factors that affect runoff and sediment transport include shape of the drainage basin, relief and slope characteristics, and the orientation of the stream basins to prevailing storms.

The *shape of the drainage basin* is greatly affected by the geologic conditions. For example, drainage may develop along weak, crushed rock associated with fracture zones, producing a long, narrow drainage basin. One principal effect of basin shape on runoff and sedimentation is its role in governing the rate at which water is supplied to the main stream. Basins that are lengthy and narrow and have a long main channel with many short tributaries receive flow from the tributaries much more rapidly than do basins that have a shorter main channel with long, sinuous tributaries. Rivers in drainage basins that experience rapid rise in flow during or after precipitation are said to be "flashy" and can produce flash floods.

The factors of *relief* and *slope* are interrelated: The greater the relief (the difference in elevation between the highest and lowest points of a drainage basin or a river or any landform of interest), the more likely the stream is to have a steep gradient and a high percentage of steep, sloping land adjacent to the channel. Relief and slope are important because they affect not only the velocity of water in a stream but also the rate at which water infiltrates the soil or rock and the rate of overland flow, both of which affect the rate at which surface and subsurface runoff enters a stream.

Orientation of the stream basin to prevailing storms influences the rate of flow, the peak flow, the duration of surface runoff, and the amount of transpiration and evaporation losses. The latter is a factor because basin orientation affects the amount of heat received from the sun as well as exposure to prevailing winds.

Climatic Factors Climatic factors affecting runoff and sediment transport include the type of precipitation that occurs, the intensity of the precipitation, the duration of precipitation with respect to the total annual climatic variation, and the types of storms (whether cyclonic or thunderstorm). In general, discharge of large volumes of water and sediment is associated with infrequent high-magnitude storms that occur on steep, unstable topography underlain by soil and rocks with a high erosion potential.

Biologic Factors Vegetation, animals, and soil organisms all influence runoff and sediment yield. *Vegetation* is capable of affecting stream flow in several ways:

- Vegetation may decrease runoff by increasing the amount of rainfall intercepted and removed by evaporation. Rainfall that is intercepted by vegetation also falls to the ground more gently and is more likely to infiltrate the soil. Experimental clear-cutting of forested watersheds has been shown to increase the stream flow due to decreased evapotranspiration (water used by the trees and released to the atmosphere) following timber harvesting (5).
- Decrease or loss of vegetation due to climatic change, wildfire, or land use will increase runoff and production of sediment. Figure 10.4 shows the response of a small drainage basin following a wildfire in southern California. Figure 10.4a depicts the channel shortly following the fire, which occurred in the summer. These are assumed to be the conditions (as the channel was) before the fire as no storms or other events occurred. Following a moderate rainstorm and runoff event, the entire channel filled with fine gravel derived from the burned slopes (Figure 10.4b). Following another moderate rainstorm and flow, the sediment in the channel was transported out of the system and the channel looked much as it did after the fire before the first storm (Figure 10.4c). What happened? The fire removed vegetation on slopes, and loose material (sediment) that had accumulated on the slopes—but held there by the vegetation before the fire—moved downslope toward the stream channel. This process of dry transport of loose material is called *dry ravel*. When the first rains fell on the burned slopes, runoff was high and a voluminous amount of sediment moved down hillslopes to the stream channel. The stream flow was not sufficient to transport all the sediment, and so much of it was deposited in the channel (Figure 10.4b). Importantly, much of the sediment from the hillslope was removed by the first storm, so when the next storm struck, there was much less sediment carried from hillslopes to the stream. Runoff of water from the burned hillslopes produced lots of stream flow, which scoured the material earlier deposited in the channel. Thus, the effect of the wildfire was to cause a major flushing of sediment from burned slopes out of the drainage basin. This is a common response following wildfire. Less commonly, large debris flows may be produced if intense precipitation of sufficient duration falls on burned slopes containing abundant coarse debris (sediment) (6).
- Streamside vegetation increases the resistance to flow, which slows down the passage of floodwater.
- Streamside vegetation retards stream-bank erosion because its roots bind and hold soil particles in place.
- In forested watersheds, large organic debris (stems and pieces of woody debris) may profoundly affect

(a)

(b)

(c)

▲ **FIGURE 10.4** (a) A small stream channel in southern California shortly after a wildfire that burned vegetation in the drainage basin. Some trees near the channel survived the fire. (b) The scene after the first winter storm. Note the voluminous amount of sediment deposited. (c) After the second winter storm, which scoured the channel. Note the channel looks much as it did following the fire. See text for further explanation. (*Edward A. Keller*)

stream-channel form and process. In steep mountain watersheds, many of the pool environments important for fish habitat may be produced by large organic debris.

Animals affect streams by removing vegetation or burrowing. Large grazing mammals can damage streamside environments, causing bank-erosion problems. Animals burrowing through flood-control levees can start erosion problems that eventually lead to failure of the levees.

Soil organisms alter the physical structure of the soil, which sometimes results in greater percolation of water into the soil, reducing runoff and erosion. Plant roots and burrowing animals can produce macropores (large openings) in soil that can greatly increase the rate at which water moves through soil. Soils with a high organic content tend to be relatively cohesive—they reduce surface erosion and tend to hold water tenaciously—compared to sandy soils, which have low cohesion, high porosity, and high permeability.

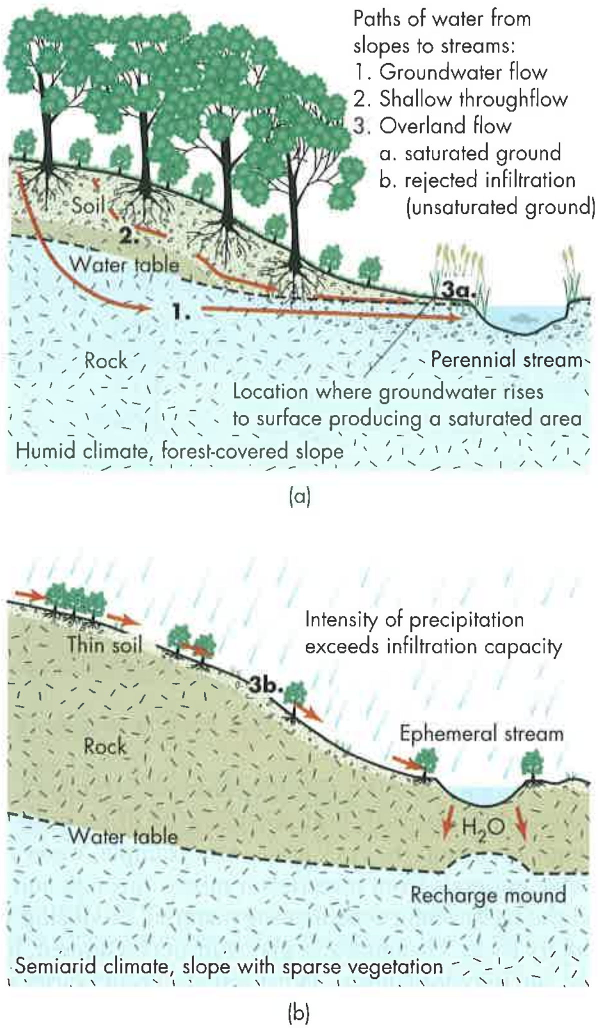
Runoff Paths

We have seen that runoff is quite variable and depends upon geologic, physiographic, climatic, and biologic conditions. Under natural conditions with continuous forest cover, the direct surface runoff shown in Figure 10.2 is unusual because trees and lower vegetation intercept the precipitation. In such cases water can easily infiltrate the soil on hillslopes, and runoff is by way of **throughflow,** which is a shallow subsurface flow above the groundwater table (Figure 10.5a). An exception may occur near streams and in hillslope depressions if the groundwater table rises to the surface. Such saturated areas can produce surface runoff even in humid climates with good vegetation cover (point 3a, Figure 10.5a). Areas that are saturated tend to expand and contract, being larger during the time of spring snowmelt than in the late summer or fall, when precipitation is less. In disturbed areas, areas with sparse vegetation cover, semiarid lands, tropical and subtropical areas with clay-rich soil that retards surface infiltration of water, and areas with such land uses as row crops or urbanization, **overland flow** is produced because the intensity (rate) of precipitation is greater than the rate at which water infiltrates the ground (Figure 10.5b).

Thus, we can identify three major paths by which water on slopes can be transported from hillslopes to the stream environment and exported from the drainage basin: overland flow, throughflow, and **groundwater flow** (Figure 10.5a). Groundwater flow is discussed in detail in the next section. Understanding potential paths of runoff for a particular site or area is critical in evaluating hydrologic impacts of projects involving land-use changes. Loss of vegetation and soil compaction during urbanization, for example, will produce more overland flow (point 3b, Figure 10.5b), as will land-use change from forest to row crops.

Sediment Yield

Variations in the natural **sediment yield** (volume or mass of sediment per unit time) for relatively small river basins are listed on Table 10.3. The amount of sediment carried by rivers as part of their work within the rock cycle varies with



▲ **FIGURE 10.5** Paths of water from slopes to streams: (a) on a humid, forest-covered slope, and (b) in a semiarid climate on a slope with sparse vegetation.

geologic, climatic, topographic, physical, vegetative, and other conditions (recall our earlier discussion of wildfire). Hence, some rivers are consistently and noticeably different in their clarity and appearance, as can be inferred from Table 10.4. Although this table reflects varying degrees of human influence, it demonstrates the sizable variations of sediment load per unit area in various parts of the world. For instance, on the average, the Lo River of China carries nearly 200 times more suspended load than does the Nile River of Egypt. In the United States, the Mississippi is not as "muddy" as the Missouri and the Colorado rivers.

The general relationship between size of drainage basin and sediment load suggests that, as basin size increases, the sediment yield per unit area decreases (Table 10.5). This relationship results from the increase in probability of sediment storage and deposition with increased basin size, the fact that smaller basins tend to be steeper (which increases the energy available for erosion and transport of sediment), and the decreased probability of total basin coverage by a single storm event with increased basin size.

Table 10.3 Estimated ranges in sediment yields from drainage areas of 260 km^2 or less

	Estimated Sediment Yield (metric tons/km^2/yr)[a]		
Region	**High**	**Low**	**Average**
North Atlantic	4,240	110	880
South Atlantic-Gulf	6,480	350	2,800
Great Lakes	2,800	40	350
Ohio	7,391	560	2,780
Tennessee	5,460	1,610	2,450
Upper Mississippi	13,660	40	2,800
Lower Mississippi	28,760	5,460	18,220
Souris-Red-Rainy	1,650	40	175
Missouri	23,470	40	5,250
Arkansas-White-Red	25,760	910	7,710
Texas-Gulf	8,140	320	6,310
Rio Grande	11,700	530	4,550
Upper Colorado	11,700	530	6,310
Lower Colorado	5,670	530	2,100
Great Basin	6,240	350	1,400
Columbia-North Pacific	3,850	120	1,400
California	19,510	280	4,550

[a]The range in high to low values reflects different years with different discharges and ability to erode and transport sediment.

Source: *The Nation's Water Resources*. Water Resources Council, 1968.

10.4 Groundwater

The major source of groundwater is precipitation that infiltrates the surface to enter and move through the top of the **vadose zone** (Figure 10.6). The vadose zone includes all earth material above the water table (for example, soil, alluvium, or rock). Water that infiltrates from the surface may move downward through the vadose zone, which is seldom saturated. Until recently, the vadose zone was called the *unsaturated zone*, but we now know that some saturated areas may exist there at times as water moves through. The vadose zone has special significance because potential pollutants infiltrating at the surface must percolate through the vadose zone before they enter the saturated zone below the water table. Thus, in environmental subsurface monitoring, the vadose zone is an area of early warning for potential pollution to groundwater resources.

Water that percolates through the vadose zone may enter the groundwater system, or **zone of saturation,** where saturated flow occurs. The upper surface of this zone is the **water table.** The **capillary fringe** just above the water table is a belt of variable thickness where water is drawn up by capillary action, which is due both to the attractive force between water and the surfaces of earth materials, and to surface tension (attraction of water molecules to each other).

Table 10.4 Some major rivers of the world ranked by sediment yield per unit area

River	Drainage Basin (10^3 km^2)	Sediment Load per Year (tons/km^2)
Amazon	5,776	63
Mississippi	3,222	97
Nile	2,978	37
Yangtze	1,942	257
Missouri	1,370	159
Indus	969	449
Ganges	956	1,518
Mekong	795	214
Yellow	673	2,804
Brahmaputra	666	1,090
Colorado	637	212
Irrawaddy	430	695
Red	119	1,092
Kosi	62	2,774
Ching	57	7,158
Lo	26	7,308

Source: Data from Holman, 1968.

Table 10.5 Arithmetic average of sediment-production rates for various groups of drainage areas in the United States

Watershed-Size Range (km^2)	Number of Measurements	Average Annual Sediment-Production Rate (m^3/km^2)
Under 25	650	1,810.3
25–250	205	762.2
250–2,500	123	481.2
Over 2,500	118	238.2

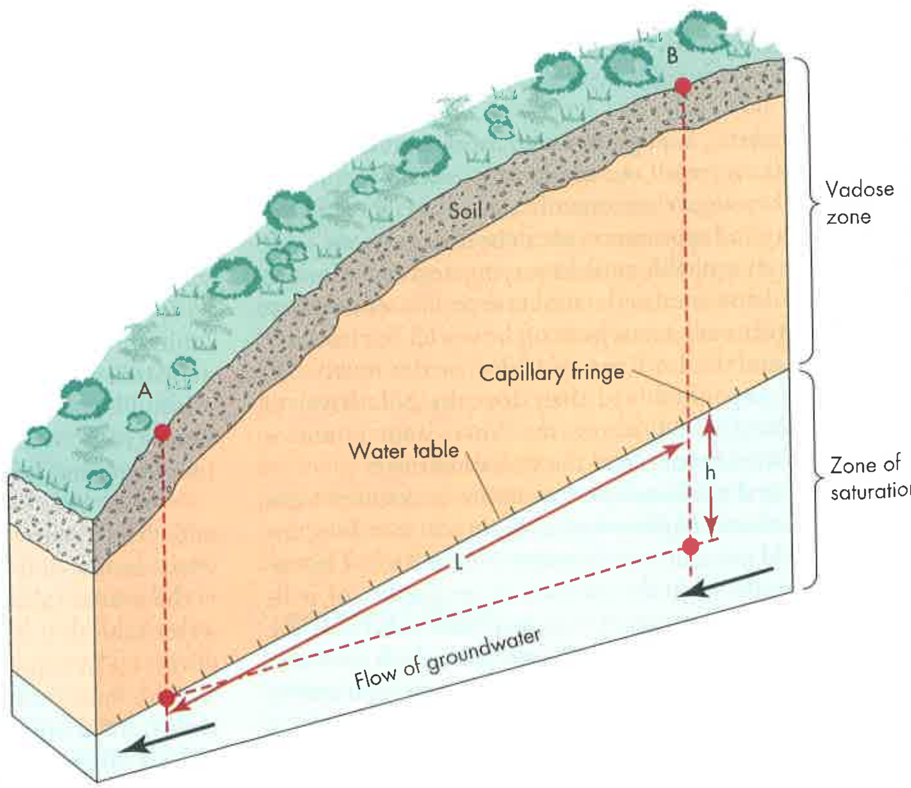
Note: Data illustrate that, as the size of a drainage basin (watershed) increases, the sediment production per unit area decreases.

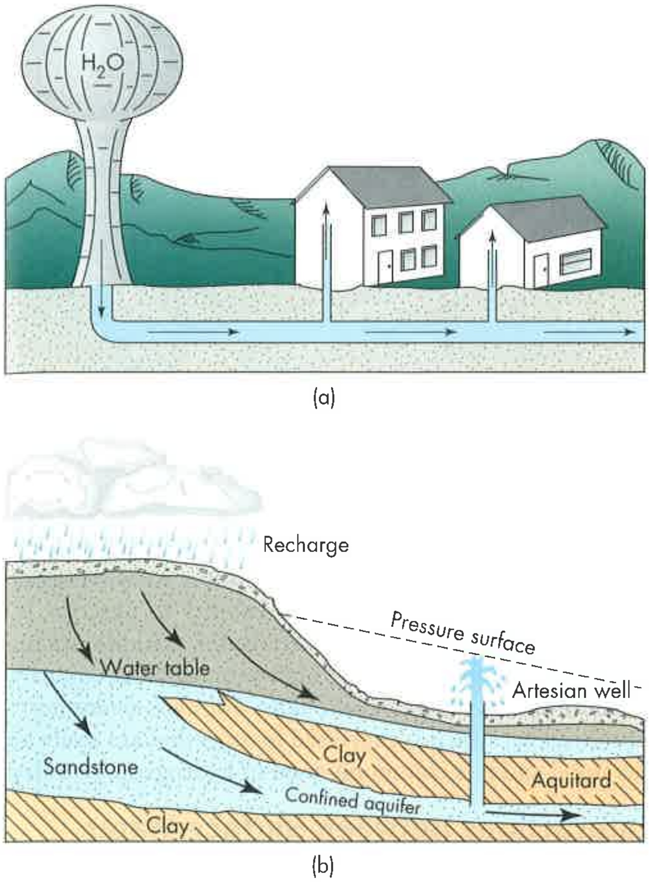
Source: From *Handbook of Applied Hydrology*, by Ven Te Chow. Copyright © 1964 by Mc-Graw Hill. Used with permission of McGraw-Hill Book Company.

In addition to precipitation, other sources of groundwater include water that infiltrates from surface waters, including lakes and rivers, artificial recharge (surface water deliberately injected into the groundwater system), stormwater retention or recharge ponds, agricultural irrigation, and wastewater treatment systems, such as cesspools and septic tank drain fields.

Movement of water into the zone of saturation and through earth materials is an integral part of both the hydrologic cycle and the rock cycle. For example, water may dissolve minerals from materials it moves through and deposit them elsewhere as cementing material, producing sedimentary rocks. Groundwater may transport sediment, heat, gases, and microorganisms. What actually occurs varies with the chemical and physical characteristics of the water, soil,

▶ **FIGURE 10.6** Generalized diagram showing zones of groundwater, capillary fringe, and water table.





▲ **FIGURE 10.7** Development of an artesian well system. In (a), water rises in homes due to pressure created by water level in the tower. If friction in pipes is small, there will be little drop in pressure. As shown in (b), the pressure surface in natural systems declines away from the source because of friction in the flow system, but water may still rise above the surface of the ground if an impervious layer such as clay is present to cap the groundwater.

▲ **FIGURE 10.8** Discharge of groundwater from Fern spring at the southern end of Yosemite Valley, California. This spring emerges like many others at the base of a hillslope. The width of the small stream emerging from the spring pool in a short cascade or falls is about 2 m. (*Edward A. Keller*)

and rock as the water infiltrates through the biologic and soil-horizon environments above the water table and moves through the groundwater system below the water table.

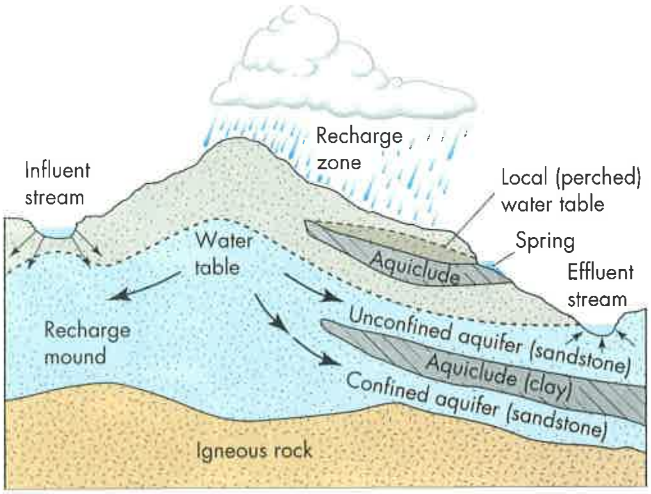
Aquifers

A zone of earth material capable of supplying groundwater at a useful rate from a well is called an **aquifer.** Gravel, sand, soils, and fractured sandstone, as well as granite and metamorphic rocks with high porosity due to connected open fractures, are good aquifers if groundwater is present. A zone of earth material that will hold water but not transmit it fast enough to be pumped from a well is called an **aquiclude** or **aquitard.** Aquitards often form a *confining layer* through which little water moves. Clay soils, shale, and igneous or metamorphic rocks with little interconnected porosity and/or fractures are likely to form aquitards.

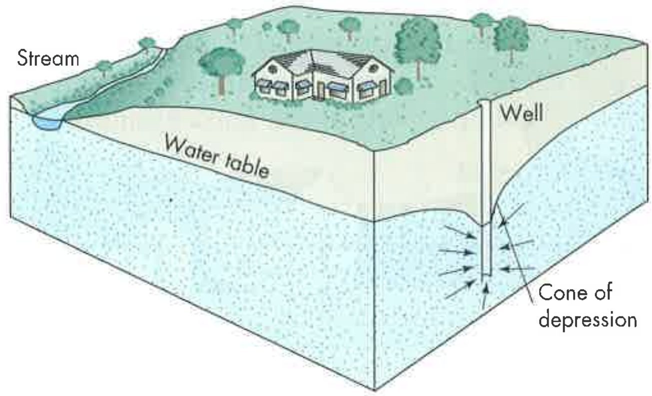
An aquifer is called an **unconfined aquifer** if there is no confining layer restricting the upper surface of the zone of saturation at the water table. If a confining layer is present, the aquifer is called a **confined aquifer,** and the water beneath it may be under pressure, forming **artesian** conditions. These conditions are analogous in their effect to a water tower that produces water pressure for homes (Figure 10.7a). Water in artesian systems tends to rise to about the height of the **recharge zone** (the zone where precipitation infiltrates the surface to move down to the groundwater system), creating an **artesian well** (Figure 10.7b).

In a more general sense **groundwater recharge** is any process that adds water to the aquifer and can be natural infiltration or human-induced as, for example, leakage and infiltration from a broken water line. **Groundwater discharge** is any process that removes groundwater from an aquifer. Included is natural discharge from a **spring** that is present where water flowing in an aquifer intersects the surface of the earth. Spring discharge can form the beginning of a stream or river (Figure 10.8). Groundwater discharge also occurs when water is pumped from a well. Both confined and unconfined aquifers may be found in the same area (Figure 10.9).

When water is pumped from a well, a **cone of depression** forms in the water table or artesian pressure surface (Figure 10.10). A large cone of depression can alter the direction in which groundwater moves within an area. Overpumping of an aquifer causes the water level to lower continuously with time, which necessitates lowering the pump settings or drilling deeper wells. These adjustments are often costly, and they may or may not work, depending



▲ **FIGURE 10.9** An unconfined aquifer, a local (perched) water table, and influent and effluent streams.



▲ **FIGURE 10.10** Cone of depression in water table resulting from pumping water from a well.

on the hydrologic conditions. For instance, continued deepening to correct for overpumping of wells that tap igneous and metamorphic rocks is limited. Water from these wells is pumped from open fracture systems that tend to close or diminish in number and size with increasing depth. Also, the quality of groundwater may be degraded if it is extracted from deeper water containing more dissolved minerals.

Groundwater Movement

Both the rate and the direction of groundwater movement depend upon the gradient of the water table and the properties of the materials present. The **hydraulic gradient** in the simplest cases for an unconfined aquifer is approximately the slope of the water table (see Figure 10.6). The ability of particular material to allow water to move through it is called its **hydraulic conductivity,** which is expressed in units such as meters per day. Expressing the relationship of hydraulic gradient and hydraulic conductivity to groundwater flow quantitatively allows us to solve many problems involving groundwater (see *Putting Some Numbers On Groundwater Flow*).

The hydraulic conductivity of an earth material is a function of both the properties of the material (such as particle diameter, size of pores, and how interconnected the pore spaces are) and the properties of the fluid moving through it (such as viscosity and density). The percentage of void (empty) space in soil or rock is called its **porosity** and depends on the nature and extent of its primary (intergranular) and secondary (fracture) openings. Table 10.6 shows the porosity and hydraulic conductivity of some common earth materials. Notice that some of the most porous materials, such as clay, have a very low hydraulic conductivity. Although clay has a great deal of pore space because of its small, flat particles, the individual openings are very small and hold water tenaciously.

The term *permeability* is also used as a measure of the ability of an earth material to transmit fluid, but only in terms of the properties of that material (not the properties of the fluid). In talking about groundwater, we will use both hydraulic conductivity and permeability to describe hydraulic properties of earth materials; for example, we may say that gravel and sands have high permeabilities compared to silt and clay. However, the term *hydraulic conductivity* is preferred because it is expressed in units that are easily understood and it is commonly used in hydrogeology today.

Interactions Between Surface Water and Groundwater

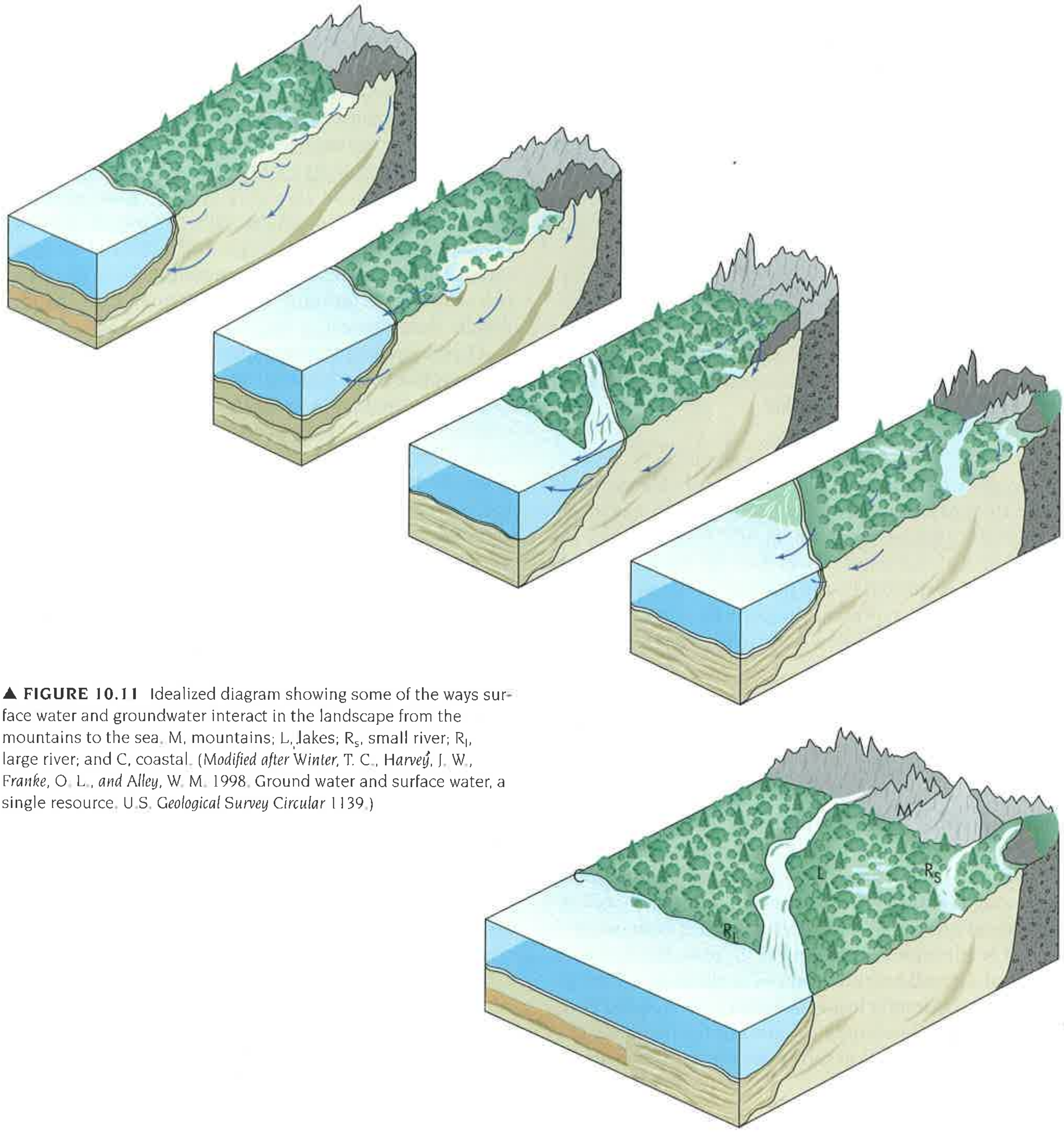
Interactions between surface water and groundwater are so interrelated that we need to consider both as part of the same resource (Figure 10.11) (7). Nearly all natural surface water environments such as rivers, lakes, and wetlands, as well as human-constructed water environments such as

Table 10.6 Porosity and hydraulic conductivity of selected earth materials

Material	Porosity (%)	Hydraulic Conductivity[a] (m/day)
Unconsolidated		
Clay	45	0.041
Sand	35	32.8
Gravel	25	205.0
Gravel and sand	20	82.0
Rock		
Sandstone	15	28.7
Dense limestone or shale	5	0.041
Granite	1	0.0041

[a]In older works, may be called coefficient of permeability.

Source: Modified after Linsley, Kohler, and Paulhus, *Hydrology for Engineers* (New York: McGraw-Hill, 1958. Copyright © 1958 by McGraw-Hill Book Company. Used by permission of McGraw-Hill Book Company.)



▲ **FIGURE 10.11** Idealized diagram showing some of the ways surface water and groundwater interact in the landscape from the mountains to the sea. M, mountains; L, lakes; R_s, small river; R_l, large river; and C, coastal. (*Modified after* Winter, T. C., Harvey, J. W., *Franke*, O. L., *and* Alley, W. M. 1998. Ground water and surface water, a single resource. U.S. *Geological Survey Circular* 1139.)

reservoirs, have strong linkages with groundwater. Withdrawal of groundwater by pumping from wells can reduce stream flow, lower lake level, reduce water in wetlands, or change the quality of surface water (when groundwater discharges at the surface from springs or seeps into streams, rivers, or ponds). Conversely, withdrawal of surface water can deplete groundwater resources or change the quality of the groundwater (for example, reduced groundwater recharge may result in increasing the concentration of dissolved constituents in the groundwater that otherwise would be diluted by mixing with infiltrated surface water). Finally, pollution of either surface water or groundwater can result in pollution of groundwater or surface water, respectively. As a result, groundwater management requires that the linkages between surface water and groundwater be known and understood (7).

Figure 10.9 shows some of the interesting interactions between surface water and groundwater. In particular, two types of streams may be defined. **Effluent streams** tend to be perennial, that is, to flow all year. During the dry season, groundwater seeps into the channel, maintaining stream flow (Figure 10.9, right). **Influent streams** are everywhere along their channel above the groundwater table and only flow in direct response to precipitation. Water from influent streams

PUTTING SOME NUMBERS ON Groundwater Flow

In 1856 an engineer named Henry Darcy was working on the water supply for Dijon, France. He performed a series of important experiments that demonstrated that the discharge *(Q)* of groundwater may be defined as the product of the cross-sectional area of flow *(A)*, the hydraulic gradient *(I)*, and the hydraulic conductivity *(K)*. Thus,

$$Q = KIA$$

The unit on each side of the equation is a volumetric flow rate (such as cubic meters per day), and this relationship is known as **Darcy's law**. The quantity $Q/A = KI$ is the **Darcy flux** *(v)*. We may say that

$$v = Q/A \text{ or } Q = vA$$

Although v has the units of a velocity, the Darcy flux is only an apparent velocity. To determine the actual velocity of groundwater in an aquifer *(vx)* we must remember that the water moves through pore spaces, so its velocity is affected by the porosity of the aquifer material. If we let n represent the porosity, then the actual cross-sectional area of flow is An, and it follows from $Q = vA$ that

$$vx = Q/An = v/n \text{ or } vx = KI/n.$$

The actual velocity vx is about three times the Darcy flux (assuming an average value of $n = 0.33$).

The driving force for groundwater flow is called the **fluid potential** or **hydraulic head,** which at the point of measurement is the sum of the elevation of the water (elevation head) and the ratio of the fluid pressure to the unit weight of water (pressure head). For our simple example in Figure 10.6, the pressure head at both points A and B is atmospheric (defined as 0); thus, the hydraulic heads at A and B are their respective elevations. The difference in hydraulic heads between points A and B *(h)* divided by the flow length *(L)* gives us the hydraulic gradient *(I)*. The condition shown for Figure 10.6 is an unconfined aquifer. If a confining layer is present, then the fluid pressure must be considered in the calculation of the hydraulic gradient. However, Darcy's law still applies.

Groundwater always moves from an area of higher hydraulic head to an area of lower hydraulic head and may therefore move down, laterally, or upward, depending upon local conditions. The water in Figure 10.7 flows upward at the artesian well because the hydraulic head below the clay confining layer is greater than the hydraulic head above it.

Darcy's law has many important applications to groundwater problems. For example, consider an area underlain by sedimentary rocks with a semiarid climate. The area is dissected by a river system in a valley approximately 4 km wide. Alluvial deposits in the valley form an aquifer, and two wells have been drilled approximately 1 km apart in the down-valley direction (Figure 10.A, part a). A cross-valley section between the wells (Figure 10.A, part b) shows that the saturated zone is 25 m thick, consists of sand and gravel, and has a hydraulic conductivity of 100 m/day (1.2×10^{-3} m/sec). Porosity *(n)* of the aquifer materials is 30 percent (0.3). A down-valley section is shown in Figure 10.A, part c. The wells are separated by 1000 m and the elevation of the water in wells 1 and 2 are, respectively, 98 and 97 m. Two questions we might ask concerning the conditions shown in Figure 10.A are:

1. What is the discharge Q (m^3/sec or gallons per day) of water moving through the aquifer in the down-valley direction?
2. What is the travel time *(T)* of the groundwater between wells 1 and 2? This question is particularly interesting from an environmental standpoint if a water pollution event is detected at well 1 and we want to know when the pollution will reach well 2.

Answering these two questions requires us to apply Darcy's law to the situation outlined above. To answer the first question, which asks how much water is moving

moves down through the vadose zone to the water table, forming a recharge mound (Figure 10.9, left). Influent streams may be intermittent or ephemeral in that they flow only part of the year.

From an environmental standpoint, influent streams are particularly important because water pollution in the stream may move downward through the stream bed and eventually pollute the groundwater below. Dry river beds are particularly likely to experience this type of problem. For example, the Mojave River in southern California is dry almost all of the time in the vicinity of Barstow. Solvents introduced into the dry river bed as part of a large cleaning operation for equipment have infiltrated down through the vadose zone to contaminate and threaten groundwater that is used by several communities for municipal purposes, including drinking.

Perceptions About Groundwater

People's perceptions about groundwater affect the way they view our water resource:

- People tend to assume that water is available when, where, and in the amounts they want. We turn on a faucet and expect water—it is somebody else's responsibility to see that we have it.

through the aquifer, recall that $Q = KIA$. We will solve for Q. The hydraulic gradient, as illustrated in Figure 10.6, is the ratio of the difference in elevation of the water between the two wells to the length of the groundwater flow between the wells. The difference in elevation of the groundwater table between the wells is 1 m and the flow length is 1000 m. Thus, the hydraulic gradient *(I)* is 0.001 (1×10^{-3}). The hydraulic conductivity is given as 1.2×10^{-3} m/sec. The cross-sectional area of the aquifer *(A)* is 25 m × 4000 m, or 100,000 m² (1×10^{5} m²). Multiplying these numbers, we find that Q is equal to 0.12 m³/sec. This is equivalent to 10,368 m³/day, which is approximately 2.7 million gallons per day. Of course, all of this water could not be pumped from the aquifer. Pump tests of the wells would be necessary to determine how much of the 2.7 million gallons per day could be pumped without depleting the resource.

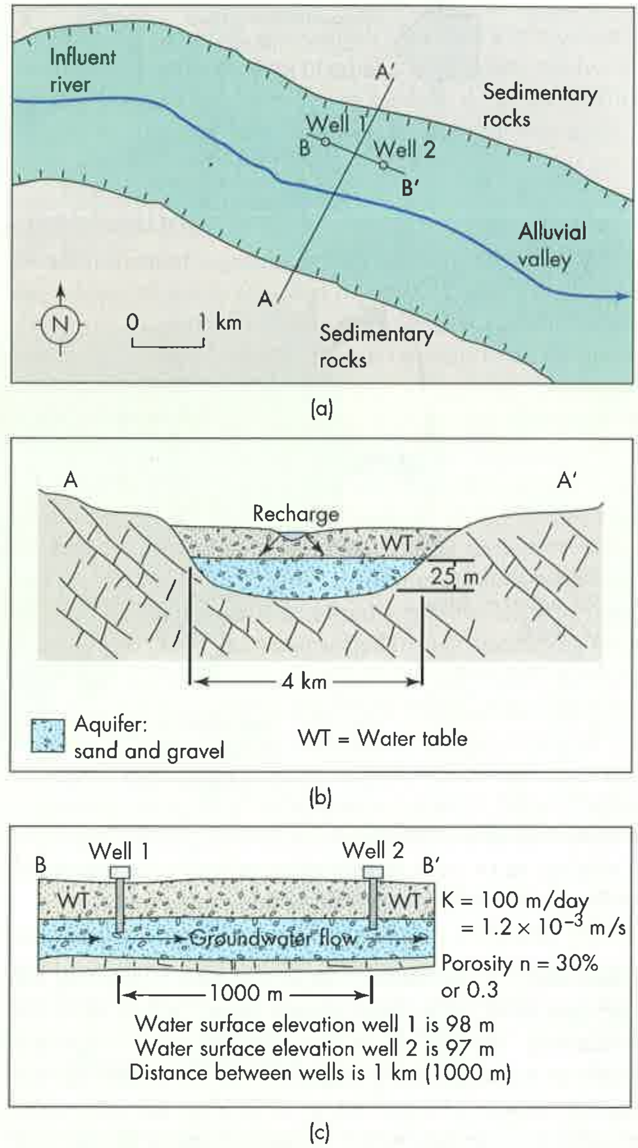
Turning now to the second question, which concerns the travel time of the water from one well to the other, we again apply Darcy's law. In this case we calculate the Darcy flux *(v)*, which is

$$v = Q/A = KI$$

Remember that the Darcy flux is only an apparent velocity and does not reflect the fact that the actual movement of the groundwater is through the pore spaces between the grains of sand and gravel in the aquifer. The actual velocity **(vx)** is the ratio of the product of KI to the porosity.

$$vx = KI/n$$
$$= (1.2\times10^{-3} \text{ m/sec})\,(1\times10^{-3})/0.3$$
$$= 4.0\times10^{-6} \text{ m/sec}$$

Travel time *(T)* then is the ratio of the length of flow *(L)* to the velocity of the water moving through the pore spaces *(vx)*. This follows from the fact that distance L is the product of velocity vx and time T ($L = vxT$). Thus, $T = 1000 \text{ m}/4.0\times10^{-6} \text{ m/sec} = 2.5\times10^{8}$ sec. This is approximately 7.9 years.



▲ **FIGURE 10.A** Hypothetical map of an alluvial valley (a); cross-valley profile (b); and profile down-valley (c) showing groundwater conditions.

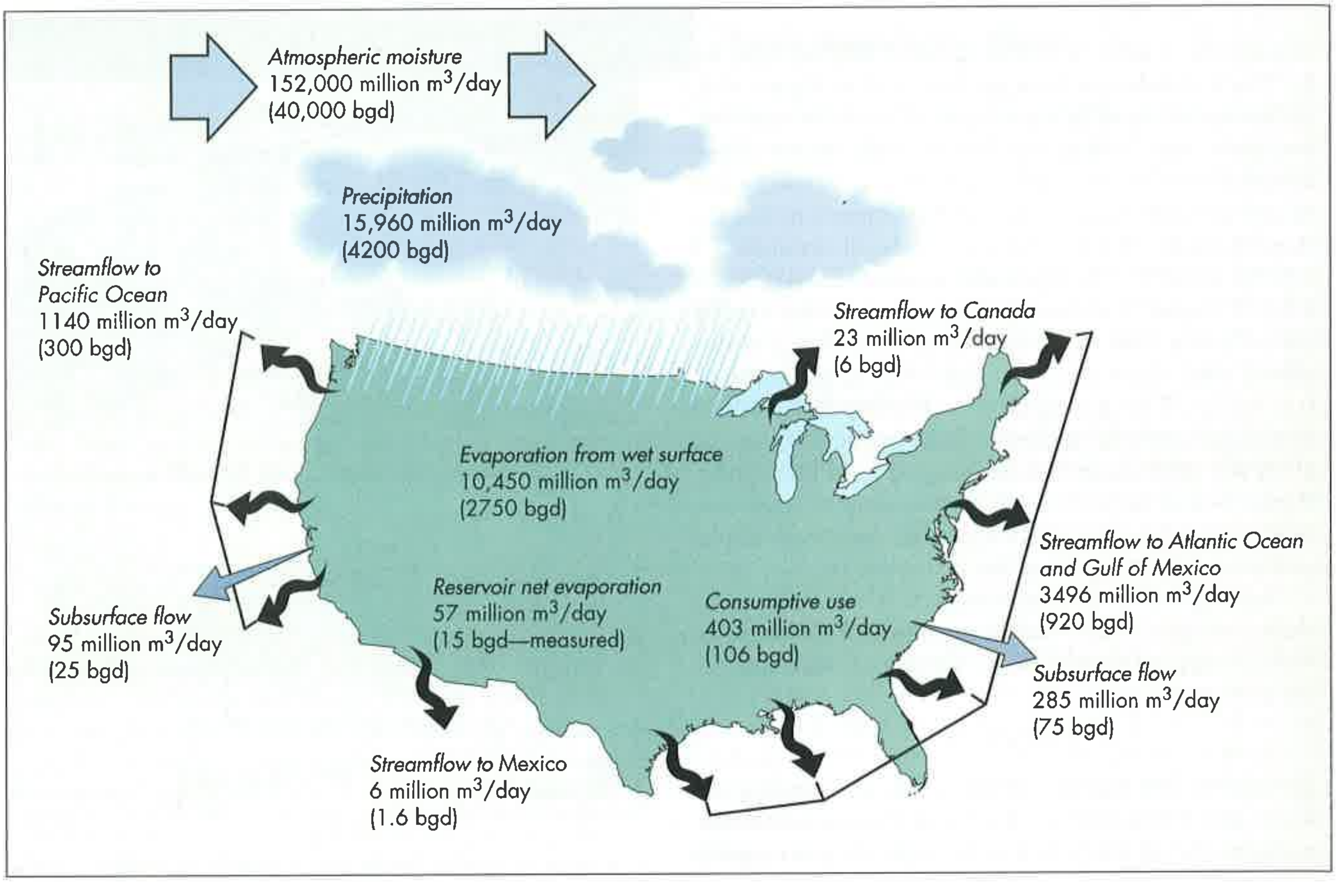
- Because groundwater is out of sight, it is out of mind or mysterious.
- Groundwater is not as easily measured quantitatively as surface water. Therefore, precise quantitative values of groundwater reserves are not available, and we rely on estimates of the probable reserves.

10.5 Water Supply

The water supply at any place on the land surface depends upon several factors in the hydrologic cycle, including the rates of precipitation, evaporation, stream flow, and subsurface flow. The various uses of water by people also significantly affect water supply. In this section we will focus on the U.S. water supply as an example of the problems occurring in many parts of the world.

The Water Budget

A concept useful in understanding water supply is the **water budget**—the inputs, outputs, and storage of water in a system. The water budget for the conterminous United States is shown in Figure 10.12. The amount of water vapor passing over the United States daily is equivalent to approximately 152,000 million m³ or 40,000 billion gallons (bg) of



▲ **FIGURE 10.12** Water budget for the conterminous United States. (*From* U.S. *Water Resources Council.* 1978. The Nation's Water Resources, 1975–2000.)

liquid water. Of this amount approximately 10 percent falls as precipitation in the form of rain, snow, hail, or sleet. Approximately two-thirds of the precipitation evaporates quickly or is transpired by vegetation. The remaining one-third, or about 5510 million m^3 (1450 bg) per day, enters the surface or groundwater storage systems, flows to the oceans or across the nation's boundaries, is used by consumption, or evaporates from reservoirs. Unfortunately, owing to natural variations in precipitation that cause either floods or droughts, only a portion of this water can be developed for intensive uses. Thus, only about 2565 million m^3 (675 bg) per day are considered to be available 95 percent of the time (3).

On a regional scale, it is critical to consider annual precipitation and runoff patterns in order to develop water budgets. Potential problems with water supply can be predicted in areas where average precipitation and runoff are relatively low, such as in the southwestern and Great Plains regions of the United States as well as in some of the intermontane valleys in the Rocky Mountain area. The theoretical upper limit of surface water supplies is the *mean annual runoff,* assuming it could be successfully stored. Unfortunately, storage of all the runoff is not possible because of evaporative losses from large reservoirs, the limited number of suitable sites for reservoirs, and need for other water uses such as river transportation and wildlife. As a result, shortages in water supply are bound to occur in areas with low precipitation and runoff. Strong conservation practices are necessary to ensure an adequate supply (3).

Because of the large annual variations in stream flow, even areas with high precipitation and runoff may periodically suffer from droughts. For example, the dry years of 1961, 1966, and 1999 in the northeastern United States, and 1976–1977 and 1985 to 1990 in parts of the western United States, produced serious water shortages. Fortunately, in the more humid eastern United States, stream flow tends to vary less than in other regions, and drought is less likely (3). Nevertheless, the summers of 1986 and 1999 brought droughts in the southeastern and northeastern United States respectively, causing billions of dollars in damage.

The Groundwater Supply

Nearly half the population of the United States uses groundwater as a primary source of drinking water. Fortunately, the total amount of groundwater available in the United States is enormous, accounting for approximately 20 percent of all water withdrawn for consumptive uses. Within the conterminous United States the amount of groundwater within 0.8 km of the land surface is estimated to be between 125,000 and 224,000 km^3. To put this in perspective, the lower estimate is about equal to the total discharge of the Mississippi River during the last 200 years. Unfortunately, owing to the cost of pumping and exploration, much less than the total quantity of groundwater is available (3).

Protecting groundwater resources is an environmental problem of particular public concern because so many people derive their domestic water supplies from groundwater. The residence time for groundwater in aquifers is often measured in hundreds to thousands of years; therefore, once aquifers are damaged by pollutants, it may be difficult or impossible to reclaim them for continued use. Aquifers are also very important because approximately 30 percent of the stream flow in the United States is supplied by groundwater that emerges as springs or other seepages along the stream channel. This phenomenon, known as **base flow,** is responsible for the low flow or dry-season flow of most perennial streams. Therefore, maintaining high-quality groundwater is important in maintaining good-quality stream flow.

In many parts of the country, groundwater withdrawal from wells exceeds natural inflow. In such cases, water is being mined and can be considered a nonrenewable resource. Groundwater overdraft is a serious problem in the Texas–Oklahoma–High Plains area; in California, Arizona, Nevada, New Mexico; and in isolated areas of Louisiana, Mississippi, Arkansas, and the South Atlantic–Gulf Coast region (Figure 10.13a). In the Texas-Oklahoma-High Plains area alone, the overdraft amount is approximately equal to the natural flow of the Colorado River (Figure 10.13b) (3). In this area lies the Ogallala aquifer, which is composed of water-bearing sands and gravel that underlie an area of about 400,000 km^2 from South Dakota into Texas. Although the aquifer holds a tremendous amount of groundwater, it is being used in some areas at a rate that is up to 20 times that of natural recharge by infiltration of precipitation. The water level in many parts of the aquifer has declined in recent years, and eventually a significant portion of land now being irrigated may return to dry farming if the resource is used up.

To date, only about 5 percent of the total groundwater resource has been depleted, but water levels have declined as much as 30 to 60 m in parts of Kansas, Oklahoma, New Mexico, and Texas. As the water table becomes lower, yields from wells decrease and energy costs to pump the water increase. The most severe problems in the High Plains and the Ogallala aquifer today are in those locations where irrigation has been going on the longest—that is, since the 1940s.

In many areas, pumping of groundwater has forever changed the character of the land. For example, rivers in the Tucson, Arizona, area, prior to lowering of the water table through pumping, were perennial, with healthy populations of trout, beaver, and other animals. Today the native riparian trees have died (the water table is below their roots) and the rivers are dry much of the year. Ironically, these processes also increased the flood hazard in Tucson, which currently gets its entire water supply from groundwater sources. Loss of riparian trees and the root strength they provided to stream banks render the channels much more vulnerable to lateral bank erosion. During the 1983 and 1993 floods in Tucson (see Chapter 5), this became very apparent as roads, bridges, and buildings were damaged by the shifting channels. Tree-lined channels are much more stable, but riparian trees need a groundwater table sufficiently close to the surface for healthy growth. Unfortunately, mining of groundwater in the Tucson area has precluded restoration of trees.

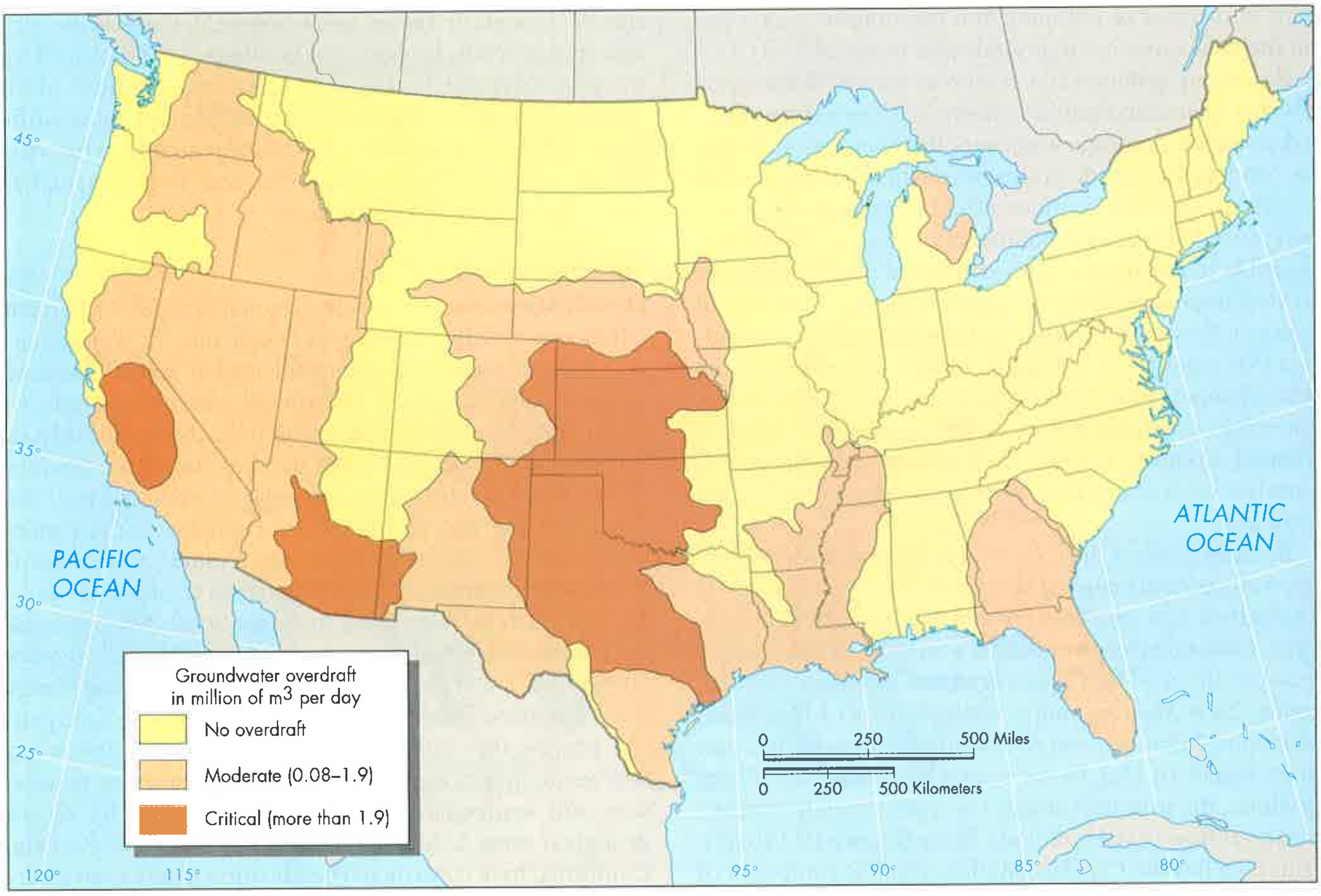
Desalination

Desalination of seawater, which contains about 3.5 percent salt (about 40 kilograms [kg] per cubic meter), is an expensive form of water treatment practiced at several hundred plants around the world. The salt content must be reduced to about 0.05 percent for the water to be drinkable and pass water-quality standards. Large desalination plants produce 20,000 to 30,000 m^3 of water per day at a cost of about ten times that paid for traditional water supplies in the United States. Desalinated water has a "place value," which means that the price increases quickly with the transport distance and elevation increase from the plant at sea level. Because the various processes that actually remove the salt require energy, the cost of the water is tied to ever-increasing energy costs. For these reasons, desalination will remain an expensive process that will be used only when alternative water sources are not available. Because of an increasing population and inadequate water supply, accented by recent droughts, some U.S. communities such as Santa Barbara, California, have constructed desalination plants as an emergency measure for future droughts.

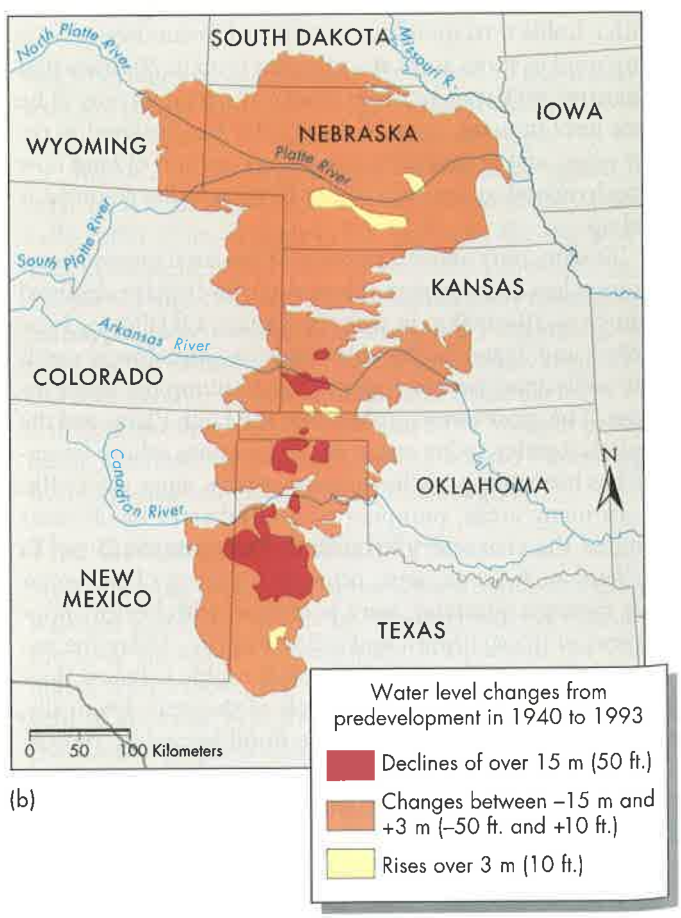
Middle Eastern countries in particular will continue to use desalination. In many arid regions, including the Middle East, there are brackish ground and surface waters with a salinity of about 0.5 percent (one-seventh that of seawater). Obviously, desalination of this water is less expensive, and plants may be located at inland sites.

10.6 Water Use

To discuss water use, we must distinguish between instream and offstream uses. **Offstream uses** remove or divert water from its source. Examples include water for irrigation, livestock, thermoelectric power generation, industrial processes, and public supply. **Consumptive use** is an offstream use in which water does not return to the stream or groundwater resource immediately after use. This is the water that evaporates, is incorporated into crops or products, or is consumed by animals and humans (3,8). **Instream use** relates to the water that is used but not withdrawn from its source. Examples include use of river water for navigation, hydroelectric power generation, fish and wildlife habitats, and recreation. In general, consumptive use is much less than offstream use, which is much less than instream use. For example, in the United States in 1995, consumptive use was about 100 billion gallons (3.8×10^8 m^3) per day; offstream use was about 400 billion gallons (1.5×10^9 m^3) per day, and instream use (for hydroelectric power generation) was about 3,000 billion gallons (1.1×10^{10} m^3) per day (8).



(a)



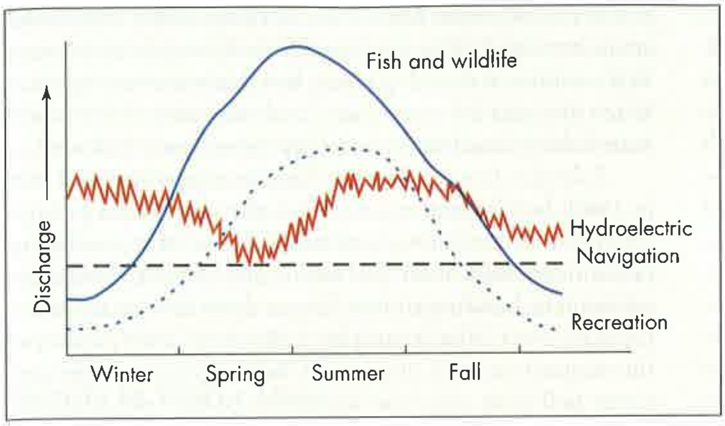
(b)

▲ **FIGURE 10.13** (a) Groundwater overdraft for the conterminous United States. (b) A detail of water-level changes in the Texas–Oklahoma–High Plains area. (*Source:* U.S. *Geological Survey*)

Multiple instream uses of rivers and streams usually create controversy because each use requires different conditions to prevent damage or detrimental effects. Fish and wildlife require certain water levels and flow rates for maximum biological productivity, and these levels and rates may differ from the requirements for hydroelectric power generation, which requires large fluctuations in discharges to match power needs. Similarly, both of these may conflict with requirements for shipping and boating. The discharge necessary to move the sediment load in a river may require yet another pattern of flow. Figure 10.14 diagrams the seasonal patterns of discharge for some of these uses.

A major problem concerns how much water may be removed from a stream or river and transported to another location without damaging the stream system. This is a problem in the Pacific Northwest, where certain fish, including the steelhead trout and salmon, are on the decline partly because people have induced alterations in land use (for example, timber harvesting) and stream flows (building dams that block seasonal migration of fish and change downstream hydrology) that have degraded fish habitats.

Important concepts associated with water use are illustrated in Figure 10.15. Surface and groundwater sources are moved to the users, often by way of a public supplier, which

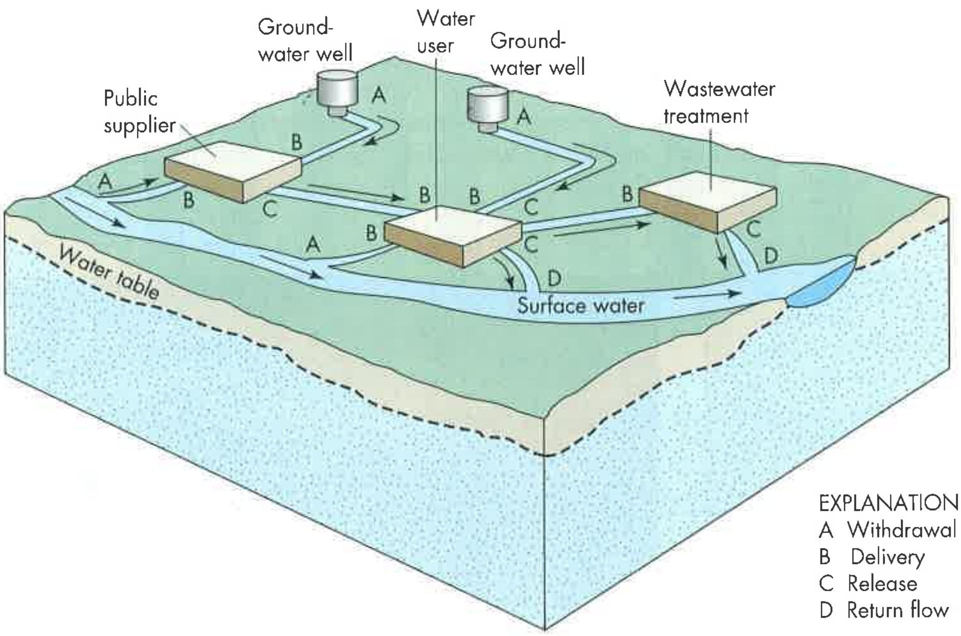


◀ **FIGURE 10.14** Diagram of instream water uses and the varying discharges for each use. Discharge is the amount of water passing by a particular location and is measured in cubic meters per second (cms).

may be a local or regional water district. Knowing the volumes of water moved from point to point allows quantities such as conveyance losses and consumptive use to be calculated (8).

Movement of Water to People

In our modern civilization, water is often moved vast distances from areas with abundant rainfall to areas of high usage. In California, demands are being made on northern rivers for reservoir systems supplying the cities in the southern part of the state. Two-thirds of California's runoff occurs north of San Francisco, where there is a surplus of water, while two-thirds of the water use occurs south of San Francisco, where there is a deficit. In recent years, canals constructed by the California Water Project and the Central Valley Project have moved tremendous amounts of water from the northern to the southern part of the state, adversely affecting ecosystems (especially fisheries) in some northern California rivers through diversion of waters.



◀ **FIGURE 10.15** Important concepts associated with water use. (*Source*: W. B. *Solley*, R. R. *Pierce, and* H. A. *Perlman*, 1993. Estimated use of water in the United States in 1990. U.S. *Geological Survey Circular* 1081.)

1. Withdrawal—The quantity of water diverted or withdrawn from surface or groundwater (A in sketch).
2. Delivery/release—The quantity of water delivered at the point of use (B) and the quantity released after use (C).
3. Conveyance loss—The quantity of water that is lost in transit, for example, from point of withdrawal to point of delivery (A–B), or from point of release to point of return (C–D).
4. Consumptive use—That part of water withdrawn that is evaporated, transpired, or incorporated into products or crops. In some instances, consumptive use will be the difference between the volume of water delivered and the volume released (B–C).
5. Return flow—The quantity of water that is discharged to a surface or groundwater source (D) after release from the point of use and thus becomes available for further use.

The major water-diversion projects in California are shown in Figure 10.16. Of particular interest is the long-standing dispute between the city of Los Angeles and the people in Owens Valley on the eastern side of the Sierra Nevada. Los Angeles suffered a drought near the end of the nineteenth century and, after looking for a potential additional water supply, settled on the Owens Valley. By various means, some of which were controversial, to say the least (some have contended the water was stolen), the city purchased most of the water rights and constructed the Los Angeles Owens River Aqueduct, completed in 1913. Since that time groundwater has also been pumped and taken from Owens Valley via the aqueduct. As a result of the tremendous exportation of surface water and groundwater, Owens Valley, which before water exportation to Los Angeles contained wetlands and lakes, has suffered from desertification (the production of a more desertlike environment), producing "Owens Dry Lake," perhaps the single largest point source of hazardous alkaline dust in the U.S. Recently, Los Angeles has agreed to reduce water exports to attempt to control the production of dust. Protests that were more violent in the early 1900s are now court battles; only recently have both parties come closer to a settlement that will include limits on the amount of water taken by Los Angeles and projects to halt environmental degradation.

Many large cities in the world must seek water from areas increasingly farther away. For example, New York City has imported water from nearby areas for more than a century. Water use and supply in New York City represent a repeating pattern. Originally, local groundwater, streams, and the Hudson River itself were used. However, water needs exceeded local supply, so in 1842 the first large dam was built more than 48 km north of the city. As the city expanded rapidly from Manhattan to Long Island, water needs again increased. The sandy aquifers of Long Island were at first a source of drinking water, but this water was removed faster than rainfall replenished it. Local cesspools contaminated the groundwater, and salty ocean water intruded.

A larger dam was built at Croton in upstate New York in 1900, but further expansion of the population brought repetition of the same pattern: initial use of groundwater; pollution, salinification, and exhaustion of this resource; and subsequent building of new, larger dams farther upstate in forested areas. The boroughs of Brooklyn and Queens, on the western end of Long Island, have experienced groundwater pollution since the beginning of the twentieth century, and they import upstate water. Eastern counties of Long Island (Nassau and Suffolk) do not import water and, of necessity, have enacted strict regulations to protect and conserve their groundwater supply. Nevertheless, they also are experiencing problems of pollution, salinification, and exhaustion of the resource.

It is important to recognize that New York City and Los Angeles are not unique. Many urban areas are having problems with their water supply as a growing population demands more water, which is becoming harder to obtain. One would think that eventually the cost of obtaining water from long distances would place an upper limit on growth, and to some extent this may be true, but the price of water is often kept artificially low through a variety of government programs. People in urban environments could do much more through increased water conservation to alleviate or reduce the problems related to water supply, but shortages have not yet become sufficiently acute. Nevertheless, urban water districts are developing strategies to

(a)

(b)

◀ **FIGURE 10.16** (a) California aqueducts and irrigation canals. (b) View of the California aqueduct in the San Joaquin Valley. *(Allan Pitcairn/Grant Heilman Photography, Inc.)*

encourage conservation. These include water prices that increase with water use and rebates for installing water-conserving fixtures such as low-flow flush toilets and low-flow shower heads. Manufacturers are also now producing washing machines and other appliances that use less water or have low water-use settings.

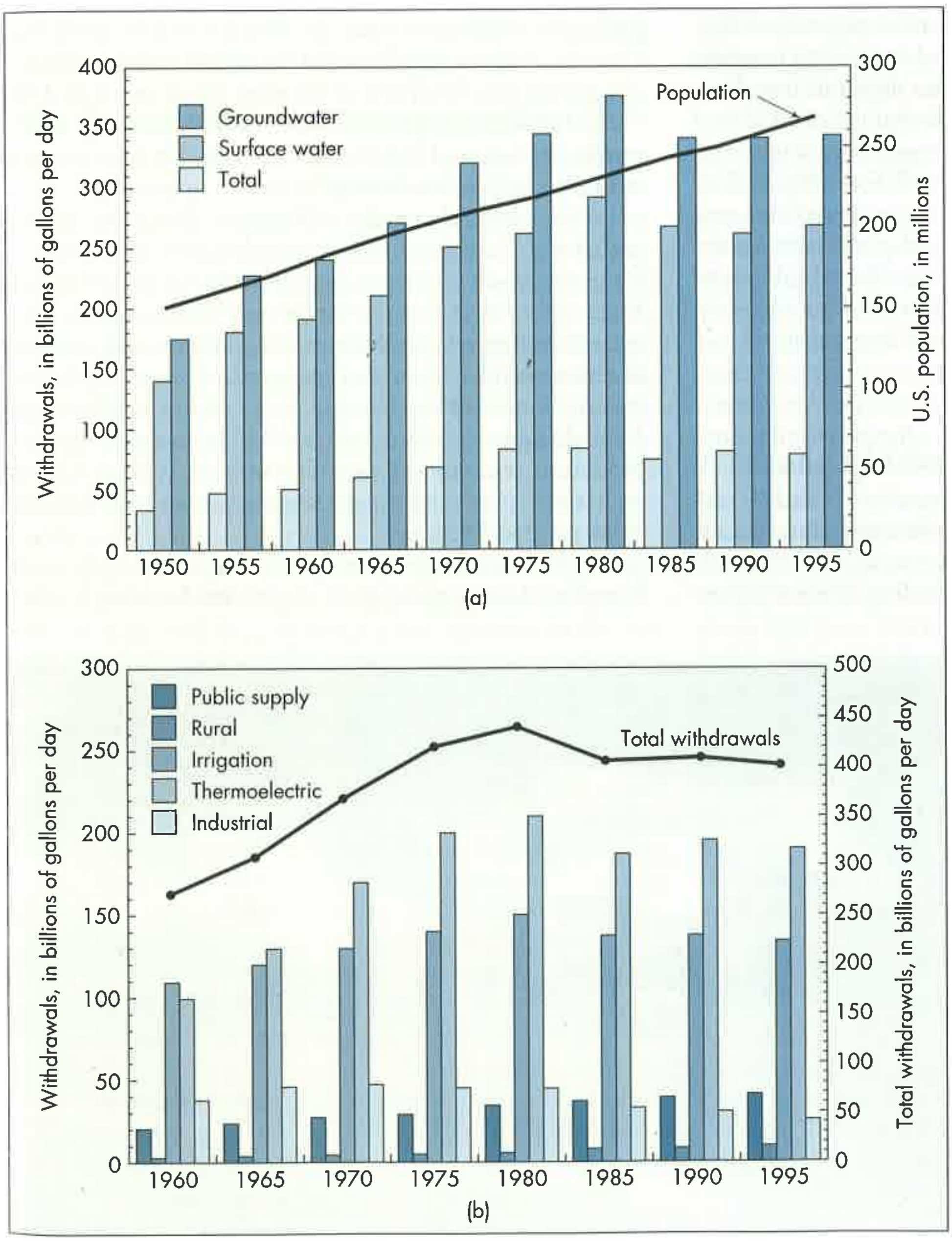
As greater quantities of water are needed for cities and agriculture, conflicts will increase and intensive argument will center on instream water use. An important, fruitful area of research is more careful evaluation of what flows are necessary to maintain a natural river system.

Trends in Water Use

Trends in water withdrawals for various uses in the United States provide insight that is both interesting and necessary for managing our water resources. Figure 10.17a shows trends in fresh ground- and surface water withdrawals from 1950 through 1995. These data suggest:

- Surface water withdrawals far exceed groundwater withdrawals.
- Water withdrawals increased until 1980, and since then has decreased and leveled off. The population of the United States was about 151 million in 1950 and has continued to increase, reaching 267 million in 1995. Thus, during the period when water withdrawals decreased and leveled off, population was increasing. This suggests better water management and conservation during the past 15 years (8).

Figure 10.17b shows trends in water withdrawals by water-use category from 1960 through 1995. These data show that:



◀ **FIGURE 10.17** Trends in withdrawal of fresh groundwater and surface waters (1950–1995) (a); and withdrawal of both fresh and saline water use by category (1960–1995) (b). (*Source: Solley*, W. B., *Pierce*, R. R., *and Perlman*, H. A. 1998. Estimated use of water in the United States in 1995. U.S. *Geological Survey Circular* 1200.)

- Irrigation needs and the thermoelectric industry are the big users of fresh water.
- Use of water by the public (urban and rural sectors) has increased through the period, a trend presumably related to the increase in population of the country.
- The use of water by agriculture for irrigation leveled off in 1980 and has decreased slightly since then. This presumably is related to efforts in water conservation.
- Water used for the thermoelectric power increased dramatically from 1960 to 1980, as numerous power plants came on-line, and has since decreased somewhat due to more efficient use of water.
- Since 1980, industry has used significantly less fresh water. This is due, in part, to new technologies that require less water as well as improved plant efficiencies and increased water recycling.

There are encouraging signs that the general public is more aware of our water resources and the need to conserve them. As a result, in many states water demands have been reduced. Another encouraging sign is that use of reclaimed wastewater is now much more common, increasing from about 200 million gallons per day in 1955 to 1000 million gallons daily in 1995. This is about 1 percent of the consumptive use of water and 0.25 percent of offstream water use in the United States today. More significantly, the trend seems to be accelerating: From 1990 to 1995 the use of reclaimed wastewater increased by about 36 percent (8).

Water Conservation

What can be done to use water more efficiently and reduce withdrawal and consumption? Improved agricultural irrigation could reduce withdrawals by between 20 and 30 percent. Such improvements in **water conservation** include lined and covered canals that reduce seepage and evaporation; computer monitoring and scheduling of water releases from canals; a more integrated use of surface waters and groundwaters; night irrigation; improved irrigation systems (sprinklers, drip irrigation); and better land preparation for water application.

Domestic use of water accounts for only about 6 percent of the total national withdrawals. However, because this use is concentrated, it poses major local problems. Withdrawal of water for domestic use may be substantially reduced at a relatively small cost with more efficient bathroom and sink fixtures, night irrigation, and drip irrigation systems for domestic plants.

How people perceive the water supply is important in determining how much water is used. For example, people in Tucson, Arizona, perceive the area as a desert (which it is) and cultivate many native plants such as cactus in their yards and gardens (Figure 10.18). Tucson's water supply is from groundwater, which is being mined (used faster than it is being naturally replenished); the water use is about 605 liters (160 gallons) per person per day. Not far away the people of Phoenix, Arizona, use about 983 liters (260 gallons) of water per person per day. Parts of Phoenix use as much as 3780 liters (1000 gallons) per person per day to water large lawns, mulberry trees, and high hedges! Phoenix has been accused of having an "oasis mentality" concerning water use.

Water rates also make a difference. People in Tucson pay about 75 percent more for water than do people in Phoenix, where the water supply is drawn from the Salt River rather than from groundwater. Water rates in Tucson are structured to encourage conservation, and some industries consider water as a cost-control measure (9). The message here is that, because water in the southwestern United States and other locations will be in short supply in the future, we could all do with a little of Tucson's "desert mentality," particularly such large urban areas as Los Angeles and San Diego.

Water removal for steam generation of electricity could be reduced as much as 25 to 30 percent by using cooling

FIGURE 10.18 Home in Tucson, Arizona, with native vegetation and rocks as ground cover. This type of landscaping minimizes water use. (*Edward A. Keller*)

towers designed to use less or no water. Manufacturing and industry might curb water withdrawals by increasing in-plant treatment and recycling of water or by developing new equipment and processes that require less water. Because the field of water conservation is changing so rapidly, it is expected that a number of innovations will reduce the total withdrawals of water for various purposes, even though consumption will continue to increase (3).

10.7 Water Management

Management of water resources is a complex issue that will become more difficult in coming years as the demand for water increases. While this will be especially true in the southwestern United States and other arid and semiarid parts of the world, New York and Atlanta, among other U.S. cities, also face future water-supply problems. Options open to people who want to minimize potential water-supply problems include locating alternative supplies, managing existing supplies better, or controlling growth.

The Future of Water Management

Cities in need of water are beginning to treat water like a commodity that can be bought and sold on the open market, like oil or gas. If cities are willing to pay for water and are allowed to avoid current water regulation, then allocation and pricing as they are now known will change. If the cost rises enough, "new water" from a variety of sources may become available. For example, irrigation districts (water managers for an agricultural area) may contract with cities to supply water to urban areas. They could do this without any less water being available for crops by using conservation measures to minimize present water loss through evaporation and seepage from unlined canals. Currently, most irrigation districts do not have the capital to finance expensive conservation methods, but money paid by cities for water could finance such projects. It seems apparent that water will become much more expensive in the future and, if the price is right, many innovative programs are possible. Serious consideration is being given to ideas as original as towing icebergs (which are composed of frozen fresh water) to coastal areas where fresh water is needed.

Luna Leopold (a leader in the study of rivers and water resources) has suggested that a new philosophy of **water management** is needed—one based on geologic, geographic, and climatic factors as well as on the traditional economic, social, and political factors. He argues that the management of water resources cannot be successful as long as it is naively perceived primarily from an economic and political standpoint. However, this is how water use is approached. The term *water use* is appropriate because we seldom really "manage" water (10). The essence of Leopold's water-management philosophy is summarized in this section.

Surface water and groundwater are both subject to natural flux with time. In wet years, surface water is plentiful, and the near-surface groundwater resources are replenished. During these years, we hope that our flood-control structures, bridges, and storm drains will withstand the excess water. Each of these structures is designed to withstand a particular flow (for example, the 20-year flood), which, if exceeded, may cause damage or flooding.

All in all, Leopold concluded we are much better prepared to handle floods than water deficiencies. During dry years, which must be expected even though they may not be accurately predicted, we should have specific strategies to minimize hardships. For instance, subsurface waters in various locations in the western United States are either too deep to be economically extracted or have marginal water quality. These waters may be isolated from the present hydrologic cycle and therefore may not be subject to natural recharge. Such water might be used when the need is great, but this will be possible only if plans are in place for drilling the wells and connecting them to existing water lines when the need arises. Another possible emergency plan might involve the treatment of wastewater. Reuse of water on a regular basis might be too expensive or objectionable for other reasons, but advance planning to reuse treated water during emergencies might be wise (10).

When dealing with groundwater that is naturally replenished in wet years, we should develop plans to use surface water when it is available and not be afraid to use groundwater during dry years. In other words, groundwater could be pumped out at a rate exceeding the replenishment rate in dry years, but it would be replenished during wet years by both natural and artificial recharge (pumping excess surface water into the ground). This water-management plan recognizes that excesses and deficiencies in water are natural and can be planned for.

A Managed River: The Colorado

No discussion of water resources and water management would be complete without a mention of the Colorado River Basin and the controversy that surrounds the use of its water. People have been using the water of the Colorado River for about 800 years. Early Native Americans in the basin had a highly civilized culture with a sophisticated water-distribution system. Many of their early canals were later cleared of debris and used by settlers in the 1860s (11). Given this early history, it is somewhat surprising to learn that the Colorado was not completely explored until 1869, when John Wesley Powell, who later became director of the U.S. Geological Survey, navigated wooden boats through the Grand Canyon.

Although the waters of the Colorado River Basin are distributed by canals and aqueducts to many millions of urban residents, and to agricultural areas such as the Imperial Valley in California, the basin itself, with an area of approximately 632,000 km^2, is only sparsely populated. Yuma, Arizona, with approximately 42,000 people, is the largest city on the river, and within the basin only the cities of Las Vegas, Phoenix, and Tucson have more than 50,000 inhabitants. Nevertheless, only about 20 percent of the total population of the basin is rural. Vast areas of the basin have extremely low densities of people, and in some areas measuring several thousand square kilometers there are no permanent residents (11).

Rod Nash, writing about the wilderness values of the river, states that at the confluence of the Green and Colorado rivers, it is 80 km to the nearest video game and you are in the heart of a national park (12).

The headwaters of the Colorado River are in the Wind River Mountains of Wyoming, and in its 2300-km journey to the sea the river flows through or abuts seven states—Wyoming, Colorado, Utah, New Mexico, Nevada, Arizona, and California—and Mexico (Figure 10.19). Although the drainage basin is very large, encompassing much of the southwestern United States, the annual flow is only about 3 percent of that of the Mississippi River and less than a tenth of that of the Columbia. Therefore, for its size the Colorado River has only a modest flow, and yet it has become one of the most regulated, controversial, and disputed bodies of water in the world. Conflicts that have gone on for decades extend far beyond the Colorado River Basin itself to involve large urban centers and developing agricultural areas of California, Colorado, New Mexico, and Arizona. The need for water in these semiarid areas has resulted in overuse of limited supplies and deterioration of water quality. Interstate agreements, court settlements, and international pacts have periodically eased or intensified tensions among people who use the waters along the river. The legacy of laws and court decisions, along with changing water-use patterns, continues to influence the lives and livelihood of millions of people in both Mexico and the United States (13).

Waters of the Colorado River have been appropriated among the various users, including the seven states and the Republic of Mexico. This appropriation has occurred through many years of negotiation, international treaty, interstate agreements, contracts, federal legislation, and court decisions. As a whole, this body of regulation is known as the "Law of the River." Two of the more important early documents in this law were the Colorado River Compact of 1922, which divided water rights in terms of an upper and lower basin (see Figure 10.19), and the treaty with Mexico in 1944, which promised an annual delivery of 1.85 km^3 (1.5 million acre-feet [1 acre-foot is the volume of water covering 1 acre to a depth of 1 ft], or 325,829 gallons) of Colorado River water to Mexico. More recent was a 1963 U.S. Supreme Court decision involving Arizona and California. Arizona refused to sign the 1922 compact and had a long conflict with California concerning appropriation of water. The Court decided that southern California must relinquish approximately 0.74 km^3 (600,000 acre-feet) of Colorado River water when the Central Arizona Project is completed. Finally, in 1974 the Colorado River Basin Salinity Control Act was approved by Congress. The act authorized procedures to control adverse salinity of the Colorado River water, including construction of desalination plants to improve water quality.

Management of the Colorado River Basin and its waters has been frustrating in part because the basin is characterized by inherent instabilities (11). For example, in 1922 when the Colorado River Compact was worked out, the hypothesis was that the virgin flow of the river was approximately 20 km^3 (16.2 million acre-feet) per year. That annual flow is now believed to average closer to 16.6 km^3 (13.5 million acre-feet) annually (14). Even these numbers are misleading, however, because of the tremendous hydrologic

▶ **FIGURE 10.19** The Colorado River Basin.

Table 10.7 Legal and actual distribution of Colorado River water

State	Legal Entitlements (million ac ft per yr)	Actual Distribution (million ac ft per yr)
California	4.400[a]	4.400[f]
Arizona	3.800[a]	2.050[f]
Nevada	0.300[a]	0.300
Lower Basin	**8.500[b]**	**6.750**
Colorado	3.881[c]	2.406
Utah	1.725[c]	1.070
Wyoming	1.050[c]	0.651
New Mexico	0.844[c]	0.523
Upper Basin	**7.500[b]**	**4.650**
Mexico	1.500[d]	1.500
Total	**17.500**	**14.500**

[a]1928 Boulder Canyon Project Act

[b]1922 Colorado River Compact

[c]1948 Upper Colorado River Basin Compact

[d]1944 Mexico-U.S. Treaty

[e]Includes losses to evaporation of 0.6 million ac ft per year in the Upper Basin and 0.9 million ac ft per year in the Lower Basin, and 0.9 million ac ft per year inflow to Lower Basin from local streams.

[f]Agreement at time of Central Arizona Project authorization by Congress Upper Basin amounts agreed to by states as percentages.

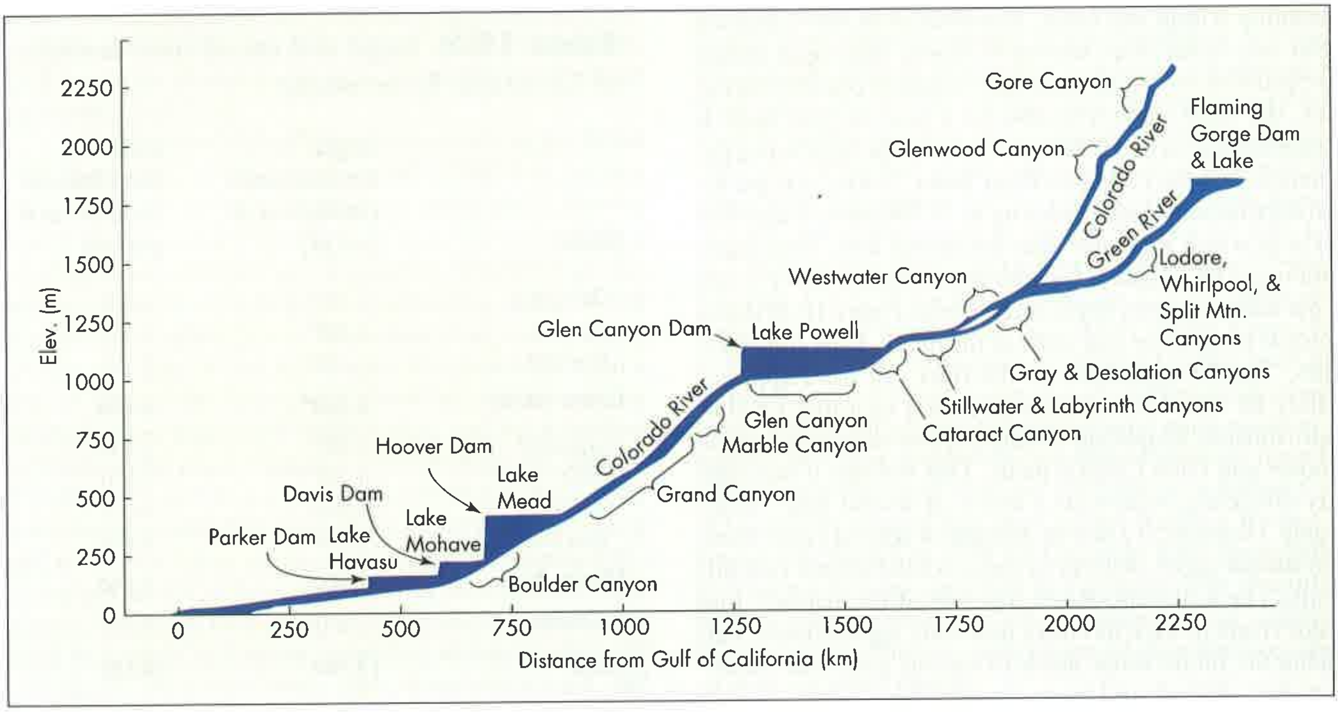
Source: W. L. Graf, 1985. *The Colorado River,* Resource Publications in Geography, Association of American Geographers.

instability within the basin. Floodwaters in the Colorado River may come from snowmelt floods, long-term winter precipitation events, or short-term summer thunderstorms; thus, the total water available on a year-to-year basis is tremendously variable. Table 10.7 shows the legal water entitlements for the Colorado River Basin. Notice that the actual distribution of water adds up to 14,500 million acre-feet per year, which is greater than the annual flow. This distribution can be obtained because the Colorado River is one of the most regulated rivers in the world. Figure 10.20 shows a profile of the river and some of the major dams and reservoirs. The 19 high dams on the river can store approximately 86.3 km^3 (70 million acre-feet) of water. Of this, approximately 80 percent is stored in two reservoirs, behind Hoover and Glen Canyon dams. This storage, if managed very efficiently, represents a buffer of several years' water supply. However, if a severe drought of several years' duration should occur, delivery of water could become very difficult. The Colorado River was one of the nation's first major rivers to have its entire flow fully appropriated. Balancing the future water needs of various users will continue to be a difficult and frustrating problem.

Construction of dams, reservoirs, and diversions on the Colorado River has generally been viewed as a successful venture from the viewpoint of supplying water. However, this has not always been the case. For example, the present Salton Sea in the Imperial Valley formed in 1905 and 1906 when virtually the entire Colorado River was unintentionally diverted into the southern Imperial Valley (Salton Basin). At that time the Colorado River was completely undammed, and "control works" (structures constructed to control the flow of the Colorado River) located in Mexican territory failed because of flooding in 1905 and 1906. By the time the river was controlled in 1907, the present Salton Sea had formed and was at a level higher than present. Water in the Salton Sea today is maintained through inflow from irrigation waters used to leach salts out of agricultural lands. Should this inflow stop or be reduced, the Salton Sea would soon dry up, owing to high evaporation rates there. Because the lake has become an important recreation (sport fishing) area, its future is controversial. If the lake waters become much saltier than they are now, the ecosystem and present fishery would be significantly damaged. However, the present lake is not unique to the Salton Basin. Other earlier lakes in the Imperial Valley present during recent geologic history have also dried up.

Although water supply is the primary problem in the Colorado River Basin, the problem of how to manage water quality is also significant. Although heavy metals and radioactive materials have become concentrated in the basin's waters and reservoirs, salt is causing the most problems. A salinity of 550 ppm (parts per million) is the upper limit set for human consumption, and more than 750 ppm may damage agriculture. The natural salinity of the Colorado River in the headwaters is only 50 ppm. As the river flows toward the sea, tributaries flow over exposed salt beds, and salt springs add salt to the river, so under natural conditions the salinity of the Lower Colorado is probably in the range of 250 to 380 ppm. However, upstream irrigation and evaporation have increased the salinity of the Lower Colorado River to an average of 1500 ppm, and at times the salinity reaches 2700 ppm. The quality of the water is so poor that Mexican farmers have allowed it to pass their fields rather than damage their crops and soils. The United States and Mexico agreed in 1973 that the United States would deliver water to Mexico with a salinity of no more than 115 ppm greater than the salinity at the Imperial Dam, a short distance upstream from the border. The salinity there is approximately 800 ppm. To achieve this goal, a large desalination plant near the border, costing several hundred million dollars in capital expenses and more than $10 million a year to operate, is necessary. This is a tremendous investment in a structural effort to control the salinity of the river water. Only time will tell how effective it will be (11).

Issues of water and basin management in the Colorado River are complex, but they firmly illustrate some of the major



▲ **FIGURE 10.20** Longitudinal profiles of the Colorado and Green rivers, showing the major dams, reservoirs, and canyons. (From W. L. Graf. 1985. The Colorado River. *Association of American Geographers*.)

problems likely to face other parts of the arid Southwest in coming years: How are we to appropriate water? How can we best control water quality? Answers to these questions are not simple; what we have learned so far from our experiences with the Colorado River should help in future planning.

10.8 Dams, Reservoirs, and Canals

Our discussion of water supply established that many agricultural and urban areas require water delivered from nearby—and, in some cases, not so nearby—sources. To accomplish this a system of water storage and routing by way of canals and aqueducts from reservoirs is needed. The parties interested in water and water development range from government agencies to local water boards and conservation groups. A good deal of controversy often surrounds water development, and the day of developing large projects in the United States without careful environmental review has passed. The resolution of development issues now involves input from a variety of groups that may have very different needs and concerns. These range from agricultural groups who see water development as critical for their livelihood to those whose primary concerns are with wildlife and wilderness preservation. It is a positive sign that the various parties on water issues are now at least able to meet and communicate their needs and concerns.

Dams and Reservoirs

Dams and their accompanying reservoirs are generally designed to be multifunction structures. That is, those who propose the construction of dams and reservoirs point out that reservoirs may be used for activities such as recreation in addition to providing flood control and assuring a more stable water supply. It is important to recognize that reconciling these various uses at a given site is often difficult. For instance water demands for agriculture might be high during the summer, resulting in a drawdown of the reservoir and the production of extensive mud flats. Those interested in recreation find the low water level and the mud flats to be aesthetically degrading, and these effects of high water demand may also interfere with wildlife (particularly fish) by damaging or limiting spawning opportunities. Finally, as we saw in Chapter 5 dams and reservoirs tend to instill a false sense of security to those living below the water-retention structures, because dams cannot fully protect us against great floods.

There is little doubt that we may need some additional dams and reservoirs if our present practices of water use are continued. Some existing structures may also need to be heightened. As more people flock to urban areas, water demands there are going to increase and additional water storage will be required. This is particularly true in the more arid parts of the country, including the southern California belt extending eastward into Arizona, where populations are growing rapidly.

Conflicts over construction of additional dams and reservoirs are bound to occur. Water developers may view a canyon dam site as a resource for water storage, whereas other people view it as a wilderness area and recreation site for future generations. The conflict is particularly pointed because good dam sites are often sites of high-quality scenic landscape. Unless water-use patterns change in agricultural and urban areas, however, additional water-supply facil ities will be a high priority for rapidly growing urban areas, perhaps taking precedence over aesthetic and environmental concerns.

Whenever a dam and reservoir are constructed on a river system, that system is changed forever (see *Case History: The Grand Canyon*). The flow of water and sediment is changed, as are the physical and biological habitats and land uses below the dam. As a result of ecological damage to rivers below dams, a few dams have been removed and several others from Washington State to Florida will likely be removed in coming years. This represents an important shift in our view of the river and its environmental significance. As dams and their reservoirs age and become less useful, or hazardous, their removal may become both an environmental and economic alternative to expensive rebuilding or repairs (15).

Canals

Water from upstream reservoirs may be routed to downstream needs by way of natural watercourses or by canals and aqueducts.

Canals, whether lined or unlined, are often attractive nuisances to people and animals. Where they flow through urban areas, drownings are an ever-present threat. When they are unlined, canals may lose a good deal of water to the subsurface flow system. Although it may be argued that this is a form of artificial groundwater recharge, it may be an inefficient one because canals may cross areas with little potential for groundwater development or areas of poor groundwater quality. In these cases, water seeping from unlined canals is essentially lost water.

The construction of canal systems, especially in developing countries, has led to serious environmental problems. For example, when the High Dam at Aswan, Egypt, was completed in 1964, canals were needed to convey the water to agricultural sites. The canals became infested with snails that carry the dreaded disease schistosomiasis (snail fever). This disease has always been a problem in Egypt, but the swift currents of Nile River floodwaters flushed out the snails each year. The tremendous expanse of waters in irrigation canals now provides happy homes for these creatures. The disease is debilitating and so prevalent in parts of Egypt that virtually the entire population of some areas is affected by it. The Egyptian canals are also a home for mosquitoes, some of which carry malaria.

Reservoirs and canal systems are being planned in a variety of environments around the world today. Environmental concern (and laws) in the United States ensures that important environmental review will take place. This is not always true in many developing countries, where attention to environmental concerns is not as high a priority as, for instance, the production of food. In such areas, construction of large and lengthy canals may considerably alter land use and the biologic environment by producing new and different water systems and barriers to migration of wildlife. This is not to say that water development in these countries should not take place, but it does emphasize the need for environmental concern at the ecosystem level when planning and developing water resources. At the very least, we can give developing countries information about our successes and failures in planning water projects, so that they may benefit from our experience. Water development and environmental concern are not necessarily incompatible. However, trade-offs must be made if a quality environment is to be preserved.

10.9 Water and Ecosystems

The major ecosystems of the world have evolved in response to physical conditions that include, among others, climate, nutrient input, soils, and hydrology. Changes in these factors affect ecosystems; in particular, changes induced by humans may have far-reaching consequences. Throughout the world today, with few exceptions, people are degrading natural ecosystems on a regional and global scale. Hydrologic conditions, particularly surface water processes and quality, along with interactions with groundwater, are becoming limiting factors for the existence of many ecosystems. This is particularly true for wetlands (20) (see *A Closer Look: Wetlands*).

Development of water resources often has an extensive impact on ecoystems. Construction of large dams, for example, can permanently change not only rivers but also the bodies of water they supply. Recall our Case History of the Grand Canyon, and see *A Closer Look: The Three Rivers Gorges, China*, in Chapter 15.

SUMMARY

The global water cycle involves the movement, storage, and transfer of water from one part of the cycle to another. The movement of water on land—that is, surface runoff and subsurface flow—is the part of the cycle of most direct concern to people. Globally, water is one of our most abundant renewable resources. However, more than 99 percent of the earth's water is unavailable or unsuitable for human use because of its location or its salinity. Water is used in tremendous quantities compared to other resources, and ensuring an adequate quantity and quality of water will be an increasing problem.

Water's unique properties make it indispensable to life as we know it. Many of these properties arise from the dipolarity (unequal charge distribution) of its molecules. As the

CASE HISTORY The Grand Canyon

The Grand Canyon of the Colorado River (Figure 10.B) provides a good example of a river's adjustment to the impact of a large dam. In 1963 the Glen Canyon Dam was built upstream from the Grand Canyon. Construction of the dam drastically altered the pattern of flow and channel process downstream: From a hydrologic viewpoint, the Colorado River was tamed. Before the Glen Canyon Dam, the river reached a maximum flow in May or June during the spring snowmelt, then flow receded during the remainder of the year, except for occasional flash floods caused by upstream rainstorms. During periods of high discharge, the river had a tremendous capacity to transport sediment (mostly sand and silt) and vigorously scoured the channel. The high floods also moved large boulders off the rapids, which formed because of shallowing of the river where it flows over alluvial fan or debris flow deposits delivered from tributary canyons to the main channel. As the summer low flow approached, the stream was able to carry less sediment, so deposition along the channel formed large bars and terraces, known as **beaches** to people who rafted the river.

After the dam was built, the mean annual flood (the average of the highest flow each year) was reduced from approximately 2500 cubic meters per second (cms) to 800 cms, and the 10-year flood was reduced from about 3500 cms to 860 cms. On the other hand, the dam did control the flow of water to such an extent that the median discharge actually increased from about 210 cms to 350 cms. The flow is highly unstable, however, because of fluctuating needs to generate power, and the level of the river may vary by as much as 5 m per day, with a mean daily high discharge of about 570 cms and a daily low of 130 cms. The dam also greatly affected the sediment load of the Colorado River through the Grand Canyon: The median suspended sediment concentration was reduced by a factor of about 200 immediately downstream from the dam. A lesser reduction in sediment load occurred farther downstream because tributary channels continued to add sediment to the channel (16).

The change in hydrology of the Colorado River in the Grand Canyon has greatly changed the river's morphology. The rapids may be becoming more dangerous because large floods no longer occur—flows that had previously moved some of the large boulders farther downstream. In addition, some of the large sandbars (beaches), which are valuable

▲ **FIGURE 10.B** The Colorado River in the Grand Canyon. The sandbar in the lower left corner is being used by river rafters whose numbers have begun to impact the canyon environment. As a result, the number of people allowed to raft through the canyon is restricted. (*Larry Minden/Minden Pictures*)

"universal solvent," water is an essential component of all organisms and is important in determining the composition of soils. Water forms thin films around soil particles, and these films are important in the movement of water above the groundwater table.

The flow of water on land is divided by drainage basins, or watersheds. Surface-water runoff and sediment yield vary greatly from one drainage basin to another and are influenced by geographic, physiographic, climatic, and biologic factors. The three major paths by which water on slopes reaches a stream channel and is exported from the drainage basin are overland flow (surface flow), throughflow (shallow subsurface flow), and groundwater flow (flow of water below the water table). Understanding these paths is critical to understanding how land-use change may influence runoff and sediment production.

Groundwater occurs in a *zone of saturation* below the water table. Its major source is precipitation that infiltrates the *recharge zone* on the land surface and moves down through the *vadose zone*, which is seldom saturated. An *aquifer* is a zone of earth material capable of supplying water at a useful rate from a well. The presence of a *confining layer* above an aquifer may raise water in the aquifer to the surface. Both the direction and the rate of ground-wildlife habitat, are eroding because the river is deficient in sediment below the dam and is picking up more sediment and thus causing erosion.

Changes in the river flow (mainly deleting the high flows) have also resulted in vegetational shifts. Before the dam was built, three nearly parallel belts of vegetation were present on the slopes above the river. Adjacent to the river and on sandbars grew ephemeral plants, which were scoured out by yearly spring floods. Above the high-water line were clumps of thorned trees (mesquite and catclaw acacia) mixed with cactus and Apache plume. Higher yet could be found a belt of widely spaced brittle brush and barrel cactus (17). Closing the dam in 1963 tamed the spring floods for 20 years, and plants not formerly found in the canyon, including tamarisk (salt cedar) and indigenous willow, became established in a new belt along the river banks.

In June 1983 a record snowmelt in the Rocky Mountains forced the release of about 2500 cms, which is about three times that normally released and about the same as an average spring flood prior to the dam. The resulting flood scoured the river bed and banks, releasing stored sediment that replenished the sediment on sandbars and scoured out or broke off some of the tamarisk and willow stands. The effect of the large release of water was beneficial to the river environment and emphasizes the importance of the larger events (floods) in maintaining the system in a more natural state. Perhaps management of rivers below some dams should call for periodic release of large flows to help cleanse the system. As an experiment, or "test flood," between March 26 and April 2 of 1996, 1274 cms of water was released from the dam in order to redistribute the sand supply. The floods resulted in the formation of 55 new beaches and added sand to 75 percent of the existing beaches. It also helped rejuvenate marshes and backwaters, which are important habitats to native fish and some endangered species. The experimental flood was hailed as a success (18), but a significant part of the new sand deposits were subsequently eroded away (19).

The 1996 test flood remobilized sand, scouring it from the channel bottom and banks of the Colorado River below Glen Canyon Dam, depositing it on sandbars (beaches). However, little new sand was added to the river system from tributaries to the Colorado River, as they were not in flood flow during the test flood. The sand was mined from the river bed below the dam, and as such is a limited, nonrenewable source that can't supply sand to sandbars on a sustainable basis. A new, creative idea has recently been suggested (19). The plan is to use the sand delivered to the Grand Canyon by the Little Colorado River (a relatively large river with drainage area of 67,340 km^2) (Figure 10.19) that joins the Colorado River in the canyon downstream from Lee's Ferry. In 1993 a flood on the Little Colorado River delivered a large volume of sand to the Colorado River in the Grand Canyon, and prominent beaches were produced. Unfortunately, a year later the beaches were nearly eroded away by the flow of the Colorado River. The problem was that the beaches were not deposited high enough above the bed of the Colorado and so were vulnerable to erosion from normal post-dam flows. The idea suggested in the new study is to time the releases of flood flows from Glen Canyon Dam with sand-rich spring floods of the Little Colorado River. The resulting combined flood of the two rivers would be larger, and the new sand from the Little Colorado would be deposited higher above the channel bed and less likely to be removed by lower flows of the Colorado. Evaluation of the hydrology of the Little Colorado River suggests the opportunity to replenish sand on the beaches occurs, on average, once in 8 years. The proposed plan would restore or recreate river flow and sediment transport conditions to be more as they were prior to the construction of Glen Canyon Dam, conditions that formed and maintained the natural ecosystems of the canyon (19).

One final impact of the Glen Canyon Dam is the increase in the number of people rafting through the Grand Canyon. Although rafting is now limited to 15,000 people annually, the long-range impact on canyon resources is bound to be appreciable. Prior to 1950, fewer than 100 explorers and river runners had made the trip through the canyon. We must concede that the Colorado River of the 1970s and 1980s is a changed river. Despite the 1983 and 1996 floods that pushed back some of the changes, river restoration efforts cannot be expected to return it to what it was before construction of the dam (16,17,19). On the other hand, better management of the flows and sediment transport will improve and better maintain river ecosystems.

water movement depend on the *hydraulic gradient* (in the simplest case, approximately the slope of the water table) and the *hydraulic conductivity* of the earth material through which the water moves. This relationship is expressed quantitatively by *Darcy's law*, which has many important applications to groundwater problems. Interactions between surface water and groundwater are important environmentally because pollution in surface water may eventually contaminate the groundwater.

To evaluate a region's water supply, a water budget is developed to define the natural variability and availability of water. Water supply is limited, even in areas of high precipitation and runoff, by our inability to store all runoff and by the large annual variation in stream flows. In many areas groundwater is being mined (withdrawal exceeds natural replenishment), and in some areas this has permanently changed the character of the land. Desalination of seawater will continue to be used where other water sources are unavailable, but large-scale desalination is not likely because of the high costs of energy and transportation involved.

Water uses are categorized as offstream (including consumptive) and instream. Multiple instream uses—hydroelectric power, recreation, and fish and wildlife habitats—often have conflicting requirements; how water resources should

A CLOSER LOOK Wetlands

The term **wetlands** (21) refers to landscape features such as swamps (wetland dominated by trees or shrubs), marshes (a wetland that is frequently or continuously inundated by water), bogs (a wetland that accumulates peat deposits), prairie potholes (small marshlike ponds), and vernal pools (shallow depressions that occasionally hold water). Some of these features are shown in Figure 10.C. The common feature and operational definition of wetlands is that they are inundated by water or the land is saturated to a depth of a few centimeters for at least a few days most years. The major components used to determine the presence or absence of wetlands are hydrology (wetness), type of vegetation, and type of soil. Of the three, hydrology is often the most difficult to define because some wetlands are only wet for a very short period each year. However, the presence of water, even for short periods on a regular basis, does give rise to characteristic wetland soils and specially adapted vegetation. Recognition of soils and vegetation greatly assists in identifying the wetland itself in many cases (22, 23).

Wetlands and their associated ecosystems have many important environmental features:

- Coastal wetlands such as salt marshes provide a buffer for inland areas from coastal erosion associated with storms and high waves.
- Wetlands are one of nature's natural filters. Plants in wetlands may effectively trap sediment and toxins.
- Freshwater wetlands are a natural sponge. During floods, they store water, helping to reduce downstream flooding. The stored water is slowly released following the flood, nourishing low flows of river systems.
- Wetlands are often highly productive lands where many nutrients and chemicals are naturally cycled while providing habitat for a wide variety of wildlife and plants.
- Freshwater wetlands are often areas of groundwater recharge to aquifers. Some of them—a spring-fed marsh, for example—are points of groundwater discharge.

Although most coastal marshes are now protected in the United States, freshwater wetlands are still threatened in many areas. It is estimated that 1 percent of the nation's total wetlands is lost every 2 years. Freshwater wetlands account for nearly all of this loss. In just the past 200 years about one-half of the wetlands in the United States, including about 90 percent of the freshwater wetlands, have disappeared as a result of being drained for agricultural purposes or filled for urban or industrial development.

Because so many wetlands have been damaged or destroyed, there is a growing effort to restore wetlands. Unfortunately, restoration is not usually an easy task, for wetlands are a result of complex hydrologic conditions that may be difficult to restore if the water has been depleted or is being used for other purposes. Ongoing research is carefully documenting the hydrology of wetlands as well as the movement of sediment and nutrients. As more information is gathered concerning how wetlands work, restoration is likely to be more successful.

be partitioned to meet the various uses is a controversial subject. Water is often transported long distances by canals, from areas of abundant rainfall to areas of high use, sometimes with severe adverse effects on ecosystems. Trends in water use during the last few decades are encouraging: Total withdrawals of water have been reduced and leveled off somewhat as the U.S. population has increased. This suggests water conservation has improved and more water is being reclaimed. During the next several decades, consumptive use of water will increase because of greater demands from a growing population and industry. However, the total water withdrawn from streams and groundwater in the United States may decrease slightly because of greater awareness of the need for conservation by individuals and industries.

Water-resource management needs a new philosophy that considers geologic, geographic, and climatic factors and utilizes creative alternatives. The Colorado River is one of the most heavily regulated rivers in the world, with all of its flow apportioned among a large number of users; it therefore provides many lessons for future water management. Damming of the river has helped ensure delivery of the allocated water and allowed irrigation of formerly dry areas, but it has brought about significant ecosystem changes. In addition, upstream irrigation has greatly increased the salinity of the water downstream.

Construction of dams, reservoirs, and canal systems has caused significant environmental and health problems, especially in developing countries. For example, the Aswan Dam, along with its associated canal system in Egypt, has brought an increase in diseases carried by snails and mosquitoes. As nations continue to develop their water resources, they will need to plan at the ecosystem level to try to avoid these problems.

Water is an integral part of ecosystems, and its increasing use by people is a major contributor to the degradation of ecosystems. Loss or damage of wetlands is an area of particular environmental concern in the United States because significant portions of these ecosystems have already been lost, including 90 percent of the freshwater wetlands.

(a) (b) (c)

◀ **FIGURE 10.C** Several types of wetlands: (a) Chesapeake Bay salt marsh (*Comstock*); (b) freshwater cypress swamp in North Carolina (*Carr Clifton/Minden Pictures*); and (c) prairie potholes in the Dakotas (*Jim Brandenburg/Minden Pictures*).

REFERENCES

1. **Gleick, P. H.** 1993. An introduction to global fresh water issues. In *Water in crisis*, ed. P. H. Gleick, pp. 3–12. New York: Oxford University Press.
2. **Council on Environmental Quality and the Department of State.** 1980. *The global 2000 report to the president: Entering the twenty-first century*, vol. 2. Washington, DC: Council on Environmental Quality.
3. **Water Resources Council.** 1978. *The nation's water resources, 1975–2000*, vol. 1.
4. **Singer, M. J., and Munns, D. M.** 1978. *Soils: An introduction.* New York: Macmillan.
5. **Likens, G. E., Bormann, F. H., Pierce, R. S., Eaton, J. S., and Johnson, N. M.** 1977. *The biogeochemistry of a forested ecosystem.* New York: Springer-Verlag.
6. **Florsheim, J. L., Keller, E. A., and Best, D. W.** 1991. Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California. *Geological Society of America Bulletin* 103:504–11.
7. **Winter, T. C., Harvey, J. W., Franke, O. L., and Alley, W. M.** 1998. *Ground water and surface water. A single resource.* U.S. Geological Survey Circular 1139.

8. **Solley, W. B., Pierce, R. R., and Perlman, H. A.** 1998. *Estimated use of water in the United States in 1995.* U.S. Geological Survey Circular 1200.
9. **Alexander, G.** 1984. Making do with less. *National Wildlife* (Special Report), February–March, 11–13.
10. **Leopold, L. B.** 1977. A reverence for rivers. *Geology* 5:429–30.
11. **Graf, W. L.** 1985. *The Colorado River.* Association of American Geographers.
12. **Nash, R.** 1986. Wilderness values and the Colorado River. In *New courses for the Colorado River,* eds. G. D. Weatherford and F. L. Brown, pp. 201–14. Albuquerque: University of New Mexico Press.
13. **Hundley, N., Jr.** 1986. The West against itself: The Colorado River—An institutional history. In *New courses for the Colorado River,* eds. G. D. Weatherford and F. L. Brown, pp. 9–49. Albuquerque: University of New Mexico Press.
14. **Ballard, S. C., Michael, D. D., Chartook, M. A., Clines, M. R., Dunn, C. E., Hock, C. M., Miller, G. D., Parker, L. B., Penn, D. A., and Tauxe, G. W.** 1982. *Water and western energy: Impacts, issues, and choices.* Boulder, CO: Westview Press.
15. **Joseph, P.** 1998. The battle of the dams. *Smithsonian* 29:48–61.
16. **Dolan, R., Howard, A., and Gallenson, A.** 1974. Man's impact on the Colorado River and the Grand Canyon. *American Scientist* 62:392–401.
17. **Lavender, D.** 1984. Great news from the Grand Canyon. *Arizona Highways Magazine,* January, 33–38.
18. **Hecht, J.** 1996. Grand Canyon flood a roaring success, *New Scientist* 151:8.
19. **Lucchitta, I., and Leopold, L.B.** 1999. Floods and sandbars in the Grand Canyon. *Geology Today* 9:1–7.
20. **Covich, A. P.** 1993. Water and ecosystems. In *Water in crisis,* ed. P. H. Gleick, pp. 40–55. New York: Oxford University Press.
21. **Gleick, P. H., Ed.** 1993. *Water in crisis,* Table F.1, p. 288. New York: Oxford University Press.
22. **Levinson, M.** 1984. Nurseries of life. *National Wildlife* (Special Report), February–March, 8–21.
23. **Holloway, M.** 1991. High and dry. *Scientific American* 265(6): 16–20.

KEY TERMS

water cycle (p. 263)
watershed (drainage basin) (p. 264)
throughflow (p. 266)
overland flow (p. 266)
groundwater flow (p. 266)
sediment yield (p. 266)
vadose zone (p. 267)
water table (p. 267)
capillary fringe (p. 267)
aquifer (p. 269)
aquitard (p. 269)
artesian (p. 269)
cone of depression (p. 269)
hydraulic gradient (p. 270)
hydraulic conductivity (p. 270)
porosity (p. 270)
effluent stream (p. 271)
influent stream (p. 271)
Darcy's law (p. 272)
Darcy flux (p. 272)
fluid potential (hydraulic head) (p. 272)
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water conservation (p. 280)
water management (p. 281)
wetlands (p. 288)

SOME QUESTIONS TO THINK ABOUT

1. You have been hired by a consulting company to evaluate the water resources of the region in which you live. Your first task is to develop a rough water budget. How would you go about doing this? What sorts of data would you need? How could the data be used to evaluate your water-resource situation?
2. You are working for a planning agency trying to come to grips with potential water use for a moderately sized river basin of about 5000 km^2 that discharges into the ocean. People interested in environmental quality and wilderness want to see adequate river flows to maintain healthy ecosystems along the river, whereas agricultural and urban interests see the flow as a potential source of water to irrigate crops and provide basic water supply. Finally, the river is navigable, and certain users are interested in seeing that there are adequate flows for using the river as a transportation route. After examining the idealized diagram shown in Figure 10.14, you are fairly certain that conflicts of interest will arise in the use of the water in the river. Outline what these conflicts are likely to be and what steps could possibly be taken to help in mediation or conflict resolution concerning the water resources of the river.
3. Find out what (if any) management principles are being used for the water resources of your community. How could some of the suggestions put forth by Luna Leopold be applied to your specific water-management needs? Pay particular attention to those times when water shortages might occur.
4. What sort of wetlands are found in your region? Outline a plan to inventory the wetlands and make an assessment of how much of the resource has been lost or damaged. Is wetlands restoration possible in your region, and what would you need to do to make it successful?