CHAPTER 3

SURFACE WATER HYDROLOGY

WHAT IS SURFACE WATER HYDROLOGY?

WATERSHEDS

OVERLAND FLOW

RIVERS

LAKES

TRANSPORT AND DEPOSITION

WATER MEASUREMENT

FLOOD EVENTS

The rapids beat below the boat
Deep in the heart of the land
Feel the pulse of the river in the pulse of your throat
Deep in the heart of the land.

"Veins in the Stone" © Lynn E. Noel 1993.
In *Voyages: Canada's Heritage Rivers*
(St. John's, Newfoundland, CANADA: Breakwater Books, 1995).
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Leonardo da Vinci (1452–1510) spent much of his life studying human anatomy. Through his dissections and observations, da Vinci developed comparisons of the body to natural features of the world (Figure 3.1). He compared human arteries to rivers on Earth, the pulsing of blood through the body to the flow of mountain streams, and arterial bleeding to river flooding.

Hydrology, the study of moving water, is somewhat similar to the science of medicine. Rivers deliver the life-blood of water, analogous to the veins and arteries of the human body, throughout the world. Like blood, water cleanses, nourishes, and gives life to plants and animals. Like medicine, water is a fascinating field of study and involves water engineers, hydrologists, and other scientists who investigate water movement, its interaction with landforms, chemical processes, and how water affects other natural systems on Earth. Similarly, medical doctors, nurses, and other health professionals study the movement of blood through the body, its interaction with glands, chemical processes, and how blood affects other physiological processes in the human body. Da Vinci was a keen observer of these similarities in his study of anatomy and hydrology.

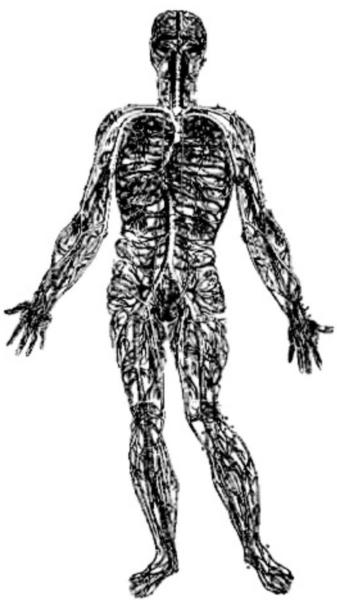

FIG. 3.1 Leonardo da Vinci was fascinated by the similarities between the organization of rivers on the surface of the Earth and the human circulatory system. He developed numerous sketches of both natural systems.

WHAT IS SURFACE WATER HYDROLOGY?

Chapter 2 presented the hydrologic cycle processes of precipitation, runoff, storage, evaporation, and condensation. **Surface water hydrology** is the study of moving water found in rivers, open channels, and runoff flowing across the open land surface. Many ancient cultures utilized the science of hydrology to create sophisticated practices to control or capture moving surface water. This was especially true for cultures in arid settings such as the Anasazi Indians of southwest Colorado, the Sumerians along the Tigris and Euphrates rivers, and the Egyptians along the Nile River (see Chapter 1).

According to the dictionary, a *stream* is a "flow of running water, large or small," whereas a *river* is a "large stream of water." Most people use these terms interchangeably to denote a body of running water of any size. However, a stream is generally considered to be smaller than a river, a creek smaller than a stream, and a brook even smaller. Rills form during precipitation events and gather downhill to form a brook which, if it grows, creates a creek. In this textbook, river and stream will be used to denote a flow of running water, large or small.

WATERSHEDS

The total land area that drains surface water to a common point (or common body of water) is called a **watershed** (also called a *river basin, drainage basin,* and *catchment*). Watersheds can be as small as a parcel of ground that drains into a pond or as large as the 1.26 million square miles (3.26 million km^2) in the United States and Canada that drain into the Mississippi River and its tributaries (see Figure 3.2). The world's largest watershed, the Amazon River Basin, is located in South America and empties into the Atlantic Ocean. Although it contains only 2 percent of the global land area, the Amazon delivers almost 20 percent of the global river discharge to the ocean.

States, provinces, and countries generally contain several watersheds. Canadian watersheds, for example, drain into the Pacific, Atlantic, and Arctic oceans. In Colorado, surface water located west of the Continental Divide of the Rocky Mountains flows toward the Pacific Ocean, whereas surface water east of the divide flows toward the Gulf of Mexico and the Atlantic Ocean. In eastern North Dakota and western Minnesota, water located in the Red River Basin flows north through Manitoba, into Lake Winnipeg, and northward into Hudson Bay. Water in western North Dakota flows south to the Mississippi River and ultimately into the Gulf of Mexico near New Orleans, Louisiana.

Table 3.1 shows the 10 largest watersheds in the world. The quantities under the column "Average Discharge" are in cubic feet per second (cfs) and cubic meters per second (cms). These are rates of flow and are common units of water measurement. (These units will be explained later in this chapter but are presented now to show relationships between drainage areas and average water discharge.) Note that the average discharge of the Amazon River is nearly 10 times greater than that of the Mississippi.

Table 3.1 also shows that the drainage areas of the Zaire River in central Africa and the Mississippi River in the United States are almost identical. Yet, the average discharge is over double in the Zaire River Basin. What climatic factors discussed in Chapter 2 would probably account for this difference?

DELINEATING A WATERSHED

A watershed is delineated by a ridge or drainage divide that marks the boundary of the drainage basin and can be easily identified on topographic maps. All surface water runoff below a ridge line will flow downhill within the watershed. The incline of terrain is generally downhill toward the

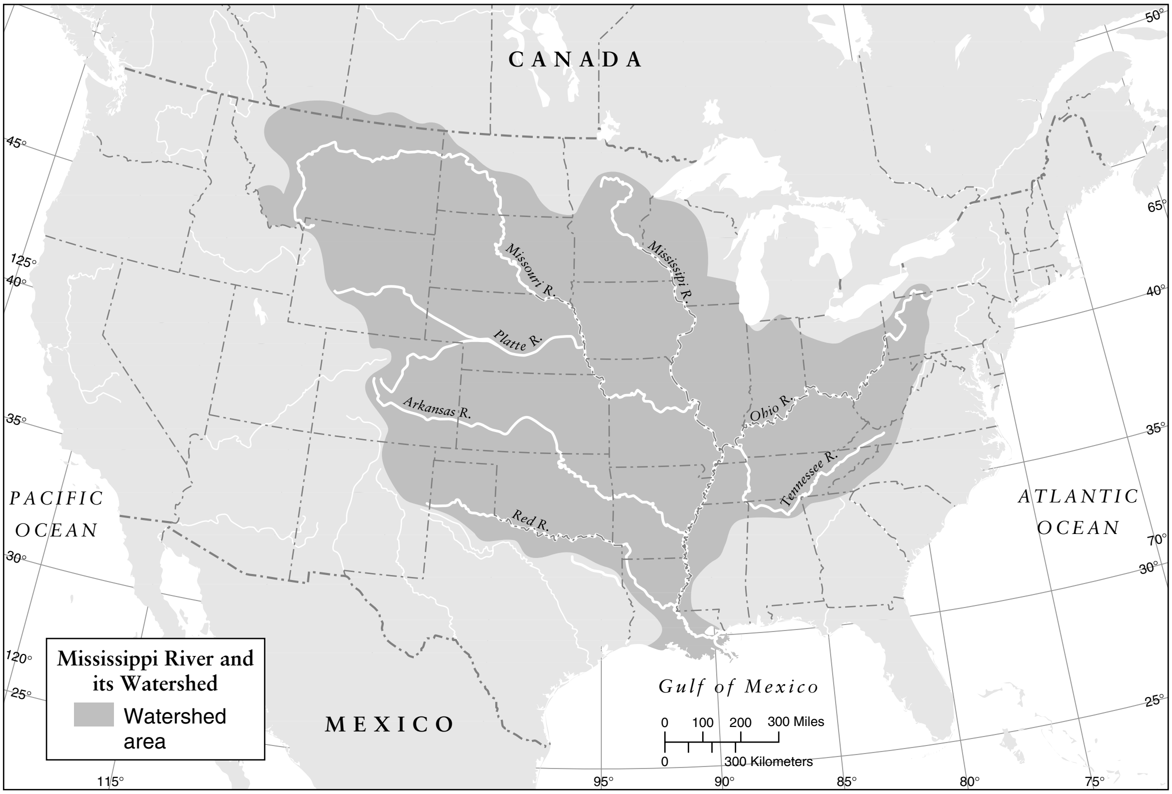

FIG. 3.2 Mississippi River Watershed

TABLE 3.1 World's Largest Drainage Basins

River Basin	Drainage Area (1000 mi²)	Drainage Area (1000 km²)	Average Discharge cfs*	Average Discharge cms*
Amazon, South America	2380	6160	6,183,750	175,100
Zaire (Congo), Africa	1480	3830	1,413,430	40,000
Mississippi, United States	1260	3260	649,820	18,400
Parana-La Plata, South America	1090	2820	526,500	14,910
Yenisei, Russia	1000	2590	627,560	17,770
Lena, Russia	970	2510	568,900	16,110
Yangtze (Chang Jiang), China	750	1940	1,008,480	28,560
Ganges-Brahmaputra, India	570	1480	1,087,990	30,810
Orinoco, South America	380	980	1,232,510	34,900
Mekong, Vietnam	310	800	526,500	14,910

*cubic feet per second and cubic meters per second.

Source: Adapted from *The World in Figures* by Victor Showers (Toronto: John Wiley & Sons, 1973).

main channel of a river. The boundaries of a watershed can be delineated by first locating the lowest point, or watershed outlet, on a topographic map. Then, higher elevations can be followed until a ridge, or high point, is identified.

A CLOSER LOOK

Topography maps are invaluable tools for geographers, planners, engineers, hikers, and others. Since 1879, the U.S. Geological Survey (USGS) has developed **topographic (topo) maps** that provide information on slope, elevation, distance, and physical features for the entire United States. USGS topographic maps (also called quad sheets) present land surface information at various scales of measurement. **Scale** is the relationship between the size of a map feature and its actual dimensions on the ground. USGS maps are drawn in many scales, but 1:24,000 is the most common. The first number of the scale represents the units on the map (i.e., 1 in.), and the second number represents the units on the ground (i.e., 24,000 in.). This means that a distance of 1 inch on a map, with a scale of 1:24,000, equals 24,000 inches (2,000 feet, or 0.8 km) on the land surface being displayed.

Contour lines follow a constant elevation above sea level. A USGS topographic map generally has intervals of 20 feet (6 m) between contour lines to show changes in elevation. In a relatively level area, the contour lines on a topographic map will be fairly straight with large distances (perhaps miles or kilometers) between them. On the other hand, contour lines may almost touch in a mountainous location because the change in elevation (gradient) is very steep and abrupt (see Figure 3.3).

The USGS has maps available through the Internet at http://mcmcweb.er.usgs.gov/topomaps/ordering_maps.html. Topo maps can be obtained by calling 1-800-USA-MAPS, or by writing to the following address: USGS Information Services, Box 25286, Denver Federal Center, Denver, Colorado 80225.

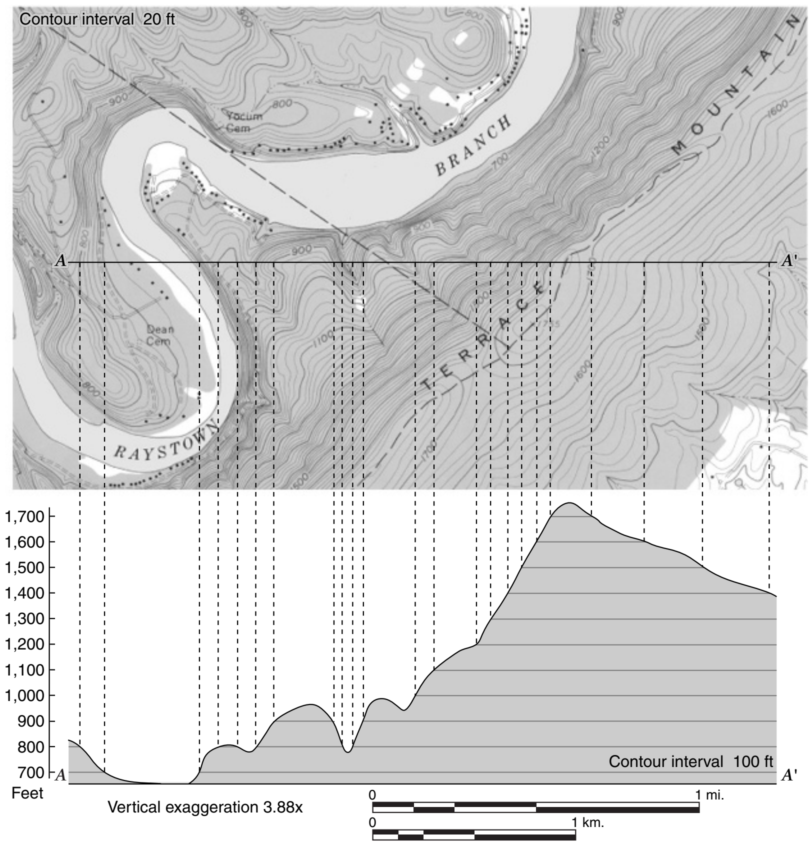

FIG. 3.3 Hills, valleys, and slopes of a topographic map. The steep slopes on the map are represented by closely spaced contour lines. Relatively level areas are shown by contour lines with greater distances between contours (or no contour lines as seen along the surface of the river). The profile below the contour map is exaggerated to make the differences in elevation prominent. Could you determine the general gradient of a river with a topographic map? How?

Another good source of topographical maps is through Topozone.com. Additional information regarding topographic maps can also be found in the Appendix.

Three simple rules can be followed when trying to determine watershed boundaries on a map:

1. Surface water generally flows at right angles across contour lines on a map.
2. Ridges are indicated by the highest elevation contour line in an area.
3. Drainages are indicated by contour lines pointing upstream.

Once the boundaries of a watershed have been determined, several watershed parameters can be computed such as size, maximum and minimum elevations, shape, slope, and drainage patterns. Surface water flows can also be predicted based on various potential precipitation events. Hydrologists—people who study and measure moving water—are also concerned with the aspect and orientation of a watershed. The **aspect** of a watershed is the direction of exposure of sloping lands, whereas **orientation** is the general direction of the main portion of a river as it moves down a watershed. A river with an east-west orientation will probably have slopes that are generally north-south in aspect.

POLICY ISSUE

Watersheds provide a basic geographic unit for water resources planning activities. Water quality plans, streamflow calculations, and flood projections are generally based on watershed size, land use, and other physical features. In 1972, the Nebraska Unicameral Legislature used watersheds to reorganize hundreds of local units of government (such as soil conservation districts, weed control districts, and flood-control districts). In place of these single-purpose agencies, 24 natural resources districts (NRDs) were created to manage surface water and groundwater, soil conservation, weed control, and many other natural resources planning, administration, and development functions. Nebraska's NRDs will be discussed in more detail in Chapter 10.

OVERLAND FLOW

Rain that falls on the land surface within a watershed will immediately move in one of three general directions. First, rain may evaporate back into the atmosphere as described in Chapter 2. Second, precipitation may **percolate**, or seep, down into the soil and eventually become groundwater. (The processes of groundwater movement will be discussed in detail in Chapter 4.) Third, rain may move along the land surface as runoff during and after a storm event. Runoff water that is moving toward a river or stream is called **overland flow.** Some overland flow may become stored in small ponds, wetlands, or lakes before reaching a flowing stream. Overland flow rates and volumes are very dependent on precipitation rates, duration of a storm event, and the spatial distribution of precipitation.

A second feature of surface water runoff, called **interflow,** occurs when precipitation percolates just below the land surface and moves in the same direction as overland flow. Interflow moves in subsurface materials at a slower rate than moving water on the surface and will arrive at a river later than overland flow. A heavy 45-minute downpour typically generates a more rapid overland flow than a calm, soaking shower over a 48-hour period that generates interflow. This variation in surface water runoff is an important reason why accurate precipitation measurement, discussed in Chapter 2, is so important in water resources management.

Both overland flow and interflow are greatly affected by human development. Hard surfaces, such as parking lots, roads, and rooftops act as funnels to drainage pathways that ultimately empty into rivers, streams, ponds, and lakes. Impervious barriers created by development also inhibit interflow and percolation into the soil. By contrast, forests, cultivated ground, open space, parks, and other vegetated areas are relatively porous and slow the runoff of precipitation and promote percolation into the soil.

RIVERS

Rivers contain less than 0.01 percent of the Earth's water but originate in several possible sources. Some are fed by springs or small streams coming together to create larger rivers of water. Some originate in lakes, such as the Mississippi River at Lake Itasca in northern Minnesota, or Egypt's Nile River which begins near Lake Tama in the highlands of Ethiopia. Other rivers, such as the Colorado River in the Rocky Mountains of Colorado, begin as trickles of melted snow water.

COMPONENTS OF A RIVER

A river consists of a main channel and all tributaries that flow into it. The beginning of a river is called its **headwaters**, or source. **Tributaries** are smaller streams that combine to form larger streams and ultimately rivers. When viewed from above or on an aerial or satellite photo, tributaries often look like the branches of a tree. The site at which a tributary joins the main river channel is called the **confluence** of a river. **Upstream** denotes a location toward the headwaters of a river or tributary, whereas **downstream** is toward the direction of a confluence with a larger stream, mouth, or other end point of a river. The imaginary line that connects the deepest points of a river channel is called the **thalweg** of a river.

Overland flow and interflow are important sources of water for many rivers. After a rainstorm, water levels in rivers often rise and cause some water to percolate into the banks (sides) of a river (called **bank storage**). As local conditions become drier, this bank storage will slowly move back into the river as flow decreases. Porous riverbanks allow significant amounts of storm runoff to be temporarily held as bank storage and can reduce the threat of flooding downstream.

The zone beneath a river is called the **hyporheic** (from the Greek meaning "to flow beneath") **zone** and varies in depth depending on the composition and size of a river bottom. The hyporheic zone can extend beneath a riverbed to a depth of a few inches (less than 10 cm) or down to several feet (1 m or more). Oxygen is the limiting factor that determines what type of organisms can survive in this area, with the colder waters of high altitudes supporting the most life. One researcher in Germany counted more than 365,000 organisms per square foot (3.9 million/m^2) beneath a German stream, while Canadian biologists found more invertebrates living in the hyporheic zone of an Ontario river than in the sand, gravel, and other materials on the river bottom itself. (1)

RIVER MORPHOLOGY

Geomorphology is the study of forces that shape the surface of the Earth. The greatest force in the alteration of land is moving water, and its effects can easily be seen along rivers. Rivers develop many features after years of traveling the same course. A "young" river has a V-shaped valley, with some rivers having almost vertical walls and swift-flowing water (see Figure 3.4). As a river continues toward its mouth and seeks a base level, the slope of the river channel generally decreases. Eventually, the river valley widens and becomes more U-shaped where silt and sand have created a wide plain caused by previous floods.

The width and depth of a river increase as it proceeds downstream. This occurs due to increased volumes of water and erosion. An individual can step across the Mississippi River at its source at Lake Itasca in northern Minnesota, where this mighty river is only 4 inches (10 cm) deep. However, one would have to be an excellent swimmer to cross the approximately half-mile-wide (0.8 km) and 200-foot-deep (61 m)

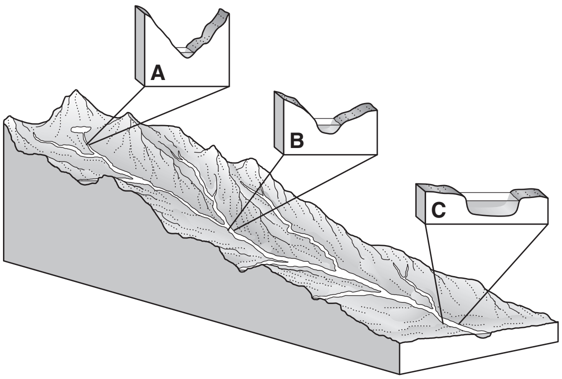

FIG. 3.4 Changes in stream properties along a watershed are denoted by changes in channel width and depth. Cross sections A, B, and C represent changing gradients and discharge as a river system flows through a watershed toward a confluence or to the ocean. Notice how the river system changes from a V-shaped channel to a U-shaped channel as it moves downstream.

channel of the Mississippi River at New Orleans before it enters the Gulf of Mexico (Figure 3.5).

In 1802, Scottish geologist John Playfair described the formation of rivers with the following statement, which today is known as Playfair's Law:

Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportional to its size, and all of them together forming a system of valleys connecting with one another, and having such a nice adjustment of their declivities that none of them join the principal valley at either too high or too low a level; a circumstance which would be infinitely improbable if each of these valleys were not the work of the stream which flows in it. (2)

Some rivers travel in relatively direct routes to their destinations while others develop meanders. **Meanders** are broad, looping bends in a river caused by the natural behavior of flowing water. A profile of a meandering stream shows a series of pools and shallows with deeper sections found downstream of a looping river bend. The inner sides of meanders, or bends, become areas where geologic material is deposited, while outer edges of meanders generally incur erosion. This combination of geologic deposition and erosion creates an asymmetrical channel cross section in a meandering river system. Pools that exist at the outsides of bends will be scoured during high flows but will

FIG. 3.5 The Mississippi River is the third largest drainage basin in the world, exceeded in size only by the watersheds of the Amazon River in South America and the Zaire River in Africa. The Mississippi provides drainage for 31 states and 2 Canadian provinces, and essentially funnels all river flows past downtown New Orleans, Louisiana (shown at right). Water from as far west as Montana and as far east as New York contributes to the flow of the river at this point. Garciliaso de la Vega, a member of DeSoto's Spanish expedition in search of gold in 1543, described the first recorded flood that winter. It began on March 10 and crested 40 days later. The Mississippi River finally returned to its banks in late May, a flood of nearly 80 days. Major floods in 1849, 1850, 1882, 1912, 1913, and 1927 led to increased federal involvement in flood-control efforts in the basin and will be discussed in Chapter 9.

receive deposits of geologic and organic materials during periods of low flow. *River crossings* are locations where flowing water moves from an inner side of a meander to outer edges, called *crossovers*. These crossovers are scoured during low flow but become covered with deposits during high-flow periods. (3) Meanders tend to migrate downstream as a result of erosion and deposition on opposite sides of meander bends.

SIDEBAR

The word *meander* is derived from the old Roman name for the Menderes River in Turkey. In Roman times it was called the Maeander River and had such a winding, circuitous course that it was thought to occasionally flow backward. (4)

A river will often develop meanders if the bank material is erodible. **Oxbow lakes** and wetlands often form in the river channel of an abandoned meander. Meanders may become isolated from the main channel if the stream becomes so sinuous that the narrow neck of land that separates adjacent meanders becomes breached during a flood event. These isolated lakes are very common along the Missouri, Mississippi, and Rio Grande rivers in the United States.

A CLOSER LOOK

The DeSoto National Wildlife Refuge in western Iowa is the site of the buried steamboat *Bertrand.* In 1865, a week before the Civil War ended, the boat was headed up the Missouri River for the goldfields of Montana. It had been heavily loaded in St. Louis, Missouri, with crates of mercury (for mining), clothing, tools, housewares, and food, including olive oil and mustard from France, canned fruits, alcoholic beverages, powdered lemonade in a can, brandied cherries, pickles, and a host of other items. The steamboat hit a snag hidden in the Missouri River and sank 20 miles (32 k) north of Council Bluffs, Iowa. Today an impressive museum has been built overlooking the abandoned oxbow lake where the *Bertrand* was found. The site is located miles from the present-day Missouri River. (5)

Braided rivers, consisting of intertwined channels separated by small, temporary islands, form when excess geologic materials cannot be removed by the flow of a river and the channel simply moves to a location of less resistance. These rivers tend to be very wide and relatively shallow, with coarse bed material. Islands are sometimes barren or can have tree and shrub communities such as willows, cottonwood trees, or other vegetation common to the area. Floods can sometimes remove this growth, but low river flows allow the plants to thrive, changing the local habitat for wildlife. Good examples of braided river systems are the Platte River in Nebraska and the Rakaia River in New Zealand.

Braided rivers are common in glacial regions where a great deal of sand and gravel are available and washed away into broad, flooded plains. Some braided rivers spread out to a width of more than 0.5 mile (0.8 km) and have a depth of only a few feet (1 m or less). Braided rivers seldom contain many living organisms because the sands and gravels of the riverbed offer little cover. In addition, the constant shifting of the riverbed reduces suitable habitat for invertebrates in the hyporheic zone. However, some braided rivers, such as the Platte River, provide excellent habitat for numerous migratory waterfowl (Figure 3.6).

FIG. 3.6 Braided Platte River channel in central Nebraska. This area of the Platte contains numerous endangered species such as the whooping crane, piping plover, and least tern, and will be discussed in Chapter 12.

TYPES OF RIVERS

Rivers located in dry climates are often **ephemeral streams** that are not fed by any continuous water source and flow only after storm events. A stream that is **intermittent** flows both after storm events and during wet seasons when fed by groundwater. In the Sahara Desert of northern Africa, the beds of ephemeral rivers are called *wadies*. These dry riverbeds are so smoothed by floods that they are often used as roads during the dry season. Flash floods can catch caravans by surprise if a sudden thunderstorm in the distance is not detected. Similar dangerous situations often occur in the southwestern United States and northern Mexico where ephemeral rivers flow down *arroyos* (Spanish for "creek" or "gulch"). Campers sometimes sleep in dry *arroyos* since these makeshift campsites have soft beds of sand. However, sudden thunderstorms have swept unwary campers to their deaths. Crayfish *(Paranephrops planifrons)*, flatworms *(Polycelis nigra)*, and fairy shrimp *(Branchinecta packardi)* can survive in the harsh environment of ephemeral streams, some by burrowing a few feet (1 m or less) underground until moist sand or soil is reached. Some species produce eggs that can survive this dry environment until floods recur.

River channels that are located above groundwater systems often discharge some water through percolation. These are called **influent** or **losing rivers** since surface water moves from the stream channel into areas of groundwater storage. An **effluent** or **gaining river** is one that receives baseflow from groundwater and increases discharge (Figure 3.7). An effluent river is usually found in humid or wetter climates. A river can be effluent during parts of the year and influent during other months. Groundwater movement, and the relationship with rivers, will be discussed in detail in Chapter 4.

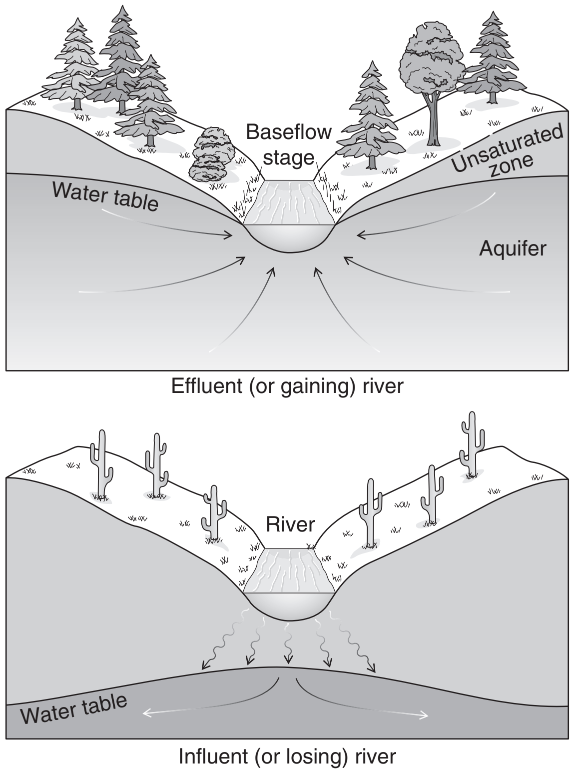

FIG. 3.7 Cross section of a gaining (or "effluent") stream, common in humid regions, and a losing (or "influent") stream, often found in arid or semiarid locations. Effluent streams actually gain water from the local groundwater system, while influent streams allow surface water to replenish groundwater in an area. Influent streams often become dry streambeds during periods of drought or in regions of arid climate.

GRADIENT

Typically, the **gradient** of a river decreases as it continues downstream, resulting in reduced stream velocity. The gradient is the slope or fall of a river and is measured in terms of feet per mile or meters per kilometer. For example, the Little Conemaugh River in Pennsylvania has an average slope of 53 feet per mile (10.0 m per km) over its 29-mile (46.7 km) length, whereas the Ohio River has an average slope of less than 6 inches per mile (9.5 cm per km). These variations in gradient affect stream velocity and material transport (discussed later in this chapter). The Red River in North Dakota and Manitoba averages a gradient of only 5 inches per mile (7.9 cm per km) and as little as 1.5 inches per mile

(2.4 cm per km) in some locations. This nearly flat gradient is located where the Red River flows through the bed of ancient Lake Agassiz, a glacial lake that covered portions of Manitoba, Ontario, Saskatchewan, North Dakota, and Minnesota. The lack of "fall" along the Red River is a major factor in the severity of floods, which can devastate the region, such as the one that occurred in 1997. During such high water, the floodwaters of the Red River essentially form a massive, slow-moving shallow lake and inundate broad areas of the ancient lake bed.

LAKES

A **lake** is any body of water, other than an ocean, that is of reasonable size, impounds water, and has little or no horizontal movement of water. Lakes can be created by glacial activity, volcanic explosions, stream channel abandonment, landslides, and human activity. Lake Superior, located between the United States and Canada, has the largest freshwater surface area in the world at 31,700 square miles (82,103 km^2).

The term *lake* can include shallow bodies of water only a few feet (meters) deep or "ponds" that can be 10 miles (16 km) long and hundreds of feet (over 60 m) deep. In Newfoundland, for example, almost every lake is called a pond, whereas in Wisconsin almost every pond is called a lake. Regardless of size, all lakes are considered **lentic** (Latin for "sluggish") habitats. The science of **limnology** deals with the characteristics and behavior of lakes. Table 3.2 presents the 10 largest lakes (in terms of surface area covered) in the world. (The Caspian Sea is listed since it is a static body of water not directly connected to an ocean.)

TYPES OF LAKES

Many natural lakes in the world were created by glacial activity. The process of scouring, gouging, and scraping by glaciers created depressions in the landscape that hold surface water. Most natural lakes are filled by rain or melting snow, although some are filled by glacial meltwater. If glacial debris blocked the upper reaches of a mountainous valley, a **cirque lake** was created when it filled with water. These are common in the Rocky Mountains of the United States and Canada, particularly in most ranges of Colorado, Wyoming, Montana, Alberta, and British Columbia. Glacial activity will be discussed in Chapter 4.

TABLE 3.2 Largest Lakes in the World

		Area		Maximum Depth	
Name	Location	(mi^2)	(km^2)	(ft)	(m)
Caspian Sea (salt water)	Azerbaijan, Russia, Kazakhstan, Turkmenistan, Iran	146,100	378,399	3363	1025
Lake Superior	Canada and United States	32,162	83,300	1332	406
Lake Victoria	Tanzania and Uganda, Africa	26,988	69,899	302	92
Lake Huron	Canada and United States	23,089	59,800	751	229
Lake Michigan	Canada and United States	22,400	50,016	935	285
Lake Tanganyika	Tanzania and Congo, Africa	13,127	33,999	4823	1470
Great Bear Lake	Northwest Territories, Canada	12,275	31,792	1460	445
Lake Baikal	Russia	12,162	31,500	5712	1741
Great Slave Lake	Northwest Territories, Canada	11,031	28,570	2014	614
Lake Erie	Canada and United States	9930	25,719	210	64

Source: Environment Canada, "World's Largest Lakes," http://www.ec.gc.ca/water/descrip/nature/prop/a2f4e.htm, June 2003.

Pluvial lakes were created in dry climates when favorable changes in precipitation and evaporation occurred during quaternary climate changes. These lakes have long since disappeared through evaporation. Examples of pluvial lakes are Pyramid Lake near Reno, Nevada, and Utah's ancient Lake Bonneville, which remains today as Great Salt Lake.

Although glaciers created many lakes in Canada, Lake Chubb in northern Quebec was created by extraterrestrial forces. It is an eerily shaped perfect circle, two miles (3.2 km) across, and occupies a meteorite impact crater estimated to be 1.4 million years old. Meteor Crater near Flagstaff, Arizona, is another meteorite impact crater formed about 50,000 years ago that once contained a similarly shaped, but much smaller, pluvial lake.

Kettle lakes are depressions created by blocks of stranded, buried glacial ice that gradually melted during the Pleistocene epoch. The melting of the ice caused the overlying land surface to collapse and create a hole. Where the depression is deep enough to reach groundwater, a lake is created. Kettle lakes are generally found in Ohio, Minnesota, North Dakota, Wisconsin, Michigan, Alaska, Colorado, Idaho, Pennsylvania, British Columbia, Manitoba, Ontario, Saskatchewan, Quebec, and central and northern Europe.

Lakes can be young, middle-aged, or old. Young, or **oligotrophic lakes,** have bottoms that are too clean (i.e., they lack enough organic material as food sources) to provide appropriate habitat to produce plants and freshwater organisms. However, earthen particles and other organic materials from decaying plants and animals can eventually build layers of materials for aquatic plant and animal habitat.

Middle-aged lakes that allow for aquatic growth are called **mesotrophic.** As a lake ages, excessive organic material and mineral deposits can actually inhibit or stop the growth of aquatic plants and animals. Such an old lake is called **eutrophic** and is typically filling in with excessive organic and mineral materials.

A **reservoir** is a human-made feature, also called a lake, created by construction of a dam or dikes. (Dams will be discussed in Chapter 7, and dikes—sometimes called levees—are explained in Chapter 10.)

ECOLOGICAL ZONES

Lakes have three ecological zones inhabited by varying organisms. The **littoral zone** is in the shallows, generally near the lake shore, where adequate sunlight penetrates the water surface to promote growth of shallow-rooted plants. This is generally a rich zone of plant and animal life. The **limnetic zone** is located further out in the open water that extends toward the center of the lake and to a depth where sunlight cannot penetrate. The limnetic zone is home to drifting and swimming organisms. The **profundal zone** is found at the lake bottom where organic material has drifted down to become lake bottom material. This bottom zone, too dark to support rooted plants, is inhabited by bacteria, worms, mollusks, insects, and algae.

THERMAL CYCLES

Lakes have stratification zones in temperate regions created by changes in water temperature (and salt content if the lake is saline). Warm air in the spring and summer heats the surface of a lake, causing the water to become less dense. (Warm water causes water molecules to move faster and further apart, similar to the atmospheric heating process described in Chapter 2.) This warmer water becomes less dense and tends to be pushed up above cooler, and more dense, water masses.

A surface layer of warm water, called the **epilimnion,** will form above a cooler layer of lake water, called the **hypolimnion.** The thickness of the epilimnion layer depends on latitude, season, and temperature. The **thermocline** is a transition zone between the epilimnion and the hypolimnion in which there is a rapid change in water temperature with depth.

The heating process of a lake is opposite to the process of atmospheric heating. In the atmosphere, air is warmed by the land surface. Cooler, denser air that sinks below the warmer air near the land surface pushes it up to mix with colder air at higher elevations. This upward movement of warm air, together with the settling of cooler air, creates a continual mixing cycle within the atmosphere in temperate climates. In a lake, some water mixing does occur at the surface owing to wind and wave action. However, during the summer months little water movement occurs between the cold hypolimnion layer and the warmer epilimnion since the cold, deeper water is much denser than the warmer water above. Later, as air temperatures cool in the autumn, surface water temperatures decrease. The water at the surface cools and settles, and replaces the now warmer water at the bottom of a lake. This is called **lake turnover** (see Figure 3.8).

Cold winter temperatures and wind often equalize lake temperatures between autumn and spring, and there is little water mixing during that time. Some lakes can have normal thermal stratification in the summer and an inverted one (warm water on the bottom) in the winter. Water at 4°C (39°F) may be at the bottom of the lake in the grips of winter, with colder water above it until the coldest water is found in a layer of ice at the lake's surface. Water has the greatest density at 4°C (39°F).

The epilimnion is an active area of surface water mixing, high oxygen concentration, and plant and animal life. The hypolimnion, by contrast, is a cold, dark, and still area. Organic material for this region is limited to drifting from above. If thermal stratification is permanent, the hypolimnion will not have oxygen levels replenished and the area will have little or no life. However, if a lake is located in a climate with hot and cold seasons, it will periodically turn over and mix water between the epilimnion and hypolimnion zones. This will bring dissolved materials to the top of the lake and oxygen to the bottom region. Lake turnover generally occurs in the autumn when the epilimnion cools to 4°C (39°F) and in the spring when the cold surface water warms to 4°C (39°F). This mixing of lake water is very important to the ecology of the lake but can produce unfavorable taste and bad odor for consumers if a lake is used as a source of drinking water. (6)

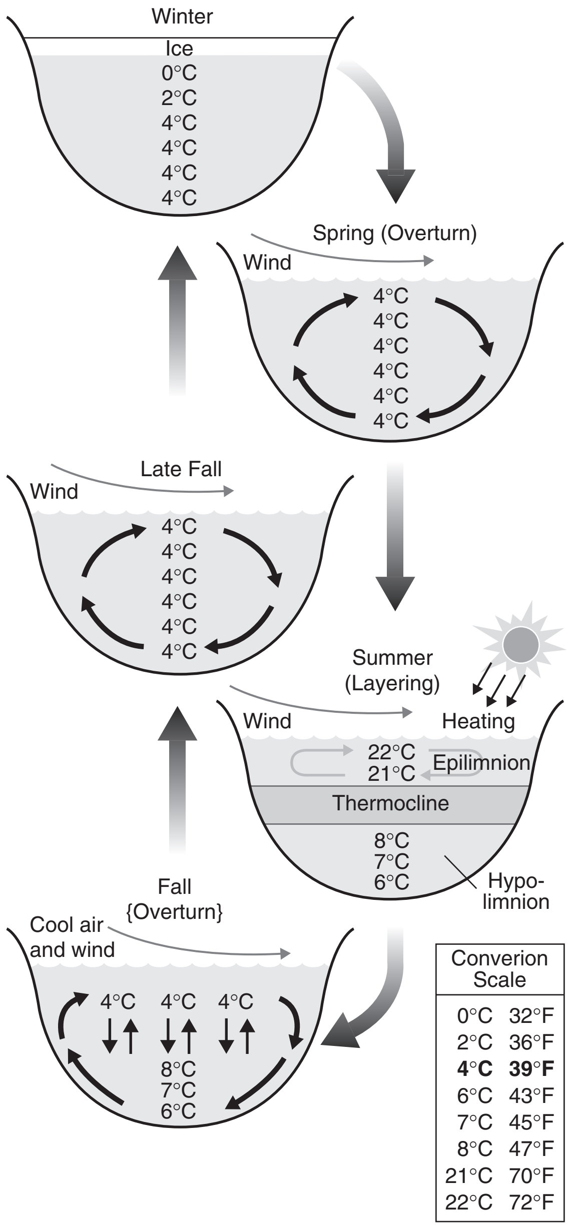

FIG. 3.8 Seasonal layering and turnover in a lake at midlatitudes.

SEICHES

Water levels in lakes routinely oscillate as a result of wind or sudden changes in atmospheric pressure. The highest recorded difference in water elevations at the Great Lakes in North America was during January 1942 when Lake Erie was 13 feet (4 m) higher at the shore of Buffalo, New York, than it was at Toledo, Ohio (a distance of approximately 300 mi, or 483 km). This difference of water-level elevation in a lake, called a **seiche** (pronounced **saysh**), is common around the world. The word was first used to describe the peculiar oscillating waves creating this phenomenon in Lake Geneva in Switzerland in the early 1800s. Seiches continue to be common at Lake Geneva and are about 3 feet (0.9 m) in variation. At Lake Erie, seiches routinely raise and lower water levels in harbors and have caused vessels to run aground. Freighters often schedule docking and departing times to avoid seiches on the Great Lakes. (7)

A CLOSER LOOK

Although seiches are usually harmless, a monster wave occurred on Lake Michigan on June 26, 1954. The lake was calm in the early morning, but a strong thunderstorm with 50 mph (80 km/h) winds blew in from the northwest around 8:00 A.M. At Michigan City, Indiana, 100 people were fishing on a pier but had to run to avoid a 2-foot-high (0.6 m) wall of water created by the wind on the lake surface. This was an *incident wave* created by a seiche pushed by wind and atmospheric pressure. No one was injured, but the *incident wave* rebounded against the shore at Michigan City and returned toward the northwest. This created a *reflective wave* that rapidly moved along the bottom of Lake Michigan toward Chicago, Illinois, some 50 miles (80 km) away. The compressed water at the lake bottom created a 10-foot-high (3 m) wall of water. People on jetties and piers along the Chicago waterfront were completely surprised by the sudden seiche, and dozens were washed into Lake Michigan. Eight people drowned. (8)

TRANSPORT AND DEPOSITION

It was the river which had laid down the new land; it was the river which took it away. The endless cycle of building up, tearing down and rebuilding, using the same material over and over, was contributed to by the river. It was the brawling, undisciplined, violent artery of life and would always be. (9)

From James A. Michener, *Centennial*

Throughout history, rivers have been given names that reflect their appearance. The Yellow River (or Huang He) in China, the Red River in North Dakota and Manitoba, and the “Muddy Mississippi” of the central United States generate images of color and content. The Platte River in Nebraska was described by pioneers in the 1800s as “too thin to plow but too thick to drink.” These images were created and enhanced by earthen materials being transported and deposited by moving water.

Transport and deposition are the movement and settling of materials such as rock, gravel, sand, soil, and other geologic materials (called **sediment**) in moving water. Moving water, which creates overland flow and swiftly flowing rivers, provides one of two primary means of transporting sediment (wind is the other main factor). Sediment settles out of moving water as the rate of flow is reduced. This process is called **sedimentation.** Certain sections of rivers in flooded lowlands and lake bottoms are common locations for sediment deposits.

Natural levees are broad, low embankments adjacent to riverbanks created from sediment deposition during flood events. **Floodplains** are relatively flat areas adjacent to rivers created by sedimentary deposits as a meandering channel migrates laterally across a valley floor, and from flood events. These landforms can be as narrow as a few hundred feet (60 m) or as wide as over 25 miles (40 km). During a flood, water often leaves the main river channel and inundates a floodplain. Water velocity decreases across the floodplain owing to lower flows and increased friction from the land surface. As this occurs, sediment rapidly falls out of the floodwater and is deposited. Floodplains can include wetlands, oxbow lakes, natural levees, and rich soils for cultivation (see Figure 3.9). Occasionally, a **yazoo stream,** one that runs parallel to a larger

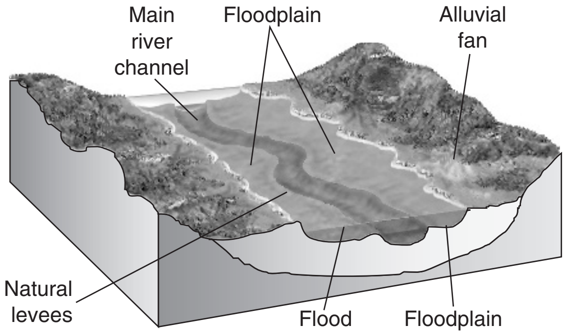

FIG. 3.9 Rivers have a profound effect on landforms. This illustration shows common landforms created by river deposits, including alluvial fans, natural levees, and floodplains.

river and helps drain a floodplain, will form. Yazoo streams are common along the Mississippi River and other large drainage systems with broad floodplains.

Sediment deposited by flowing water is called **fluvial material** or **alluvial deposits.** An **alluvial fan** is created when a river deposits material on the land surface, generally at the base of a mountain valley. A **delta** is created when sediment is deposited at the mouth of a river system, such as the Mississippi Delta located downstream of New Orleans or the Mekong Delta in Vietnam.

OUR ENVIRONMENT

Why is sediment transport important in the study of lakes and rivers? Sediments can be considered either a detriment or a benefit to a river system. Sediments deposited after flood events can benefit the health of farmland by providing nutrient-rich soils for crops. However, sediment deposits in lakes and reservoirs can destroy aquatic habitat, reduce water storage capacity, and eliminate deep water areas necessary for boating. High sediment loads in surface water can reduce the oxygen-carrying capacity of water and harm aquatic wildlife.

VELOCITY

Sedimentation is directly affected by the speed, or **velocity,** of flowing water. As velocity decreases, sediment sorting takes place. In addition, a kind of sorting occurs as finer particles are moved more frequently and farther during peaks of fluctuating discharge. **Sorting** is the process whereby particles of a similar size settle out of moving water caused by changes in velocity and fluctuating discharge. As water velocity decreases, heavier materials first sort, or fall out. This causes larger rocks to settle out, followed by gravels, sand, and finally silt and clay (particles smaller than grains of sand) as water velocity decreases. The process of sorting creates deposits of somewhat uniform size along rivers that can be utilized for mining. This accounts for the location of gravel mines (pits) near mountain foothills and sand pits farther out downstream in broad valleys. It also explains the deposition of rocks and boulders in or near mountain canyons.

A CLOSER LOOK

A meandering river causes water velocity to vary. Water flowing along the outside of a meander has greater velocity than water flowing along the inside of a meander. If you canoe, you may have noticed that deeper, faster water flows on the outside of a meander, while slower water is found on the inside of the curving river. Anglers often fish the inside of a meander because larger fish, such as trout, wait for food to come to them in slower-moving water. The lower water velocity at this location means a fish expends less energy waiting for food to arrive.

SEDIMENT LOAD

A river carries most of its sediment load in suspension, called **suspended load.** These suspended materials consist primarily of silt, clay, and some fine sand, although larger particles can be carried during flood events when water volumes and velocities are greater. A river can transport suspended materials for hundreds or thousands of miles (or km). As water velocity slows, sediments settle to the riverbed, on to adjacent natural levees, or near the mouth of a river to form a delta.

All rivers carry a **dissolved load** consisting of dissolved materials that remain in solution. Additional water flows will dilute these solutions but may not totally eliminate such dissolved materials unless the water chemistry changes.

Rivers that receive groundwater inflow generally have higher dissolved loads than rivers composed only of surface water runoff due to dissolved minerals available from underground geologic formations.

Coarse geologic material, called **bed load,** is pushed along the bottom of a river by moving water. These larger particles of sand and gravel may account for less than 10 percent of total river sediments but are important to the health of a river ecosystem. These particles roll and slide along a riverbed or can move by **saltation.** The saltation process occurs when a particle is pushed up due to a drop in pressure above the grain of sand. It is similar to the processes that affect the wings of a plane. Faster currents above the grain cause a drop in pressure above it. The relatively higher pressure below the grain lifts it up into the current, at which time the water current pushes it down the stream. Often, the settling particle collides with other material at the bottom of a river and is hurled upward again by the water current. (The word "saltate" literally means to bounce along the bottom.)

Sediment yield—the total amount of erosional material carried from a drainage basin—is generally measured in terms of weight (tons or metric tons) per day or year. A sampling device can be used to gather a known unit volume of flowing water. The water sample is then allowed to evaporate so that only dry matter remains. The difference between the weight of the water and the weight of the sediment provides the proportion of sediment to water per unit volume. Multiplication of the concentration of sediment by the rate of discharge will provide the weight of sediment per acre-foot, gallon, or cubic meter.

Sediment load is extremely important in the health of aquatic ecosystems. High sediment loads cause rivers to be smothered and leads to the loss of habitat for fish. Turbid water (water high in sediments) may be warmer and stressful for a variety of aquatic species. In addition, sediments often carry pollutants that are fixed (attached) to the sediment particles. See Chapter 5 for more information on sediment load and water quality.

A CLOSER LOOK

The Maumee River watershed drains land in Ohio, Michigan, and Indiana, and delivers surface water to Lake Erie at Toledo, Ohio. The river has an average slope of 1.3 feet per mile (0.25 m/km) and carries over 10 million tons (9.1 million metric tons) of suspended sediment to Lake Erie annually. Every year, the U.S. Army Corps of Engineers dredges approximately 850,000 cubic yards (649,910 m^3) of sedimentary material from Toledo Harbor to keep shipping viable along the Maumee. The State of Ohio, as well as many groups, are working to reduce soil erosion and sediment loading of the Maumee River through improved land-use practices upstream. (10) The dredging activities of the U.S. Army Corps of Engineers will be discussed in Chapter 9.

WATER MEASUREMENT

Surface water measurement can be fairly simple in some situations and very complex in others. Depth of water, terrain, and velocity are important when determining flow rates and volumes. Three types of surface water measurement are overland flow, discharge of rivers, and water storage in lakes and reservoirs.

OVERLAND FLOW

Overland flow, also called *sheet flow,* as defined earlier in this chapter, is surface water runoff that is moving within a watershed toward a river. Overland flow does not usually continue for more than a short distance because it combines with other moving water to collect in natural or artificial waterways. Overland flow can be mathematically calculated using the **Rational Formula:**

$$Q = KiA$$

where Q = peak rate of runoff in cubic feet or cubic meters per second
K = runoff coefficient (see Table 3.3)
i = intensity of rainfall in inches or centimeters per hour
A = watershed area in acres or hectares

The Rational Formula was proposed in 1889 by Emil Kuichling and continues to be widely used

TABLE 3.3 Runoff Coefficients for the Rational Formula

Runoff Area	Value of K
Business	
Downtown	0.70–0.95
Neighborhood	0.50–0.70
Residential	
Single-family	0.30–0.50
Apartments	0.50–0.70
Industrial	
Light	0.50–0.80
Heavy	0.60–0.90
Parks, cemeteries	0.10–0.25
Playgrounds	0.20–0.35

Source: American Society of Civil Engineers, "Design and Construction of Sanitary and Storm Sewers," *Manuals and Reports of Engineering Practice* No. 37, 1970. Reproduced by permission of the publisher, ASCE.

today around the world. It is used to design storm drains, culverts, and other structures that control runoff, primarily in urban areas.

RIVER DISCHARGE

Overland flows usually combine and eventually form a river. The amount of water carried in a river at any one time is called the river's **discharge**, which is defined as the volume of water flowing past a given point during a given period of time. It is measured in **cubic feet per second** (cfs) or gallons per minute (gpm) in the United States and as **cubic meters per second** (cms) or liters per minute in most other parts of the world (see Figure 3.10).

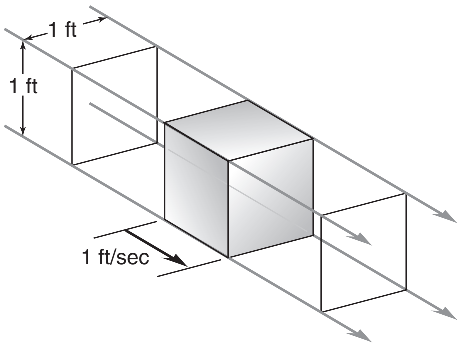

FIG. 3.10 One cubic foot per second, or cfs (or one cubic meter per second, or cms) is equivalent to one cubic foot (or cubic meter) of water flowing past a given point in a one-second time interval.

A CLOSER LOOK

A cubic foot is a volume with dimensions of 1 foot (0.3 m) on each side. A basketball would fit nicely in a box this size. It takes approximately 7.5 gallons (28.4 l) of water to fill 1 cubic foot of space. A cubic foot per second (cfs) is a volume of water equal to 1 cubic foot moving past a given point every second (1 cubic ft/sec; see Figure 3.10). Double that flow rate and a volume of water equal to 2 cubic feet will move past a given point every second, or 2 cubic feet per second (sometimes called 2 second-feet). One cfs of water is equal to approximately 7.5 gallons moving past a given point every second (or 450 gal per minute).[1]

Water managers outside the United States generally use cubic meter per second (cms) to express water flow. The concept is the same as cubic feet per second, except that a cubic meter is a volume with dimensions of 1 meter (3.28 ft) on each side and equals 1000 liters (264 gal). A cubic meter would be the approximate size of a washing machine or dryer.

Discharge in rivers can vary from a few cubic feet per second (0.06 cms) in a small stream to seasonal variations from 1.5 million to over 12 million cfs (42,480 to 339,840 cms) in the Mississippi River at New Orleans. The Colorado River in the Grand Canyon of Arizona usually has a discharge in the range of 4000 to 90,000 cfs (110 to 2550 cms), but a flood in 1921 produced a discharge of more than 200,000 cfs (5660 cms). The highest recorded river discharge in the world was 52.5 million cfs (1.49 million cms) in the Amazon River of Brazil in South America.

River discharge can be calculated by first measuring the depth of a river at a particular

[1] An excellent interactive resource on river discharge can be found on the Internet at http://vcourseware.sonoma.edu/VirtualRiver. This website was developed in part with grants from the National Science Foundation and the California State University System.

cross section. Next, water velocity is measured at several points and depths along the same cross section of the river. The results are then placed in the following calculation:

$$Q = AV$$

where Q = discharge
A = cross-sectional area of a channel
V = average water velocity

This equation provides the mean (average) velocity of flowing water in a channel waterway. The cross-sectional area is determined by the width times the depth of a channel. Width is determined with a measuring tape or laser device. The depth of a river channel can be measured with a pole, if shallow, or with sounding cables (wires with weights attached at the end) if wading is not possible. Some river channels have continually shifting riverbeds (generally consisting of sand and gravel) owing to saltation and rapidly changing bed loads. These locations are often measured weekly to provide more accurate data on the size and shape of the channel bottom. Shifting sand and gravel can drastically change the cross-sectional area of a river channel in a short time, especially during periods of high discharge (see Figure 3.11).

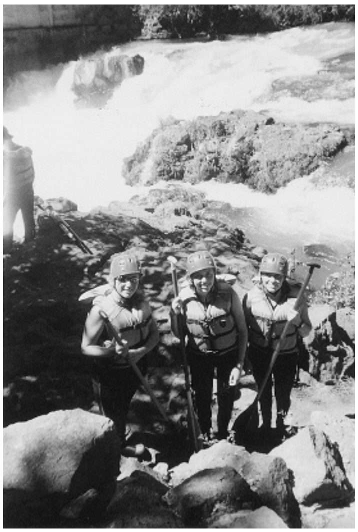

FIG. 3.11 Steep gradients and high water velocity are great combinations for moving boulders, sediment, and kayakers. This photo was taken along the White Salmon River in Washington, a tributary of the Columbia River, near Hood River, Oregon.

OUR ENVIRONMENT

Agencies around the world collect river discharge data. In the United States, the U.S. Geological Survey (USGS) is the primary agency with responsibility for river-flow data. The USGS has real-time river discharge records of nearly every river in the United States. This data is available on the Internet at http://waterdata.usgs.gov/nwis.rt. Real-time data are recorded at 15- to 60-minute intervals but may be more frequent during critical events. The data are transmitted by telephone, radio, or satellite and are available for viewing on the Internet within three minutes of arrival. Data on streamflow in Canada can be found at http://www.ec.gc.ca/water_e.html at which one selects "Monitoring."

Water velocity can be measured with an electronic device called a **flow meter.** Flowing water turns a small propeller at the end of a shaft on the meter. Propeller rotations are electronically recorded over a set period of time and allow a hydrographer to calculate average water velocity. Since flow velocity in rivers often pulsates, observations are usually taken between 40- and 70-second intervals.

Flow meter measurements are made by dividing a river into cross-channel segments of not greater than 10 percent of the total river width. Therefore, 10 to 20 vertical-section measurements are typical. Water velocity often varies from near zero at the bottom of a river to near maximum at the surface. The average of the velocities at 20 percent and 80 percent depth provides the average velocity for a given vertical section.

The **stage** of a river or lake is the height of the water surface above a set reference elevation. If the elevation of a streambed is known and the water surface stage is subtracted, the result is the depth of water in the river. **Staff gages** (usually a metal ruler attached to a permanent fixture) can be used for this purpose (Figure 3.12). The elevation of water on the staff gage is called the **gage height.** Discharge is sometimes determined directly from the river stage using a **rating curve.** Such a curve is generated by making discharge

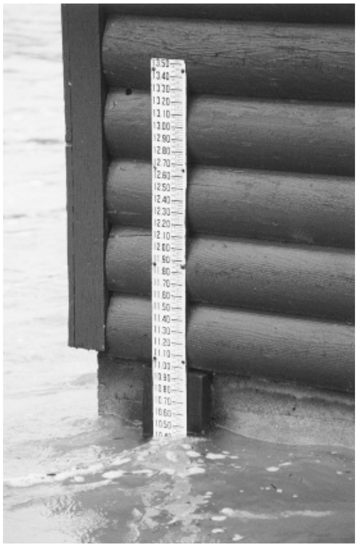

FIG. 3.12 A staff gage is nothing more than a long ruler placed in a stream or lake to monitor water depth. This staff gage is used to measure the stage of the Snake River within the Grand Teton National Park near Moran, Wyoming.

measurements during various times of the year, usually monthly, and plotting these against gage height. Once constructed, a rating curve eliminates the need for velocity and depth measurements unless the channel cross section changes.

A river **hydrograph** is a graph of discharge over time and can be plotted daily, weekly, monthly, or annually. Seasonal variations are evident on an annual hydrograph, whereas flood events are displayed on hourly, daily, or weekly hydrographs (Figure 3.13).

A **recorder** is a device used to record the elevation of water flowing through an open channel or river over time. A recorder is usually located in a vertical stilling well on a riverbank. The stilling well is connected to flowing water through a small horizontal intake, such as a 1-inch-diameter (2.5 cm) pipe, at the base of the stilling well. This opening allows river-stage changes to occur inside the stilling well but reduces fluctuation and turbulence. A cable and pulley system is attached from a float to the recorder, with a float at one end of the cable and a counterweight at the other end. The float rests on the surface of the water at the bottom of the stilling well. Changes in the stage of the river also occur inside the stilling well and are reflected on a paper chart or electronic data logger in the recorder.

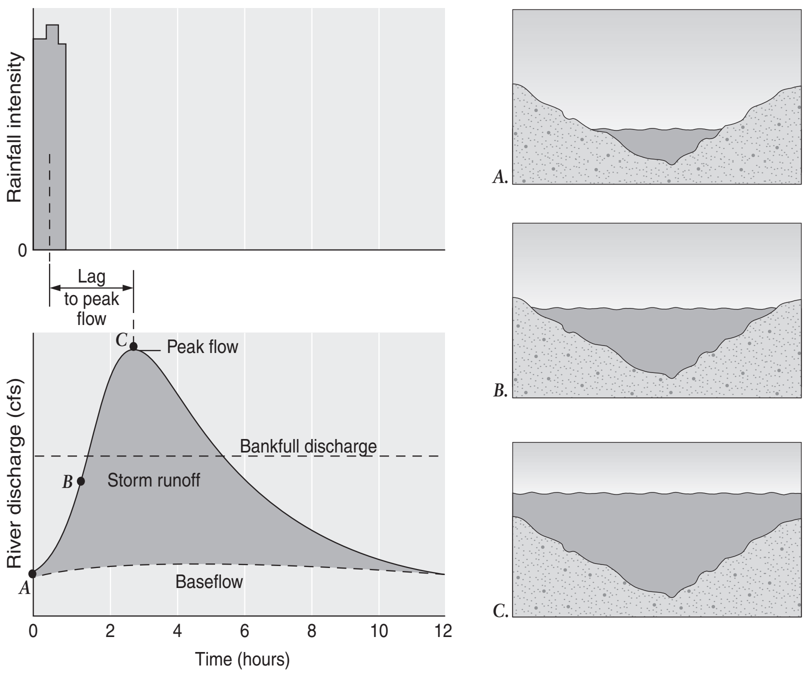

FIG. 3.13 The hydrograph of a river can look similar to this example after a brief but intense rainfall event. A heavy rainstorm can cause a rapid increase in stream discharge. As runoff collects and moves downstream in a watershed, the volume of water in a river channel will increase and flooding may occur. After a few hours, the stream discharge may decrease to near baseflow conditions.

FIG. 3.14 This Nilometer was carved into rock on the shore of the Nile River near Aswan, Egypt. During ancient times, Nilometers were used to determine taxes as well as the proper time to break dikes to begin irrigation of fields.

Measuring water is not a new concept. **Nilometers** have been used for over 5000 years and were developed in Egypt to measure the stage of the Nile River (Figure 3.14). The first Nilometers were simple marks etched on riverbanks. Later, elaborate towers protected stones etched with measurement scales to determine flood stages. A high-river stage meant the deposition of more sediments on floodplains for crops, while a low-stage meant a shortage of irrigation water and poor crops.

Taxes were based on the discharge of the Nile River—good crops meant higher taxes, whereas poor crops produced tax relief for the peasants. Nilometers were located at many locations along the Nile. As Egypt's boundaries extended further south, the Pharaoh ordered installation of additional gages upstream to provide an early warning system of future water discharges. (11)

A CLOSER LOOK

Modern-day water managers closely monitor water discharge in rivers around the world. In some locations, satellite monitoring systems are operated to provide up-to-the-minute water discharge and stage information. For example, the U.S. Geological Survey operates 18 satellite data transmitters in northeastern New Jersey as part of the Passaic Flood Warning System, one of the most flood-prone basins in the United States. River-discharge monitoring networks are also used along the Passaic River to protect water requirements for aquatic species below water supply reservoirs and pumping stations. In Arizona and Colorado, satellite monitoring systems are used to allocate scarce irrigation water supplies throughout the state during dry summer months. Irrigators in New Mexico and Colorado can access streamflow information, gathered by a satellite network, over the telephone or on the Internet.

WATER STORAGE IN LAKES AND RESERVOIRS

Reservoir storage volumes are expressed in terms of million gallons or billion gallons in the eastern United States, while acre-feet is commonly used in most western states. Million cubic meters (mcm) is used in most other countries. An **acre-foot** of water is the amount needed to cover 1 acre (0.4 ha) of land to a depth of 1 foot (0.3 m). One acre contains 43,560 square feet (4047 m^2) of surface area. Therefore, 1 acre-foot of water contains 43,560 cubic feet or 325,851 gallons (43,560 cu ft $\times$ 7.48 gal per cubic foot =

SIDEBAR

Here are some estimates of size in acres and hectares of various items:

	Approximate Size	
Item	**Acres**	**Hectares**
Average house and yard	0.25–0.3	0.10–0.12
Soccer field	1.5–2.5	0.6–1.0
Coal barge on the Mississippi River	6	2.4
Regional shopping mall with parking lots	100–300	40–120
One square mile	640	259
Central Park in New York City	843	341
Average farm in Iowa	320	130
Average ranch in Wyoming	5,000–15,000	2023–6070

325,851 gal). This is also equivalent to 1235 cubic meters, or 1.2 million liters.

An acre-foot is a volume and does not include the dimension of time. Water stored in a reservoir is measured in acre-feet, million or billion gallons, or cubic meters. Standing water is not measured in cubic feet per second, gallons per day, or cubic meters per second because there is no function of time.

How is the storage capacity of a reservoir measured? First, the storage volume is computed by taking measurements of the depth and area of the inundated area. Depth can be determined with electronic sounding equipment or cables. Area is obtained by developing topographic contour lines at various depth intervals (elevations) of the reservoir and then calculating the area at various water levels. A geographic information system (GIS) can define volumes of a site through use of various software programs.

After the storage capacity is determined, how are water quantities determined for various reservoir stages? A **stage-capacity curve** or **rating curve** is calculated to show reservoir storage volumes for various water depths. An example is shown in Table 3.4 for Loch Lomond Reservoir near San Francisco, California. In some cases, a staff gage can be installed to determine reservoir water levels. The reading on the staff gage can be correlated to the known storage volume calculations for various elevations of the water surface. Determination of changes in reservoir storage must take into account evaporation, groundwater infiltration, seepage out of the reservoir, and

TABLE 3.4 Storage Capacity for Water-Surface Elevations[a] at 2-foot Intervals, Loch Lomond Reservoir, Santa Cruz County, California, November 1998

Water-Surface Elevation	Storage Capacity	Water-Surface Elevation	Storage Capacity	Water-Surface Elevation	Storage Capacity	Water-Surface Elevation	Storage Capacity
577.5[b]	8991	542	4120	504	1340	466	148
577	8900	540	3920	502	1250	464	120
576	8730	538	3730	500	1160	462	99
574	8400	536	3550	498	1070	460	81
572	8070	534	3370	496	991	458	68
570	7750	532	3200	494	912	456	56
568	7440	530	3030	492	836	454	46
566	7140	528	2870	490	763	452	39
564	6840	526	2710	488	694	450	32
562	6550	524	2560	486	628	448	27
560	6270	522	2420	484	565	446	22
558	6000	520	2280	482	506	444	18
556	5730	518	2150	480	449	442	14
554	5470	516	2020	478	397	440	10
552	5230	514	1890	476	348	438	7
550	4990	512	1770	474	301	436	5
548	4760	510	1660	472	258	434	3
546	4530	508	1550	470	217	432	1
544	4320	506	1440	468	181	430	0

[a]Water-surface elevation is in feet above sea level. Storage capacity is in acre-feet.

[b]Maximum capacity of Loch Lomond Reservoir.

Source: Kelly R. McPherson and Jerry G. Harmon, "Storage Capacity and Sedimentation of Loch Lomond Reservoir, Santa Cruz County, California, 1998," U.S. Department of Interior, U.S. Geological Survey, Water-Resources Investigations Report 00-4016, Sacramento, California, 2000. Also found at http://www.wr.usgs.gov/rep/wrir004016, September 2001.

inflow and outflow of surface water. The following equation is generally used:

$$\text{Reservoir Storage} = Qi + Gi - S - E - Qo$$

where Qi = surface water inflow
Gi = groundwater infiltration
S = seepage
E = evaporation
Qo = surface water outflow

Reservoir storage includes the static body of water in the lake behind a dam, as well as water held as bank storage in the walls of the reservoir. The amount of bank storage depends on the geology of the reservoir site and can be great or small (similar to riverbank storage discussed earlier). Some of this water will return to the reservoir if water levels decline, while, under the force of gravity, some bank storage will percolate downward and move toward groundwater. At Hoover Dam and Lake Mead in Nevada and Arizona, reservoir operators use a bank storage rate of 6.5 percent of surface water storage and a 100 percent recovery rate when reservoir levels drop. These calculations are necessary because of the water-holding capacity of sandstone bedrock in the area. (12)

FLOOD EVENTS

Floods occur when precipitation and runoff exceed the capacity of a river channel to carry the increased discharge. Nature has provided river channels and floodplains to carry runoff water from the land surface to the oceans. A floodplain is simply an extended channel that carries high-water volumes. The amount of water carried by a river changes daily but often receives little attention in humid areas unless water overflows its banks. Floods are an inevitable component of any river system, since runoff volumes vary with time.

FLOOD FREQUENCY

The frequency of flooding is based on history—how often have floods occurred in a region, what are the historic extremes of high precipitation, and what land-use changes and development have occurred in a watershed. In some locations, flood frequency has been reduced as a result of flood-control dams and strict floodplain development regulations. However, predicting floods is still a function of determining the odds of high precipitation.

The laws of probability state that the chance of an event occurring are equal to the number of times it has occurred in the past. Floods follow the same rules of probability. Hydrologists refer to a "recurrence interval" of various flood flows, such as a **100-year flood (Q100)** (Figure 3.15). The laws of probability assign a value of 1 in 100 for a Q100 flood, or 0.01. This means that a 100-year flood has a 1 in 100 chance of a given discharge occurring (based on a river hydrograph) and flooding a given area. However, such a flood could occur once in 100 years or twice within the same month. Similarly, the laws of probability for a **500-year flood (Q500)** assign a

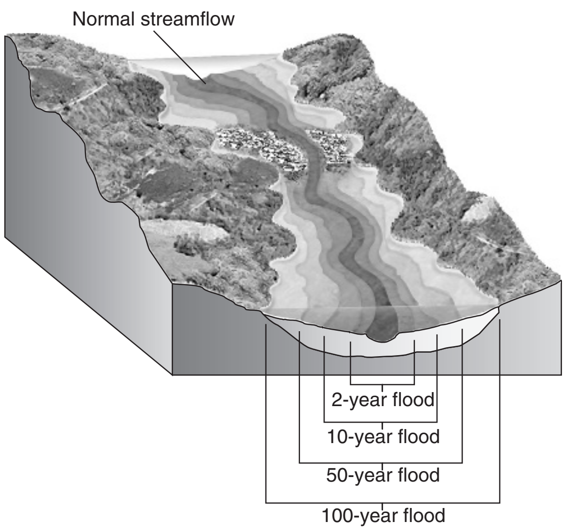

FIG. 3.15 Flood damage can be predicted based on the intensity of a storm and the topography of a region. A flood with a recurrence interval of 50 years means that it has a 1 in 50 chance of occurring in any given year (a 50-year flood, or Q50). A 100-year flood, or Q100, has a 1 in 100 chance of occurring in any given year.

frequency of a 1 in 500 chance, or a probability of 0.002 in any one year, of a given discharge (based on a river hydrograph) of flooding a given area. (13)

A 100-year flood is most commonly used for floodplain management, flood insurance regulations, and engineering designs of dam spillways, road culverts, bridge abutments, and other structures to meet estimated maximum surface water flow volumes. The term *100-year flood* is commonly misunderstood by the public and leads to confusion that can have important consequences regarding flood frequency and the hazards associated with purchasing a home or other property in a flood zone. This subject will be discussed further in Chapter 9.

PROBABLE MAXIMUM PRECIPITATION

Precipitation amounts have been recorded for thousands of years. As improved measurement methods are developed, such as with Doppler Radar, precipitation records are continually broken. The question that then arises is: Will precipitation extremes continue to break records, or is there some finite limit on the atmosphere's ability to produce rain at any given location due to climate, topography, and atmospheric moisture limits?

The answer is, yes, there is a limit. The concept of a finite limit for precipitation from a single storm event is called **Probable Maximum Precipitation (PMP)**. A PMP is the maximum depth (amount) of precipitation that is reasonably possible during a single storm event, and it is based on previous storm records, accepted meteorological knowledge, probability, and statistics. As expected, PMP estimates are higher in hot, humid equatorial regions and much lower in colder climates of the midlatitudes where the atmosphere cannot hold as much moisture.

PROBABLE MAXIMUM FLOOD

Flood events also have maximum extremes and are called a **Probable Maximum Flood (PMF).** A PMF is the maximum surface water flow in a drainage area that would be expected from a Probable Maximum Precipitation event. The concept of PMF is useful for engineering purposes because it permits computation of a maximum water inflow for structures such as dams, culverts, or other hydraulic structures. High-hazard dams (dams whose failure would result in loss of lives and widespread property damage) are required, by modern standards, to contain 100 percent of a PMF without water overtopping (spilling over) the dam. A dam overtopped would quickly erode and eventually breach (fail). PMP and PMF rates can be estimated through statistical analysis or through estimates of past meteorological events in a region. (14)

Not all watershed areas with the same PMP have the same magnitude of a PMF, primarily because drainages may differ in slope, vegetation, size, and shape. Rainfall will run off much more quickly on a steep slope than on a level area. In sandy areas, more precipitation will percolate into the soil than in urban areas covered with concrete or rooftops. All of these factors will affect runoff patterns and the discharge of floodwaters in a watershed. Excellent interactive online flood exercises are available at http://vcourseware.sonoma.edu/VirtualRiver.

GUEST ESSAY

Jake Freier with daughter Maizie.

GIS and Flooding

by **Jake Freier**

Jake Freier formerly served as the GIS coordinator for the Iowa Emergency Management Division, Des Moines, Iowa. He earned his Master's degree in Geography from the University of Iowa and his Bachelor's degree in Geography and Environmental Studies from Gustavus Adolphus College in Minnesota. Jake is now with the Evans, Colorado, Planning and Zoning Division. He lives in Greeley, Colorado, with his wife April, daughter Maizie, and dog Tucker.

FIG. 3.16 Coast Guard flight mechanic Trent Ganz views the flooded John O'Donnell Stadium near downtown Davenport, Iowa, during the Mississippi River flood of April 2001.

During April of 2001, near-record-level floods ravaged the towns of the upper Mississippi River (Figure 3.16). River towns on the eastern border of Iowa were particularly hard hit, and Davenport, a city of more than 100,000 people, saw flood levels that had been surpassed only twice before in recorded history. In response, the State of Iowa Emergency Management Division opened its Emergency Operations Center to help coordinate the flood-fighting efforts among local, state, and federal government agencies. The computer-based mapping tool called GIS aided in predicting the spatial extent of flooding and determining what critical facilities might be affected by floodwaters.

GIS, or geographic information systems, are computer-based systems used to store, retrieve, map and analyze geographic, or spatial information. Spatial information links real-world location data, such as latitude and longitude coordinate pairs, with descriptive attribute data. With such spatial information at its core, GIS is a much more powerful tool than a traditional paper map. As an illustration, we will use the example of mapping schools within a town. Both paper maps and digital GIS maps can show the location of each school in town and perhaps provide the school's name. However, with the click of a mouse button, a GIS user can gather additional information about a particular school (Figure 3.17). For example, a GIS user may be able to learn the school's address and phone number, the name of the school's principal, the school's total enrollment, the year the school was built, and more. A digital image of the school may also be available for viewing. The ability of a GIS to ask questions of a spatial data set has earned it the nickname "smart maps."

Within a GIS, similar geographic features are grouped together in a single data set and are shown in a map display as a single layer. These layers are basically transparent maps that, when stacked on top of each other, allow the user to determine whether any relationships exist between different data sets. In the preceding example, each school and road is a separate GIS layer. These layers may be turned on and off, and added or removed from display. Let's add the following layers to our map: streams, lakes, and medical facilities (see Figure 3.18). As illustrated here, GIS maps are far easier to create and customize than traditional paper maps, which may take months to produce.

Now let's do some geographic analysis using our GIS. As a town official, we are looking to

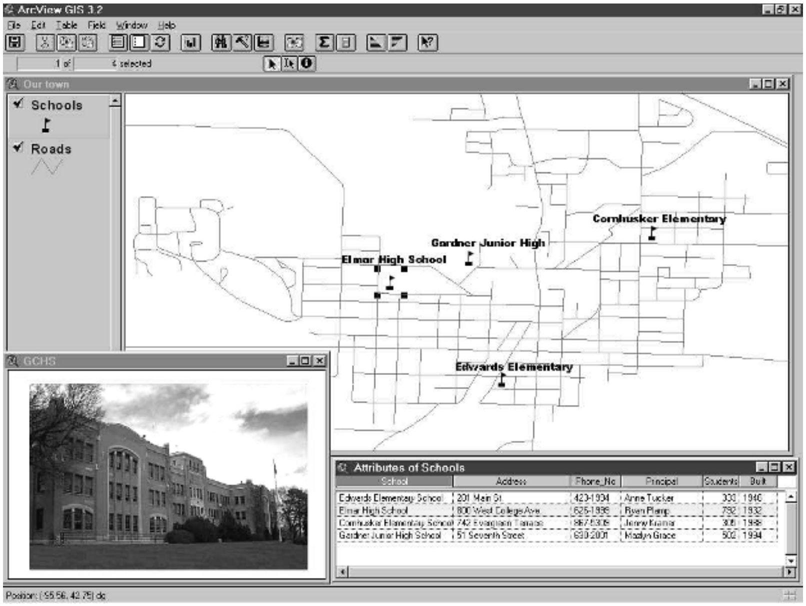

FIG. 3.17 A GIS map display showing the schools in a town. Notice that a query was made of Elmar High School, and the corresponding attribute data and digital image are shown.

analyze the hazards associated with a major flooding event so that we can take measures to ensure the safety of our citizens. With the correct GIS data, we can predict whether a 100-year flood (Q100) will affect important community facilities, such as schools. When we turn on the streams layer, we can see that two schools (Gardner Junior High and Edwards Elementary) are located near the two streams that flow through town (Figure 3.18). At this point,

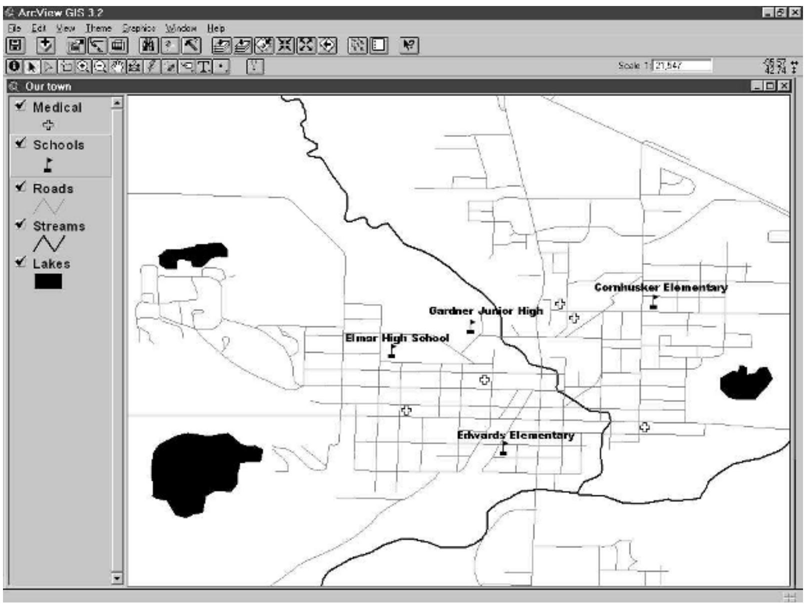

FIG. 3.18 Streams, lakes, and medical facilities are added to the original map display.

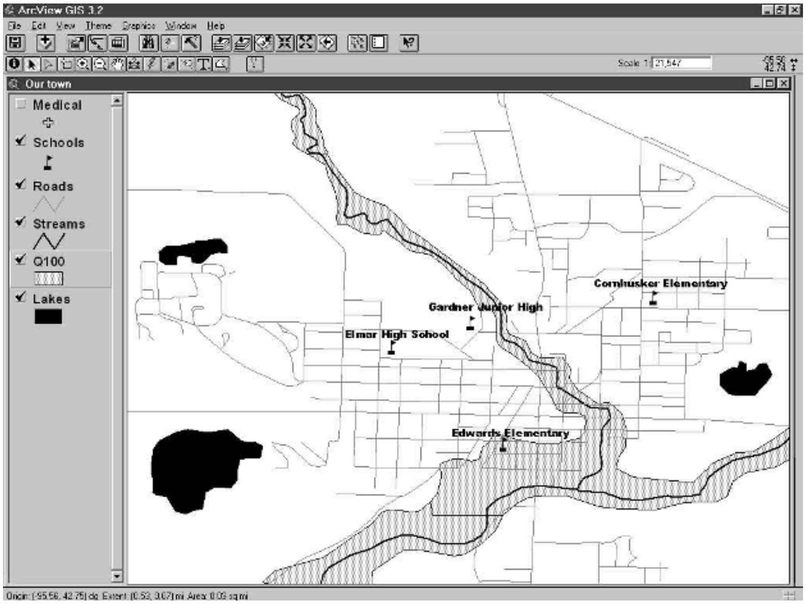

FIG. 3.19 With the Q100 layer added to the map display, it is easy to see that Edwards Elementary is the only school in the 100-year floodplain.

we can only guess as to whether or not these schools will be affected by Q100 floodwaters. To be certain, we must add a Q100 flood layer. By overlaying the Q100 floodplain data on the map (see Figure 3.19), we can clearly see that only one school, Edwards Elementary, lies within the Q100 floodplain. This knowledge allows us to plan accordingly for such an event.

This is a relatively simple example of how GIS can be used to plan for a flood event. During the Mississippi River flooding of 2001, much more complex geographic analyses were performed. State and federal agencies used GIS technology to predict the extent of a flooded area based on a reported sandbag levee breach; to model Mississippi River levels based on upstream tributary flows and recent weather events; and to determine the demographics of citizens whose property was damaged by the flood.

GIS is also used for other areas of water resources work including modeling sediment yields and discharge during extreme weather events, and predicting the effects of land-use planning on downstream water quality. However, the use of GIS is not limited to the field of water resources. Professionals in urban planning, agriculture, forestry, emergency vehicle routing, epidemiology, and others have also developed applications for use in GIS.

Questions

1. Put yourself in the role of a local official looking at the hazards associated with a 100-year flood. Aside from schools, what other features would be important to include in your GIS when doing a geographic analysis?
2. What are some of the other possible advantages of a GIS over a paper map?

POLICY ISSUE

Computer models are often used to predict water discharge for various hydrologic conditions and locations. These mathematical models can predict precipitation runoff on various slopes, river stage and discharge, interaction between surface water and groundwater, sediment transport, water quality changes, and many other scenarios.

The Storm Water Management Model (SWMM) is a popular flood prediction model developed by a consortium of engineers for the U.S. Environmental Protection Agency (USEPA) in the 1970s. Its purpose is to estimate runoff from storm events by utilizing data on rainfall, watershed characteristics, and routes of overland flow and channelized flow patterns. The model then predicts the duration and discharge of runoff to receiving waters downstream. This provides useful data for construction projects, floodplain protection, land-use patterns, and other human activities in flood-prone locations. (15)

CHAPTER SUMMARY

The natural processes of rivers and lakes can have significant effects on humans and the surrounding environment. Surface water runoff patterns, sediment transport and deposition, and lake cycles greatly affect the use and management of water resources around the world.

The measurement of water has developed into an elaborate science that relies on meticulous field measurements, engineering equations, and the use of satellites to closely monitor river and lake stages. Predictions are now being calculated on probable maximum precipitation and probable maximum floods in order to help planners and engineers design various public projects such as culverts, bridges, and other developments that could be impacted by flooding. Finally, GIS is being used to develop urban planning tools to prevent property damage from floods.

QUESTIONS FOR DISCUSSION

1. Describe the watershed that provides water supplies for your home region. Describe the location of water sources, and explain how these supplies were developed.

2. How could you delineate your local watershed?

3. During a storm event, how does interflow differ from overland flow?

4. Describe the process of bank storage and discuss why this process is important when measuring river or lake storage.

5. What was the purpose of a Nilometer? How is that same hydrologic concept used today?

6. Why is it important to know the volume of water stored in a lake or flowing in a river?

7. What insight can a stream hydrograph provide to a hydrologist regarding the climate of a region?

8. What role does water velocity play in the formation of floodplains?

9. Discuss the relationship between meanders and wetlands.

10. Describe how water management and use is dependent on a river gaging network.

11. Go to the USGS streamflow site at http://waterdata.usgs.gov/nwis.rt and determine the current flow in a river in or near your community.

12. Explain the difference between a 100-year (Q100) and a 500-year (Q500) flood.

13. What types of assumptions would be necessary when establishing a PMP (Probable Maximum Precipitation) value for an area? a PMF (Probable Maximum Flood)?

14. Discuss the differences between a gaining and a losing river.

15. Explain how a lake can turnover during autumn months. What problems can this create?

KEY WORDS TO REMEMBER

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500-year flood (Q500) p. 75
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aspect p. 59
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SUGGESTED RESOURCES FOR FURTHER STUDY

READINGS

Brater, Ernest F., Horace W. King, James E. Lindell, and C.Y. Wei. *Handbook of Hydraulics*. 7th ed. New York: McGraw-Hill, 1996.

Dennis, Jerry, and Glenn Wolff. *The Bird and the Waterfall: A Natural History of Oceans, Rivers, and Lakes*. New York: HarperCollins, 1996.

Dunne, Thomas, and Luna B. Leopold, *Water in Environmental Planning*. New York: W.H. Freeman, 1978.

Linsley, Ray K., Jr., Max A Kohler, and Joseph L.H. Paulhus. *Hydrology for Engineers*. 4th ed. New York: McGraw-Hill, 1991.

Manning, John C. *Applied Principles of Hydrology*. 3rd ed. Upper Saddle River, NJ: Prentice Hall, 1996.

Morisawa, Marie. *Streams: Their Dynamics and Morphology*. New York: McGraw-Hill, 1968.

Skinner, Brian J., Stephen C. Porter, and Daniel B. Botkin. *The Blue Planet*. New York: John Wiley & Sons, 1999.

WEBSITES

Environment Canada, "Freshwater Website," July 2003, http://www.ec.gc.ca/water/

Land and Water of Australia, Homepage, July 2003, http://www.lwrrdc.gov.au/

U.S. Department of Interior, U.S. Fish & Wildlife Service, "Wildlife Refuges," July 2003. http://midwest.fws.gov/desoto/

U.S. Department of Interior, U.S. Geological Survey, "Homepage," July 2003. http://pubs.usgs.gov

U.S. Geological Survey, "Water Resources of the United States," July 2003, http://www.water.usgs.gov/

REFERENCES

1. Dennis, Jerry, and Glenn Wolff. *The Bird and the Waterfall: A Natural History of Oceans, Rivers, and Lakes*. New York: HarperCollins, 1996, 109–110.

2. Ibid., 95.

3. Morisawa, Marie. *Streams: Their Dynamics and Morphology*. New York: McGraw-Hill, 1968, 137–139.

4. Dennis and Wolff, 84.

5. U.S. Department of Interior, U.S. Fish & Wildlife Service, "Steamboat Bertrand Collection," http://www.bluegoose.arw.r9.fws.gov/NWRSFiles/CulturalResources/Bertrand/Bertrand.html, July 2001.

6. Dennis and Wolff, 173–174.

7. Ibid., 190–191.

8. Ibid., 191.

9. Michener, James A. *Centennial*. New York: Random House, 1974, 57–58.

10. "River Basin Characteristics—Maumee River, Ohio/Indiana." http://www.glc.org/projects/sediment/maumee.html, July 2001.

11. Casson, Lionel. *Ancient Egypt*. Alexandria, VA: Time-Life Books, Time, Inc., 1965, 29–31.

12. Manning, John C. *Applied Principles of Hydrology*. 1st ed. Columbus, Ohio: Merrill Publishing Co., 1987, 233.

13. Black, Peter E. *Watershed Hydrology*. Englewood Cliffs, NJ: Prentice-Hall, 1991, 216.

14. Shaw, Elizabeth M. *Hydrology in Practice*. 3rd ed. London: Chapman & Hall, 1994, 235–237.

15. Black, 469.