5 Rivers and Flooding

Failure of a levee in Monroe County, Illinois, resulting in flooding of farmland during the great floods of the Mississippi River in 1993. (*James A. Finley/AP/Wide World Photos*)

The great Mississippi River floods of 1993 remind us just how vulnerable we are to catastrophic flooding in the United States. Shown above is the failure of a levee in Monroe County, Illinois, which resulted in flooding of farmland. This certainly was not an isolated incident of levee failure, as nearly 80 percent of the private levees along the Mississippi River and its tributaries succumbed to the flood waters. The levees were responsible for providing a false sense of security for the people living and farming behind them. The flood cost more than $10 billion in property damages and has led to an evaluation of how in the future we should deal with flood hazards in the Mississippi River Valley. Some communities will move to higher ground, avoiding the flood hazard altogether. This is the environmentally correct adjustment. In the meantime, the Mississippi River continued to roll along, again flooding some communities in 1995.

5.1 River Processes

For more than 200 years, Americans have lived and worked on floodplains, enticed to do so by the rich alluvial (stream-deposited) soil, abundant water supply, ease of waste disposal, and proximity to the commerce that developed along rivers. Of course, building houses, industry, public buildings, and farms on a floodplain invites disaster, but floodplain residents have refused to recognize the natural floodway of the river for what it is: part of the natural river system. The **floodplain** is the flat surface adjacent to the river channel, periodically inundated by floodwater and in fact produced by the process of flooding (see Figure 5.1d). As a result of not recognizing the floodplain and its relation to the river, flood control and drainage of wetlands (including floodplains) became prime concerns. It is not an oversimplification to say that as the pioneers moved west

LEARNING OBJECTIVES

Flooding is a natural process that becomes a hazard when people choose to live or work on floodplains. The main learning objectives of the chapter are:

- *To gain a general appreciation for river processes.*
- *To understand the nature and extent of the flood hazard and the difference between upstream and downstream floods.*
- *To understand the effects of urbanization on flooding in small drainage basins.*
- *To be aware of the major preventive and adjustment measures for flooding and which ones are environmentally preferable.*
- *To know what potential adverse environmental effects of channelization are and how they might be minimized.*

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
- ▶ On-line "Web Essay" Questions
- ▶ Search Engines
- ▶ Regional Updates

they had a rather set procedure for modifying the land: First clear the land by cutting and burning the trees, then modify the natural drainage. From that history came two parallel trends: an accelerating program to control floods, matched by an even greater growth of flood damages (1). In this chapter we will consider flooding as a natural aspect of river processes and examine the successes and failures of traditional methods of flood control. We will see that newer approaches, while acknowledging that people will continue to live on floodplains, attempt to work with the natural river processes rather than against them.

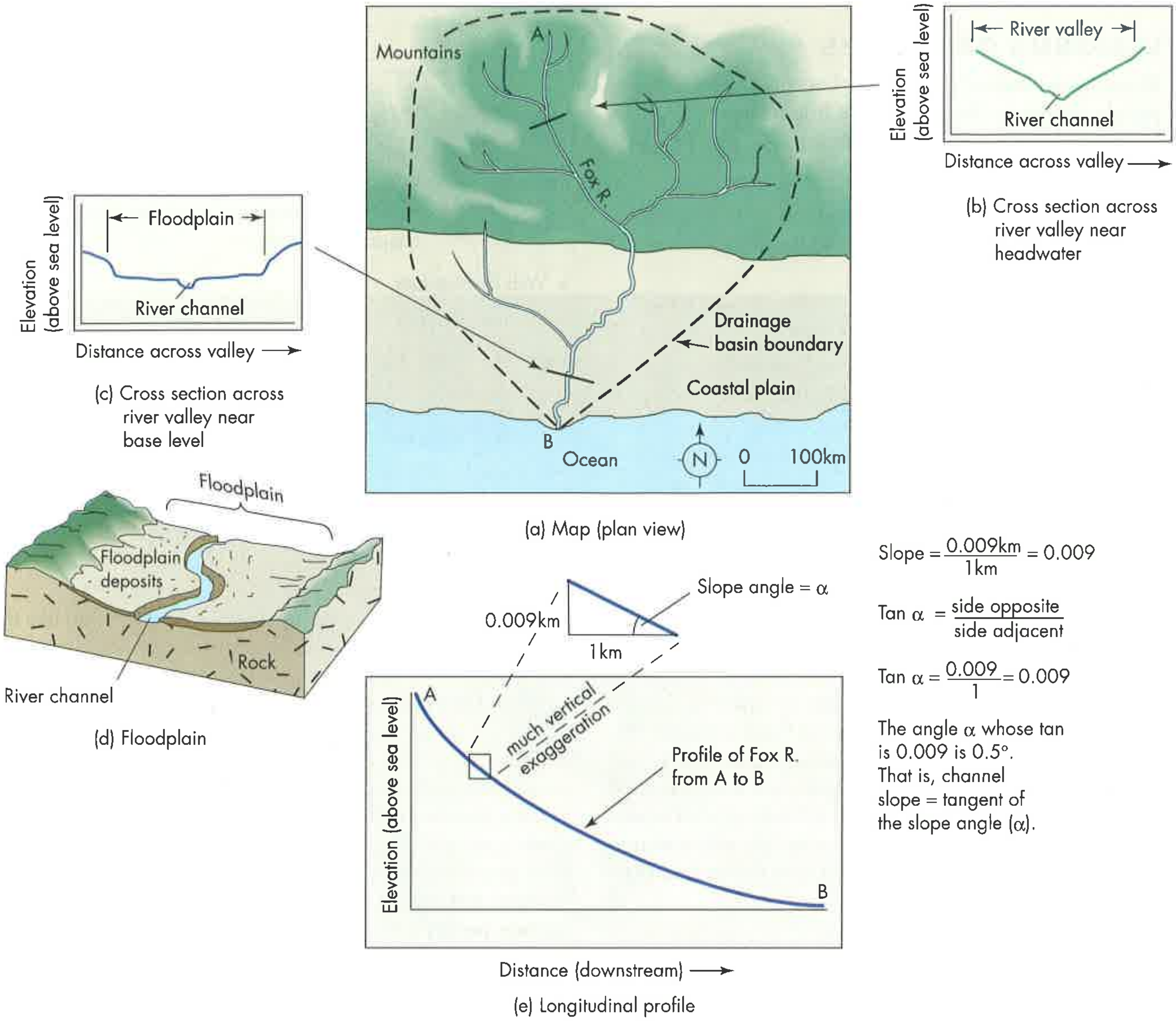
Streams and Rivers

Streams and rivers are part of the hydrologic cycle, which transports water by evaporation from the earth's surface (mostly the oceans) to the atmosphere and back again. Some of the water that falls on the land as rain or snow is absorbed; the rest drains, or runs off, following a course determined by the local topography. This **runoff** finds its way to streams, which may merge to form a larger stream or a river. Streams and rivers differ only in size (streams are small rivers), and geologists commonly use the word *stream* for any body of water that flows in a channel. The region (area, in km^2) drained by a single river or river system is called a **drainage basin,** or *watershed* (Figure 5.1a).

A stream's *slope*, or gradient, is its vertical drop per unit of horizontal distance, which can be expressed as meters per kilometer, degrees, or more commonly in hydrology as meters per meter (the units cancel). For example, a slope angle of 0.5° (see Figure 5.1e) is a slope of about 0.009 (m/m) or 9 m per km (9 m in 1000 m). In general, the slope is steepest at higher elevations and is much reduced as the stream approaches its **base level** (the theoretical lowest level to which a river may erode), commonly the ocean (a river may have a temporary base level, such as a lake). The result of rivers flowing downhill to their base level is that they have *longitudinal profiles* (that is, a graph of river elevation vs. distance downstream) like the one shown in Figure 5.1e. This profile is generally concave, like the front of a skateboard. A stream usually has steeper and higher valley sides at high elevations (near its headwaters, where the stream starts; Figure 5.1b) than near its base level (Figure 5.1c). This results because at higher elevations the stream has eroded a deeper valley in the hilly or mountainous terrain often found there. Increased erosion results in part because a steeper channel slope produces higher stream power that can cause a river to transport more sediment and erode its channel deeper than a channel with a low channel slope. Total **stream power** is the product of the volume per unit time of water flowing by a point (discharge), the water surface slope (water surface slope is approximately equivalent to channel slope), and the unit weight of water, which is a constant.

Sediments in Rivers

The total quantity of sediment carried in a river, called its **total load,** includes the bed load, the suspended load, and the dissolved load. The **bed load** moves along the bottom of the channel by bouncing, rolling, or skipping. The bed load of most rivers (usually sand and gravel) is a relatively small component (less than 10%) of the total load. The **suspended load** (usually silt and clay) is carried above the stream bed by the turbulence of the flowing water. It is often the largest part (about 90%) of the total load, and makes rivers look muddy. The **dissolved load** is carried in chemical solution and is derived from chemical weathering of rocks in the drainage basin. It is the dissolved load that may make stream water taste salty (if the dissolved load contains large amounts of sodium and chloride), and may make the stream water hard (if the dissolved load contains high concentrations of calcium and magnesium). The most common constituents of the dissolved load are bicarbonate (HCO_3^-) and sulfate ($SO_4^=$) ions and ions of calcium (Ca^{++}), sodium (Na^+), and magnesium (Mg^+). An ion is an atom or group of



▲ **FIGURE 5.1** Idealized diagram showing drainage basin (a); cross section of valley near headwater (b); near base level (c); floodplain (d); and longitudinal profile (e).

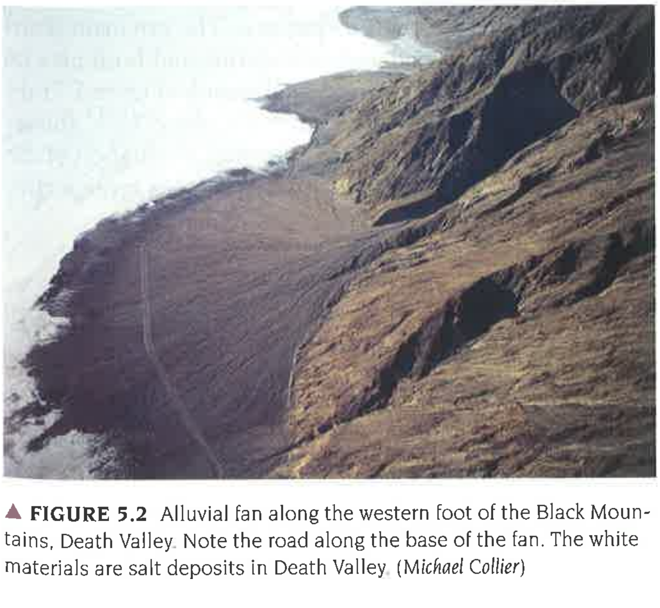
atoms (molecule) with a positive or negative charge resulting from a gain or loss of electrons. Typically, the above five atoms and molecules comprise more than 90 percent of a river's dissolved load. It is the suspended load and the bed load of streams that, when deposited in undesirable locations, produce the sediment pollution discussed in Chapter 3.

River Velocity, Erosion, and Sediment Deposits

Rivers are the basic transportation system of the part of the rock cycle involving erosion and deposition of sediments, and they are a primary erosion agent in the sculpture of our landscape. The velocity of a river varies along its course and affects both erosion and deposition of sediment.

The mean or average water velocity at any point along a river is defined as the ratio of the **discharge** (volume of water passing that point in a given time) to cross-sectional area of flow of the channel. That is, to calculate the average velocity of the water in a river you divide the total discharge by the cross-sectional area of flow. This relationship: $V = Q/A$, or $Q = V \times A$, or $Q = V \times W \times D$, where Q is discharge (m^3 per second, m^3/s, often abbreviated as cms), V is mean velocity of flow (m per second, m/s), A is cross-sectional area of flow (m^2), W is stream width in meters (m), and D is depth of flow in meters (m). The equation $Q = W \times D \times V$ is known as the continuity equation and is one of the most important relationships in understanding flow of water in rivers. We assume that if there are no additions or deletions of flow along a given length of river, then discharge is constant. It follows then that with constant discharge, if the cross-sectional area of flow decreases, then velocity must increase. This explains why a river that flows through a narrow, steep section or reach of channel has a higher velocity of flow than where it spreads out with larger cross-sectional area of flow downstream. A section of river being observed or studied is called a *reach*. A factor that allows the velocity to increase in the narrow reach of channel with reduced cross-sectional area of flow is the steeper channel slope often found there. It has been shown that average velocity of flow of water in a river is proportional to the product of the depth of flow and the slope or gradient of flow. Now we can see why slope is related to stream power (defined earlier as proportional to the product of discharge and slope). We would expect that the power of a river is related to velocity of flow and thus channel slope. If discharge is constant along a reach of river, then stream power is directly proportional to slope. Narrow reaches of a river with steep channel and water slope will have higher stream power than wide reaches with lower slope (assuming again discharge is constant).

In general, a faster-flowing river has the possibility to erode its banks more than a slower-moving one. Furthermore, the faster water flows, the greater the stream power tends to be, and the larger and heavier the sediment particles it can move. The largest and heaviest particles—boulders and gravel—are deposited in river environments at locations where stream power during relatively high flows, when these larger particles are being transported, is relatively low. Sand and silt tend to be deposited at relatively low flows in the lower-gradient, slow-moving reaches where stream power is even lower. Where streams flow from mountains onto plains, they may form fan-shaped deposits known as **alluvial fans** (Figure 5.2). Where a river flows into the ocean or other body of still water, it may deposit sediments that form a **delta,** a triangular land mass extending into the sea (Figure 5.3). The reasons deposition occurs in a specific area of a river channel or on alluvial fans or deltas are complex, related to changes in the river environment beyond the scope of our discussion here.



▲ **FIGURE 5.2** Alluvial fan along the western foot of the Black Mountains, Death Valley. Note the road along the base of the fan. The white materials are salt deposits in Death Valley. *(Michael Collier)*

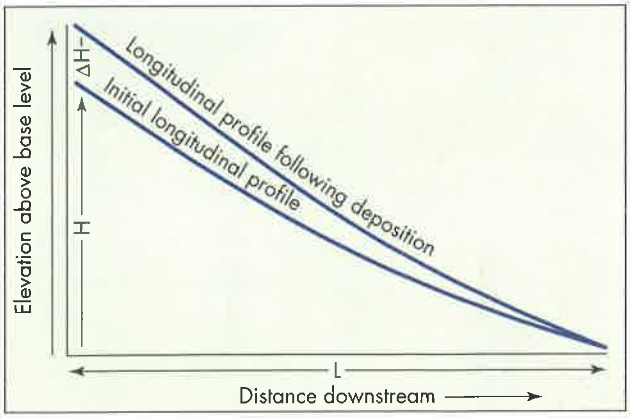
▲ **FIGURE 5.3** Delta of the Mississippi River. In this false color image, red is vegetation and sediment-laden waters are white or light blue, while deeper water with less suspended sediment is a darker blue. The system of distributary channels in the delta in the far right of the photograph looks something like a "bird's foot" and, in fact, the Mississippi River delta is an example of a bird's-foot delta. The distributary channels carry sediment out into the Gulf of Mexico and, because wave action is not strong in the gulf, the river dominates the delta system. *(Landsat image by U.S. Geological Survey; courtesy of John S. Shelton)*

The largest particle (particle diameter in mm or cm) a river may transport is called its **competency;** while the total load the river carries in a given period of time (units might be kg per second, kg/s) is its **capacity.**

Effect of Land-Use Changes

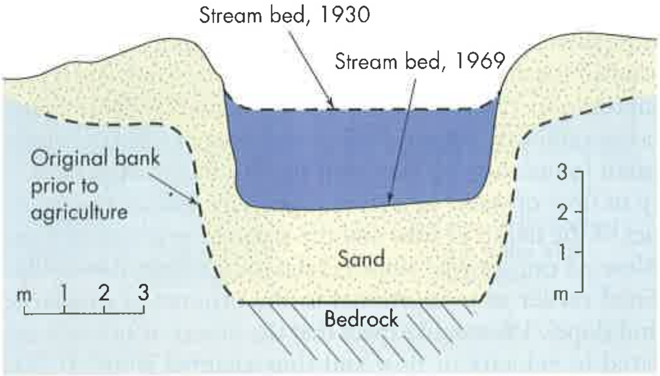
Streams and rivers are open systems that generally maintain a rough dynamic equilibrium, or steady-state, between the work done (sediment transported by the stream) and the load imposed (sediment delivered to the stream from tributaries and hill slopes) (1). The stream tends to have a slope and cross-sectional shape that provide just the velocity of flow (and stream power) necessary to do the work of moving the sediment load (2). An increase or decrease in the amount of water or sediment the stream receives usually brings about changes in the channel's slope or cross-sectional shape, effectively changing the velocity of the water. The change of velocity may, in turn, increase or decrease the amount of sediment carried in the system. Thus, land-use changes that affect the volume of sediment or of water in a stream may set into motion a series of events resulting in a new dynamic equilibrium.

Consider, for example, a land-use change from forest to agricultural row crops. This change will cause increased soil erosion and an increase in the load supplied to the stream. At first the stream will be unable to transport the entire load and will deposit more sediment, increasing the slope of the channel, which will in turn increase the velocity of water (and also stream power) and allow the stream to move more sediment. The slope (assuming base level is fixed) will continue to increase by deposition in the channel until the velocity (and stream power) increases sufficiently to carry the new load. The notion that deposition of sediment increases channel slope may be counterintuitive to



- Initial channel slope = $\frac{H}{L}$
- Slope following deposition = $\frac{H + \Delta H}{L}$
- $\frac{H + \Delta H}{L}$ is greater than $\frac{H}{L}$; so channel slope following deposition is greater than channel slope before deposition
- A similar argument can be constructed to show why channel erosion reduces channel slope.

▲ **FIGURE 5.4** Idealized diagram illustrating that deposition in a stream channel results in an increase in channel gradient.



▲ **FIGURE 5.5** Accelerated sedimentation and subsequent erosion resulting from land-use changes (natural forest to agriculture and back to forest) at the Mauldin Millsite on the Piedmont of middle Georgia. (*After S. W. Trimble, "Culturally Accelerated Sedimentation on the Middle Georgia Piedmont," master's thesis [Athens: University of Georgia, 1969.] Reproduced by permission.*)

you (see Figure 5.4 for further explanation of this principle). A new dynamic equilibrium may be reached, provided the rate of sediment increase levels out and the channel slope and shape can adjust before another land-use change occurs.

Now suppose the reverse situation occurs—that is, farmland is converted to forest. The sediment load to the stream from the land will decrease (forest lands have lower soil erosion rates than do agricultural lands), less sediment will be deposited in the stream channel, and erosion of the channel will eventually lower the slope, which in turn will lower the velocity of the water. The predominance of erosion over deposition will continue until an equilibrium between the load imposed and work done is achieved again.

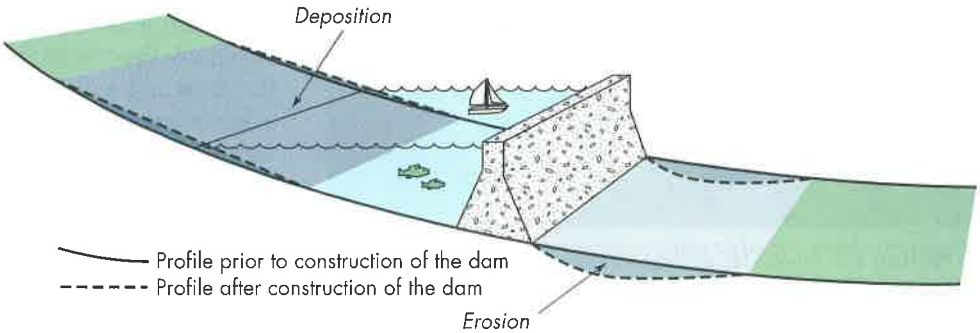
The sequence of change just described is occurring in parts of the Piedmont of the southeastern United States. There, land that was forest in the early history of the country was cleared for farming, producing accelerated soil erosion and subsequent deposition of sediment in the stream (Figure 5.5). The land is now reverting to pine forests, and this, in conjunction with soil-conservation measures, has reduced the sediment load delivered to streams. Thus, once-muddy streams choked with sediment are now clearing and eroding their channels. Whether this trend continues depends on future conservation measures and land use.

Consider now the effect of constructing a dam on a stream. Considerable changes will take place both upstream and downstream of the reservoir. Upstream, at the head of the reservoir, the effect will be to slow down the stream, causing deposition of sediment. Downstream, the water coming out below the dam will have little sediment, most of it having been trapped in the reservoir. As a result, the stream may have the capacity to transport additional sediment, and if this happens, erosion will predominate over deposition downstream of the dam. Slope then will decrease until new equilibrium conditions are reached (Figure 5.6). We will return to the topic of dams on rivers in Chapter 10.

Channel Patterns and Floodplain Formation

The configuration of the channel in plan view (as from an airplane) is called the **channel pattern.** The two main channel patterns are braided and meandering and both may be found on the same river. **Braided channels** (Figure 5.7) are characterized by numerous inchannels, gravel bars, and islands that divide and reunite the channel. Formation of the braided channel pattern, as with many other river forms,

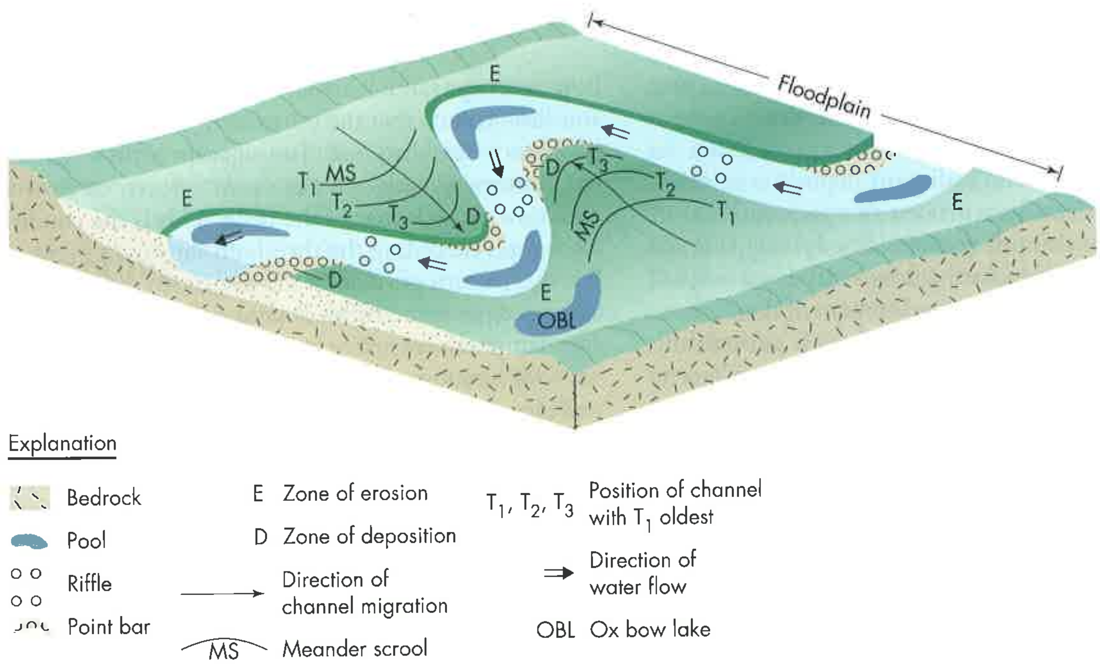
▶ **FIGURE 5.6** Upstream deposition and downstream erosion from construction of a dam and a reservoir.



▲ **FIGURE 5.7** The north Saskatchewan River here has a braided channel pattern. Notice the numerous channel bars and islands that subdivide the flow. (*John S. Shelton*)

results from the interaction of flowing water and moving sediment operating with geologic and climatic variables. If the river longitudinal profile is steep and there is an abundance of coarse sediment, the channel pattern is likely to be braided. Braided channels tend to be wide and shallow compared to meandering rivers. Steep slope and coarse sediment favor transport of bed-load material important in the development of gravel bars, which form the "islands" that divide and subdivide the flow. Braided channels tend to be associated with steep glacial meltwater rivers with an abundance of gravel or steep rivers flowing through areas being rapidly uplifted by tectonic processes. Rapid uplift produces steep river gradients and erosive power to produce coarse gravel sediment.

Meandering channels are sinuous, containing individual bends, called **meanders** (Figure 5.8a), that migrate back and forth across the floodplain. On the outside of a bend



(a)

▲ **FIGURE 5.8** Idealized diagram of a meandering stream and important forms and processes (a), and photograph of a meandering stream, Owens River, California (b). (*Edward A. Keller*)

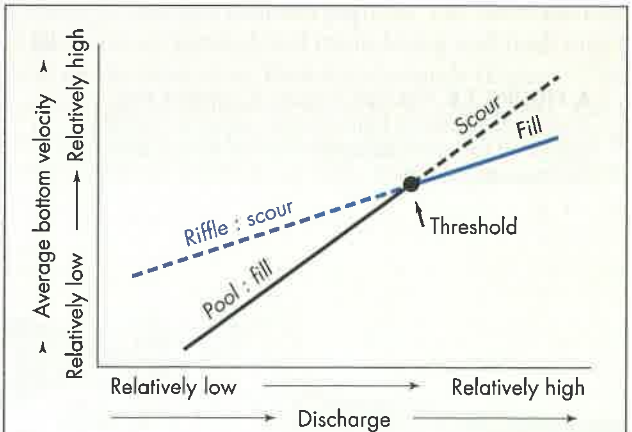
(b)

▶ **FIGURE 5.9** Well-developed pool-riffle sequence in Sims Creek near Blowing Rock, North Carolina. A deep pool is apparent in the middle distance, and shallow riffles can be seen in the far distance and the foreground. (*Edward A. Keller*)

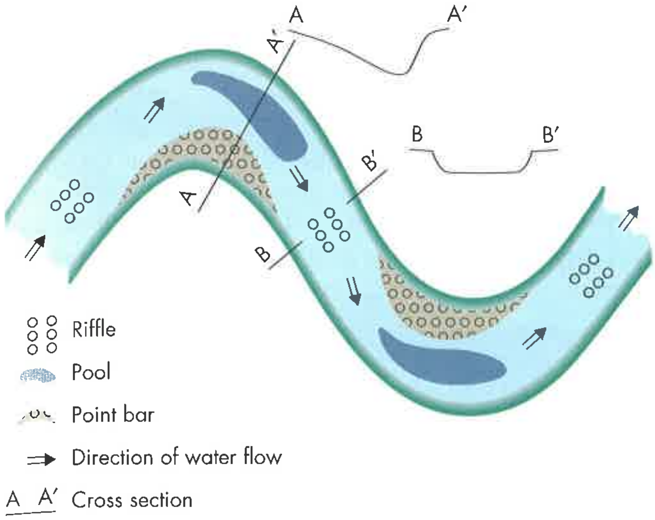
the water during high-flow events moves faster, causing more bank erosion; on the inside of a curve, it moves more slowly and sediment is deposited, forming **point bars.** As this differential erosion and sediment deposit continues, meanders migrate laterally, a process that is prominent in constructing and maintaining some floodplains (Figure 5.8b). Overbank deposition during floods causes vertical accretion that is also important in development of floodplains. Much of the sediment transported in rivers is periodically stored by deposition in the channel and on the adjacent floodplain. These areas, collectively called the **riverine environment,** are the natural domain of the river. Lateral migration of bends of rivers and overbank flow combine to produce the floodplain, which is periodically inundated by water and sediment.

Meandering channels often contain a series of regularly spaced pools and riffles (Figure 5.9). Straight channels, a relatively rare channel pattern, may also contain pools and riffles. **Pools** are deep areas produced by scour (erosion) at high flow and characterized at low flow by relatively deep, slow movement of water. Pools are places in which to take a summer swim. **Riffles** are shallow areas produced by depositional processes (fill) at high flow and characterized at low flow by relatively shallow, fast-moving water. We therefore conclude that pools scour (erode) at high flow and fill with sediment at low flow, whereas riffles fill at high flow and scour at low flow (Figure 5.10). Also, notice that while the velocity of a pool is lower than the riffle at low discharge, at high flow the velocity of water through the pool exceeds that of the riffle. This change in velocity may happen in part because the basic shape of a pool and adjacent point bar is like a triangle, whereas that of the riffle is more like a rectangle (Figure 5.11). At low flow the cross-sectional area of flow of a pool may exceed that of an adjacent riffle, and therefore by the continuity equation $Q = A \times V$, the mean velocity of the pool is less than that of the riffle (3). At high flow a change has occurred, and the geometry of the pool and riffle is such that the cross-sectional area of flow of the pool is now less than that of an adjacent riffle. Therefore, by the continuity equation the mean velocity of flow in the pool now exceeds that of the riffle. This is the condition at discharges exceeding the threshold shown on Figure 5.10). It is this pattern of velocity and associated scour and fill that maintains pools and riffles. A pool-riffle sequence is repeated approximately every five to seven times the channel width.

Observation of many streams suggest that those with well-developed pools and riffles tend to have considerable gravel in the streambed and a relatively low slope (less than about 0.015; remember: slope has no units). Streams with finer bed material or steep slopes tend to lack regularly spaced pools and riffles. The reason for this is poorly understood. We do know that pools and riffles have impor-



▲ **FIGURE 5.10** Scour-fill pattern characteristic of a pool-riffle sequence. The threshold is a critical discharge at which change in process (scour-to-fill or fill-to-scour) occurs.



▲ **FIGURE 5.11** Idealized diagram of a stream channel showing form (cross section) of pools and riffles.

tant environmental significance. This results in part because the alternation of deep, slow-moving water with shallow, fast-moving water in pools and riffles produces a variable physical environment and increased biologic diversity.

5.2 Flooding

The natural process of overbank flow is termed **flooding.** Most river flooding is a function of the total amount and distribution of precipitation in the drainage basin, the rate at which precipitation infiltrates the rock or soil, and the topography. However, some floods result from rapid melting of ice and snow in the spring or, on rare occasions, from the failure of a dam. Finally, land use can greatly affect flooding in small drainage basins.

The channel discharge (cubic meters per second, m^3/s or cms) at the point where water overflows the channel is called the *flood discharge* and is used as an indication of the *magnitude* of the flood (see *A Closer Look: Magnitude and Frequency of Floods*). The magnitude of a flood may or may not coincide with the extent of property damage. The term **flood stage** frequently connotes that the elevation of the water surface has reached a high-water condition likely to cause damage to personal property. This definition is based on human perception of the event, so the elevation that is considered flood stage depends on human use of the floodplain (4).

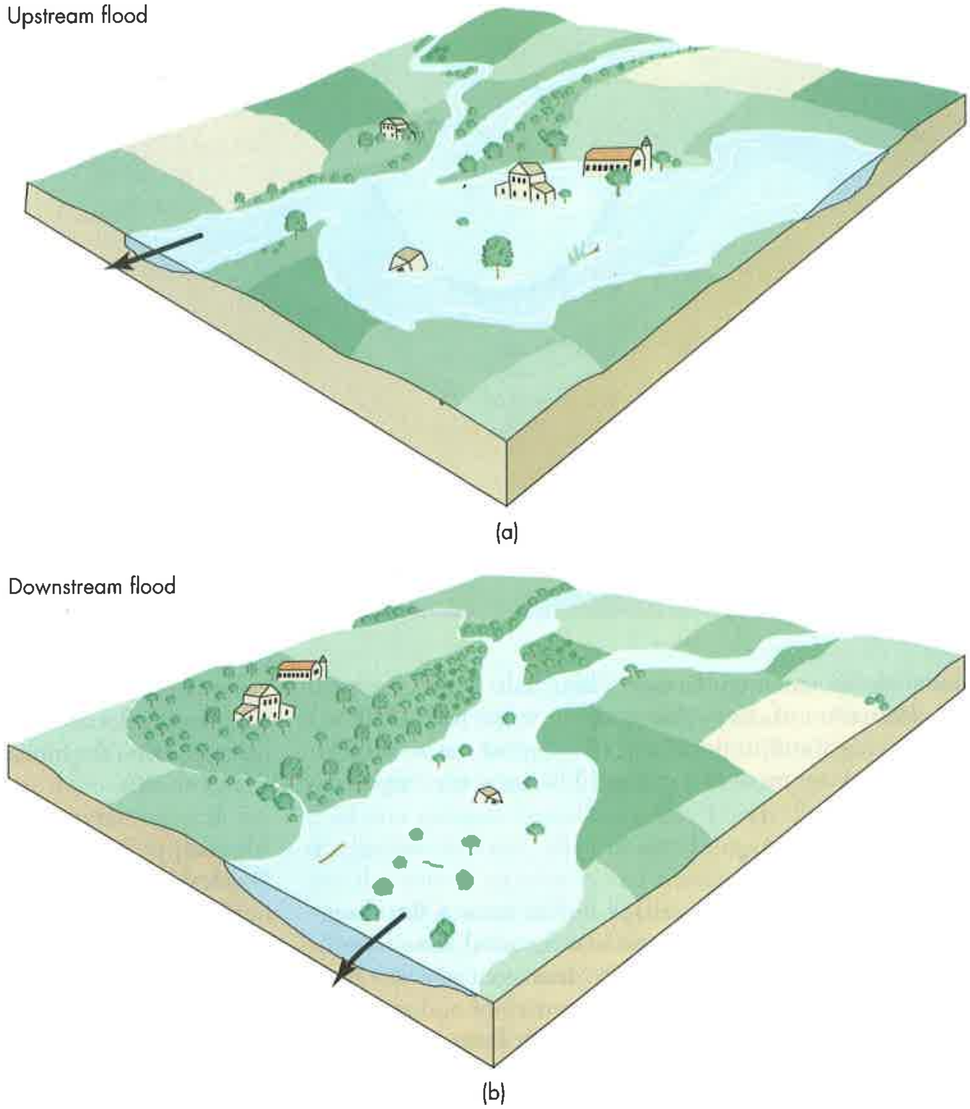
The longer flow records are collected, the more accurate the prediction of floods is likely to be. However, designing structures for a 10-year, 25-year, 50-year, or even 100-year flood, or in fact any flow below possible maximum, is a calculated risk because predicting such floods is based on probability. In the long term, a 25-year flood happens on the average of once every 25 years, but two 25-year floods could occur in any given year as could two 100-year floods (5)! As long as we continue to build dams, highways, bridges, homes, and other structures on flood-prone areas, we can expect continued loss of lives and property.

Upstream and Downstream Floods

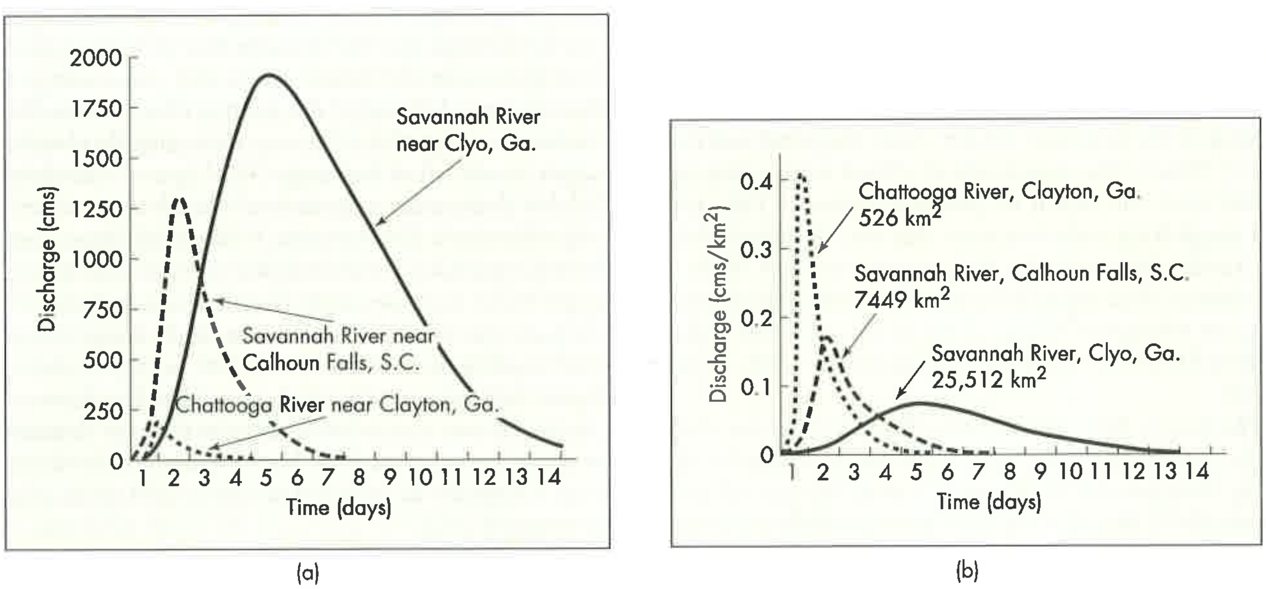
It is useful to distinguish between upstream and downstream floods (Figure 5.12). **Upstream floods** occur in the upper parts of drainage areas and are generally produced by intense rainfall of short duration over a relatively small area. These floods may not cause severe flooding in the larger streams they join downstream, although they can be quite severe locally. For example, a high-magnitude upstream flood occurred in the Front Range of Colorado in the summer of 1976, when violent flash floods, nourished by a complex system of thunderstorms delivering up to 25 cm of rain, swept through several canyons west of Loveland. This brief local flood killed 139 people and inflicted more than $35 million in damages to highways, roads, bridges, homes, and small businesses. Most of the damage and loss of life occurred in the Big Thompson Canyon, where hundreds of residents, campers, and tourists were caught with little or no warning. Although the storm and flood were rare events (several times the magnitude of the 100-year flood), comparable floods have occurred in the past and others can be expected in the future for similar canyons along the Front Range (8–10).

It is the large **downstream floods,** such as the 1993 Mississippi River floods and the 1997 Red River, North Dakota floods, that usually make television and newspaper headlines. The Mississippi flood is discussed at the end of the chapter. The Red River flood inundated the city of Grand Forks, North Dakota, initiating the evacuation of 50,000 people, causing a fire that burned part of the city center, and inflicting more than $1 billion in damage. Downstream floods cover a wide area and are usually produced by storms of long duration that saturate the soil and produce increased runoff. Flooding on small tributary basins may be limited, but the contribution of increased runoff from thousands of tributary basins may cause a large flood downstream. A flood of this kind is characterized by the downstream migration of an ever-increasing flood wave with large rise and fall of discharge (11). Figure 5.13a shows the 257-km downstream migration of a flood crest on the Chattooga–Savannah River system. It illustrates that a progressively longer time is necessary for the rise and fall of water as the flood wave proceeds downstream, and shows dramatically the tremendous increase in discharge from low-flow conditions to more than 1700 m^3/s in 5 days (12). Figure 5.13b also illustrates the same flood in terms of discharge per unit area, eliminating the effect of downstream increase in discharge. This better illustrates the shape and form (sharpness of peaking) of the flood wave as it moves downstream (12).

A few upstream floods of very high magnitude have been caused directly by structural failure. For example, the most destructive flood in West Virginia's history was caused by the failure of a coal-waste dam on the middle fork of Buffalo Creek (13).



▶ **FIGURE 5.12** Idealized diagram comparing upstream flood (a) to downstream flood (b). Upstream floods generally cover relatively small areas and are caused by intense local storms, whereas downstream floods cover wide areas and are caused by regional storms or spring runoff. *(Modified after* U.S. *Department of Agriculture drawing.)*



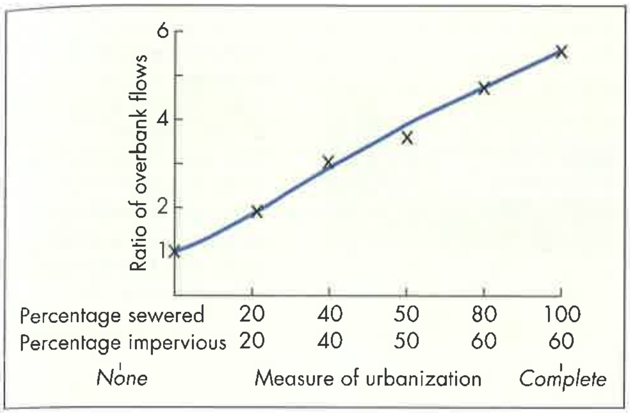
▲ **FIGURE 5.13** Downstream movement of a flood wave on the Savannah River, South Carolina and Georgia. The distance from Clayton to Clyo is 257 km. (a) Volume of water passing Clayton, Calhoun Falls, and Clyo. (b) Volume of water per unit area at the same points. *(After William G. Hoyt and Walter B. Langbein,* Floods *[© copyright 1955 by Princeton University Press], Fig. 8, p. 39. Reprinted by permission of Princeton University Press.)*

5.3 Development and Flooding

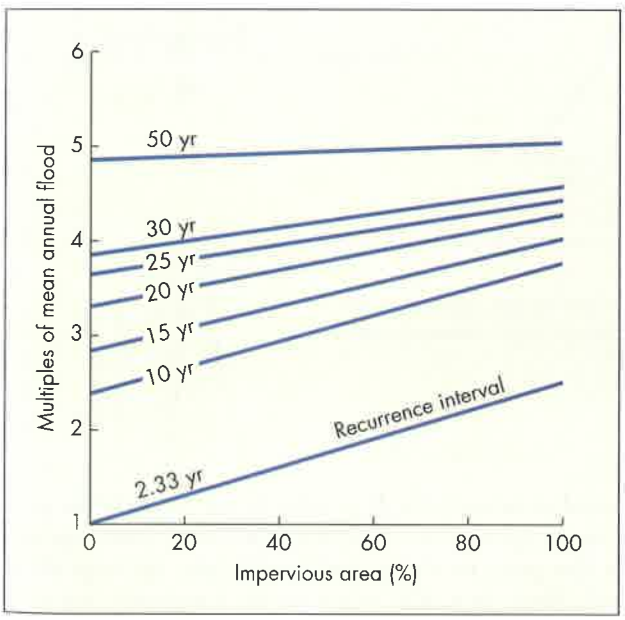
Human use of land in the urban environment has increased both the magnitude and frequency of floods in small drainage basins of a few square kilometers. The rate of increase is a function of the percentage of the land that is covered with roofs, pavement, and cement (referred to as **impervious cover**) and the percentage of area served by storm sewers. Storm sewers are important because they allow urban runoff from impervious surfaces to reach stream channels quickly. Therefore, impervious cover and storm sewers are collectively a measure of the degree of urbanization. The graph in Figure 5.14 shows that an urban area with 40 percent impervious surface and 40 percent of its area served by storm sewers can expect to have about three times as many overbank flows (floods) as before urbanization. This ratio holds for floods of small and intermediate frequency, but as the size of the drainage basin increases, floods of high magnitude with frequencies of 50 years or so are not much affected by urbanization (Figure 5.15).

Floods are a function of rainfall–runoff relations, and urbanization causes a tremendous number of changes in these relations (see *Case History: Las Vegas, Nevada*). One study showed that urban runoff from the larger storms is nearly five times preurban runoff (5). Estimates of discharge for different recurrence intervals at different degrees of urbanization are shown in Figure 5.16. The estimates dramatically indicate the tremendous increase of runoff with increasing impervious areas and storm sewer coverage.

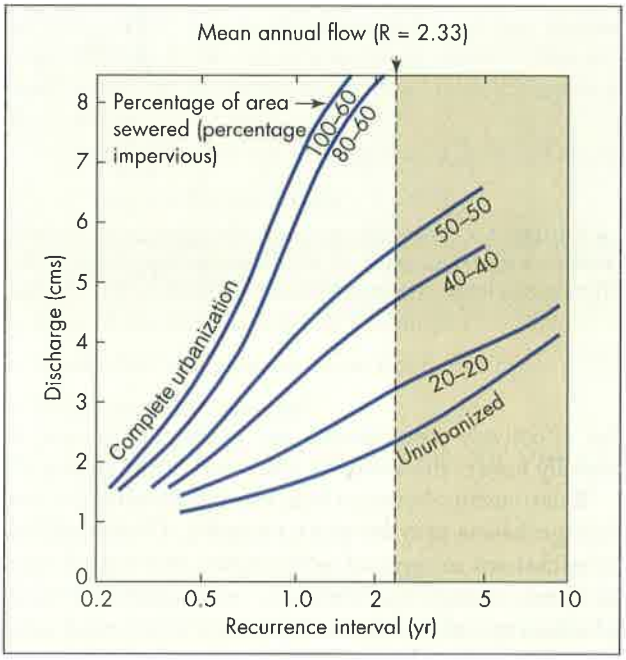
The increase of runoff with urbanization occurs because less water infiltrates the ground, as suggested by the significant reduction in time between the majority of rainfall and the flood peak **(lag-time)** for urban versus rural conditions (Figure 5.17). Short lag-times, referred to as **flashy discharge,** are characterized by rapid rise and fall of floodwaters. Because little water infiltrates the soil, the low water or dry season flow in urban streams, sustained by groundwater seepage into the channel, is greatly reduced.



▲ **FIGURE 5.14** Relationship between the ratio of overbank flows (after urbanization to before urbanization) and measure of urbanization. This figure shows that as the degree of urbanization increases, the number of overbank flows per year also increases. (*From* L. B. *Leopold*, U.S. *Geological Survey Circular* 554, 1968)



▲ **FIGURE 5.15** Graph showing the variation of flood frequency with percentage of impervious area. The mean annual flood is the average (over a period of years) of the largest flow that occurs each year. The mean annual flood in a natural river basin with no urbanization has a recurrence interval of 2.33 years. Note that the smaller floods with recurrence intervals of just a few years are much more affected by urbanization than are the larger floods. The 50-year flood is little affected by the amount of area that is rendered impervious. (*From* L. A. *Martens*, U.S. *Geological Survey Water Supply Paper* 1591C, 1968)

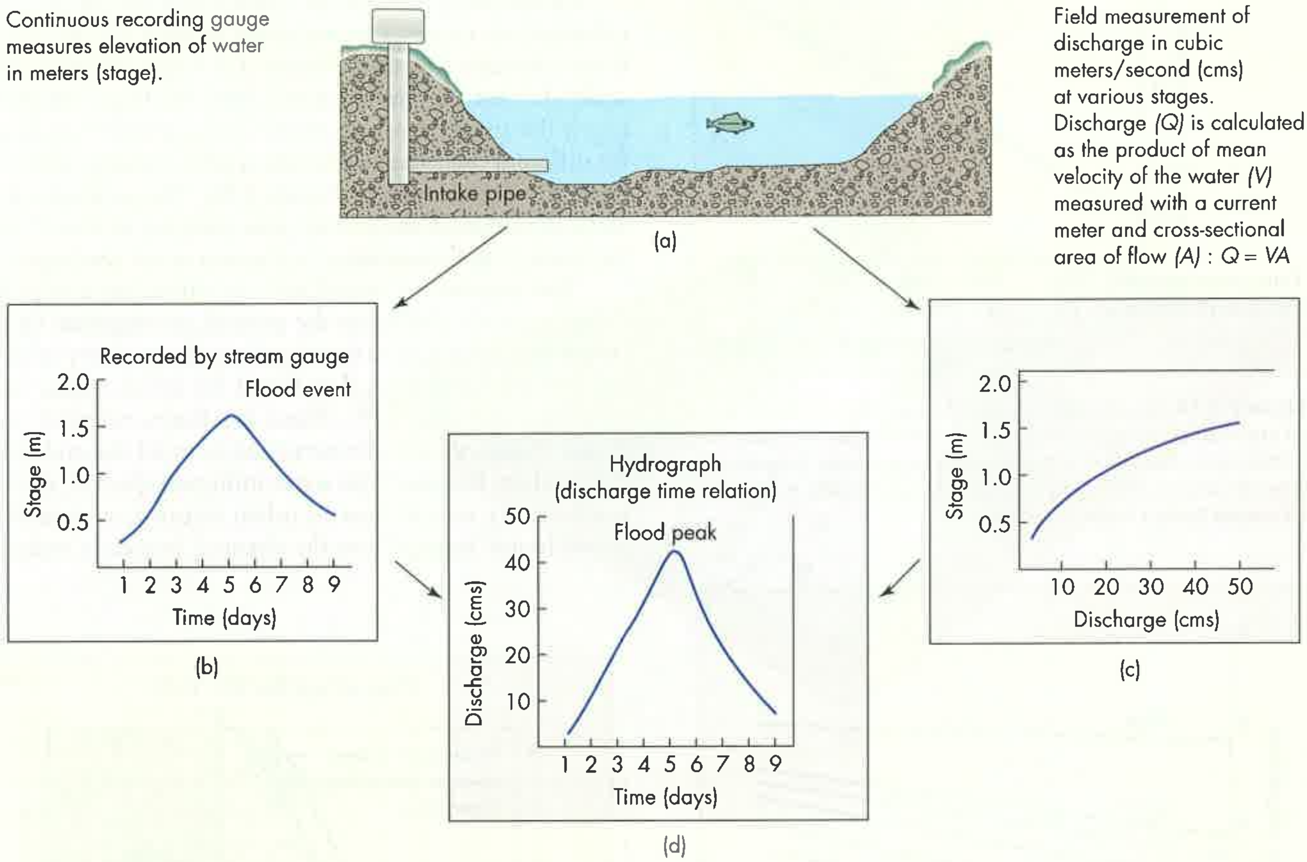


▲ **FIGURE 5.16** Flood frequency curve for a 2.6 km^2 (one-square-mile) basin in various states of urbanization. Note: 100–60 means basin is 100 percent sewered and 60 percent of surface area is impervious. Dashed line shows increase in mean annual flood with increasing urbanization. (*After* L. B. *Leopold*, U.S. *Geological Survey Circular* 554, 1968)

A CLOSER LOOK Magnitude and Frequency of Floods

Flooding is intimately related to the amount and intensity of precipitation and runoff. Catastrophic floods reported on television and in newspapers often are produced by infrequent, large, intense storms. Smaller floods or flows may be produced by less intense storms, which occur more frequently. All flow events that can be measured or estimated from stream-gauging stations (Figure 5.A) can be arranged in order of their magnitude of discharge, generally measured in cubic meters per second (m^3/s). The list of flows so arranged can be plotted on a discharge-frequency curve (Figure 5.B) by deriving the **recurrence interval** *R* for each flow from the relationship

$$R = (N + 1) \div M$$



▲ **FIGURE 5.A** Field data (a) consist of a continuous recording of the water level (stage), which is used to produce a stage-time graph (b). Field measurements at various flows also produce a stage-discharge graph (c). Then graphs (b) and (c) are combined to produce the final hydrograph (d).

This effectively concentrates any pollutants present and generally lowers the aesthetic amenities of the stream (7).

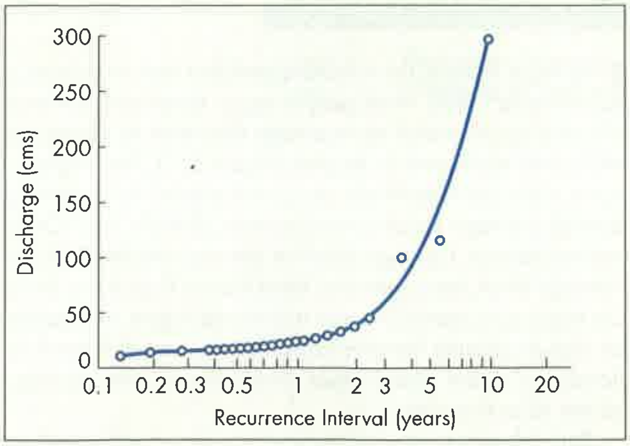
Relationships between land use and flooding for small drainage basins may be quite complex. One study concludes that not all types of urbanization increase all runoff and flood events (14). When row crops such as corn and soybeans are replaced by low-density residential development, the predicted runoff and flood peaks for low-magnitude events with recurrence intervals of 2 to 4 years increase, as expected. For events with recurrence intervals exceeding 4 years, however, the predicted runoff and flood peaks for the agricultural land may exceed that for residential development. As row crops are replaced by paved areas and grass, the runoff from the paved areas is greater, but the grass produces less runoff than the agricultural land. Therefore, the effect of the land-use change on runoff and flooding depends on the nature and extent of urbanization and in particular on the proportion of paved and grass-covered areas.

Urbanization is not the only type of development that can increase flooding. Some flash floods have occurred because bridges built across small streams caused temporary debris dams to form (see *Case History: Flash Floods in Eastern Ohio*).

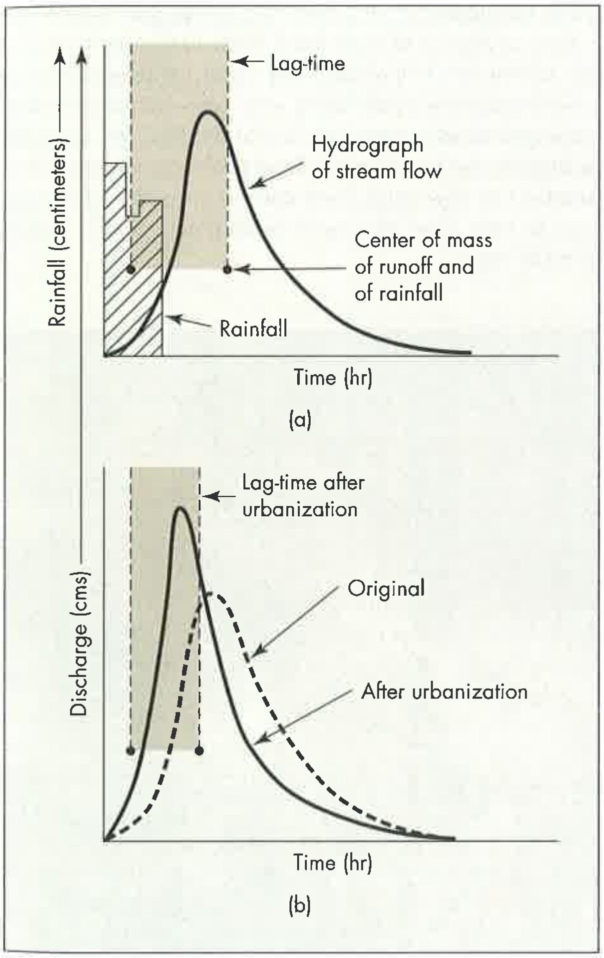
where R is a recurrence interval in years, N is the number of years of record, and M is the rank of the individual flow in the array (6). The highest flow for 9 years of data for the stream shown in Figure 5.B (about 280 m^3/s) has a rank M equal to 1 (7). The recurrence interval of this flood is

$$R = (N + 1) \div M = (9 + 1) \div 1 = 10$$

which means that a flood with a magnitude equal to or exceeding 280 m^3/s can be expected about every 10 years; we call this a 10-year flood. The probability of the 10-year flood happening in any one year is 1 ÷ 10 or 0.1 (10%). The probability of the 100-year flood occurring in any year is 1 ÷ 100 = 0.01 or 1 percent. Studies of many streams and rivers show that channels are formed and maintained by bank-full discharge with a recurrence interval of 1.5 to 2 years (about 30 m^3/s on Figure 5.B). Therefore, we can expect a stream to emerge from its banks and cover part of the floodplain with water and sediment once every year or so.



▲ **FIGURE 5.B** Example of a discharge frequency curve. Each circle represents a flow event with recurrence interval plotted on probability paper. (*After* L. B. *Leopold*, U.S. *Geological Survey Circular* 554, 1968)



▲ **FIGURE 5.17** Generalized hydrographs. Hydrograph (a) shows the typical lag between the time when most of the rainfall occurs and the time when the stream floods. Hydrograph (b) shows the decrease in lag-time because of urbanization. (*After* L. B. *Leopold*, U.S. *Geological Survey Circular* 554, 1968)

5.4 The Nature and Extent of Flood Hazards

Flooding is one of the most universally experienced natural hazards. In the United States the lives lost to river flooding number about 100 per year, with property damage of about $4 billion annually. The loss of life is low compared to loss in preindustrial societies that lack monitoring and warning systems and effective disaster relief. Although preindustrial societies with dense populations on floodplains lose many more lives to flooding, they have less property damage than do industrial societies (3,4). Table 5.1 lists some severe floods that have occurred in the United States in the past 60 years.

Factors that control the damage caused by floods include:

- Land use on the floodplain.
- Magnitude (depth and velocity of the water and frequency of flooding).
- Rate of rise and duration of flooding.
- Season (for example: crops on floodplain).
- Sediment load deposited.
- Effectiveness of forecasting, warning, and emergency systems.

The effects of flooding may be primary—that is, directly caused by the flood—or secondary, caused by disruption and malfunction of services and systems attributable to the flood (15). Primary effects include injury and loss of life, along with damage caused by swift currents, debris, and sediment to farms, homes, buildings, railroads, bridges, roads, and communication systems. Erosion and deposition of sediment in the rural and urban landscape can also involve a loss of considerable soil and vegetation. Secondary

CASE HISTORY Las Vegas, Nevada

Las Vegas, Nevada, has a flooding problem that dates back to the early 1900s when people began developing the area. The city is surrounded by mountains that drain to alluvial fans with channels known as washes (Figure 5.C). The largest of these is the Las Vegas Wash, which drains from the northwest through Las Vegas to Lake Mead on the Colorado River. Other washes join the Las Vegas Wash in the city; one of these, the Flamingo Wash, has a notorious flood history. Flash floods in the Las Vegas area generally occur in July and August in response to high-magnitude thunderstorm activity, and damage from flooding is severe where major developments have obstructed the natural washes.

Rapid development unfortunately coincided with increased thunderstorm activity from 1975 through the mid-1980s. A flood that came down the Flamingo Wash in July 1975 caused particular concern. At Caesar's Palace (a prominent casino), hundreds of cars in a parking lot, which covered part of the Flamingo Wash, were damaged, many of them moved downstream by floodwaters. Damage to vehicles and from lateral bank erosion along the wash was reported to be as high as $5 million. Following the flood, the Flamingo Wash was routed by way of a tunnel beneath Caesar's Palace. Where the tunnel emerges, the wash flows at the surface again and often down city streets! Flooding again occurred in 1983 and 1984 in the months of July and August. In particular, eight major storms from July through September 1984 resulted in tens of millions of dollars of damage in Clark County, Nevada.

Las Vegas is located in a basin at the foot of alluvial fan surfaces. In many instances, alluvial fans are very porous and surface runoff infiltrates rapidly. In the Las Vegas area, however, the calcium-carbonate-rich soil horizons (K horizon, see Chapter 3) cement alluvial deposits together and retard surface infiltration of water. As a result, the Las Vegas area is more susceptible to flood hazard than otherwise might be expected. Nonetheless, whenever urban development is built directly across active washes, trouble can be expected.

Clark County, Nevada, has developed a plan to address the flood hazard in Las Vegas. It is designed to protect the area from the 100-year peak flow resulting from a 3-hour thunderstorm and includes:

- Construction of channels, pipelines, and culverts to convey floodwaters away from developed areas.
- Construction of storm-water retention basins that will release the flow over a longer period of time.

Because there has been so much development on the washes in Las Vegas, it seems unlikely that any plan will completely alleviate the flood problem. That would require completely routing floodwaters around or safely through all the existing development. But even this precaution would not free the Las Vegas area from flood hazard resulting from the larger storms that will occasionally occur. Implementation of a flood-management plan, along with land-use planning that discourages development on natural washes, will certainly help alleviate the community's flood problems. However, it is a gamble as to how much flood-control measures can be expected to help, given the rapid development that is occurring in Las Vegas.

▶ **FIGURE 5.C** Aerial view of the Las Vegas, Nevada, area. The city is in a natural basin and many structures have been built across natural drainage channels (washes). Arrows show the direction of flow into the urban area and out to Lake Mead. (*Courtesy of Map and Image Library, University of California*)

Table 5.1 Selected river floods in the United States

Year	Month	Location	Lives Lost	Property Damage (Millions of Dollars)
1937	Jan.–Feb.	Ohio and lower Mississippi River basins	137	417.7
1938	March	Southern California	79	24.5
1940	Aug.	Southern Virginia and Carolinas, and eastern Tennessee	40	12.0
1947	May–July	Lower Missouri and middle Mississippi river basins	29	235.0
1951	June–July	Kansas and Missouri	28	923.2
1955	Dec.	West Coast	61	154.5
1963	March	Ohio River basin	26	97.6
1964	June	Montana	31	54.3
1964	Dec.	California and Oregon	40	415.8
1965	June	Sanderson, Texas (flash flood)	26	2.7
1969	Jan.–Feb.	California	60	399.2
1969	Aug.	James River basin, Virginia	154	116.0
1971	Aug.	New Jersey	3	138.5
1972	June	Black Hills, South Dakota (flash flood)	242	163.0
1972	June	Eastern United States	113	3,000.0
1973	March–June	Mississippi River	—	1,200.0
1976	July	Big Thompson River, Colorado (flash flood)	139	35.0
1977	July	Johnstown, Pennsylvania	76	330.0
1977	Sept.	Kansas City, Missouri, and Kansas	25	80.0
1979	April	Mississippi and Alabama	10	500.0
1983	Sept.	Arizona	13	416.0
1986	Winter	Western states, especially California	17	270.0
1990	Jan.–May	Trinity River, Texas	—	1,000.0
1990	June	Eastern Ohio (flash flood)	21	several
1993	June–Aug.	Mississippi River and tributaries	50	>10,000
1997	January	Sierra Nevada, Central Valley, California	23	several hundred
1997	April	Red River, Grand Forks, North Dakota	—	>1,000.0

Sources: NOAA, *Climatological Data, National Summary*, 1970, 1972, 1973, and 1977; U.S. Geological Survey. Updated by author in 1999.

effects can include short-term pollution of rivers, hunger and disease, and displacement of people who have lost their homes. In addition, fires may be caused by short circuits or broken gas mains (15).

5.5 The Response to Flood Hazards

Historically, the response to flooding has been to try to prevent the problem: to control the water by constructing dams, modify the stream by building levees, or even rebuild the entire stream so it will drain the land more efficiently. Every new project has the effect of luring more people to the floodplain in the false hope that the flood hazard is no longer significant. However, we have yet to build a dam or channel capable of controlling the heaviest rainwaters, and when the water finally exceeds the capacity of the structure, flooding can be extensive (16).

There are two general types of response to flood hazards. *Prevention* is the structural approach we have just described. Adjustment measures include *floodplain regulation*, which is assuming greater importance as we begin to recognize the limitations of the structural approach, and flood insurance (15).

Prevention: Physical Barriers

Measures to prevent flooding include construction of physical barriers such as levees (linear mound embankments of compacted earth along the banks of a river, Figure 5.18) and flood walls (usually constructed of concrete as opposed to earthen levees); reservoirs to store water for later release at

CASE HISTORY Flash Floods in Eastern Ohio

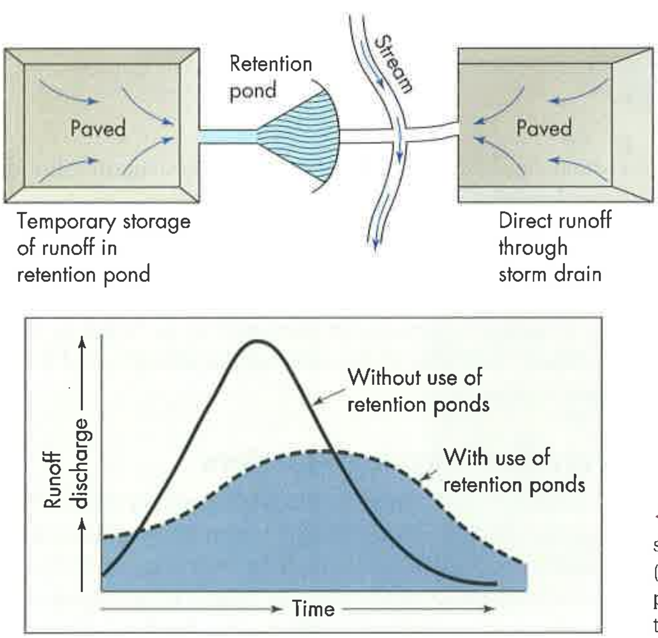
On Thursday, June 14, 1990, more than 14 cm of precipitation fell in approximately 3½ hours in some areas of eastern Ohio. Two tributaries of the Ohio River, Wegee and Pipe creeks, generated flash floods near the small town of Shadyside, killing 26 people and leaving 13 missing and presumed dead. The floods were described as walls of water as high as 5 m that rushed through the valley. In all, approximately 70 houses were destroyed and another 40 were damaged. Trailers and houses were seen washing down the creeks, bobbing like corks in the torrent.

The rush of water was apparently related to failure of debris dams that had developed upstream of bridges across the creeks. Runoff from rainfall had washed debris into the channel from sideslopes, and this debris (tree trunks and other material) became lodged against the bridges. When the bridges could no longer contain the weight of the debris, the dams broke loose, sending surges of water downstream. This scenario has been played and replayed in many flash floods around the world. All too often, the supports for bridges are not spaced far enough apart to allow the passage of large debris, which then pile up against the upstream side of the bridge, damming the stream and eventually causing a flood.

▲ **FIGURE 5.18** Levee with a road on top of it protects the bank (left side of photograph) of the lower Mississippi River at this location in Louisiana. (*Comstock, Inc.*)

safe rates; on-site storm-water retention basins (Figure 5.19); channel improvements *(channelization)* to increase channel size and move water off the land quickly; and channel diversions to route floodwaters around areas requiring protection. We will discuss the pros and cons of channel improvements and diversions later in this section.

Unfortunately, the potential benefits of physical barriers are often lost because of increased development on floodplains supposedly protected by these structures. For example, the winters of 1986 and 1997 brought tremendous storms and flooding to the western states, particularly California, Nevada, and Utah. Damages in 1986 exceeded $270 million, and at least 17 people died (17). During one of the storms and floods in 1986, a levee broke on the Yuba River in California, causing more than 20,000 people to flee their homes. An important lesson learned during this flood is that a number of the levees constructed many years ago along



(a)

(b)

◀ **FIGURE 5.19** (a) Comparison of runoff from a paved area through a storm drain with runoff from a paved area through a temporary storage site (retention pond). Notice that the paved area drained by way of the retention pond produces a lesser peak discharge and therefore is less likely to contribute to flooding of the stream. (*Modified after U.S. Geological Survey Professional Paper* 950.) (b) Photograph of a retention pond near Santa Barbara, California. (*Edward A. Keller*) rivers in California and other states are in poor condition and subject to failure. The 1997 floods damaged campsites and other development in Yosemite National Park. As a result, the park rethought its floodplain management policy—some camping and other facilities were abandoned, and the river is now allowed to "run free."

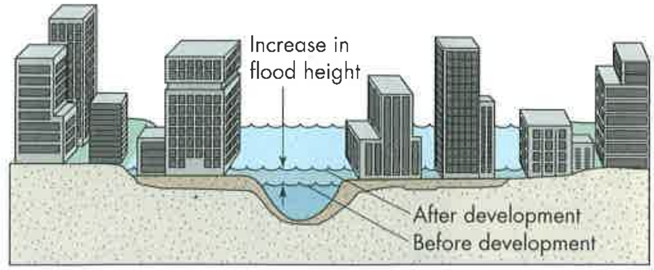
Some engineering structures designed to prevent flooding have actually increased flooding in the long term (see *Case History: Tucson, Arizona*). What we have learned from all of this is that structural control for floods must go hand in hand with floodplain regulations if the hazard is to be truly minimized (18).

As a final example of using physical barriers to control a river, consider the tremendous undertaking by the U.S. Army Corps of Engineers to keep the lower Mississippi River from shifting its course near New Orleans to a shorter route along the Atchafalaya River, approximately 180 km to the west. The Atchafalaya River via the Red River provides a shorter path to the Gulf of Mexico, and if natural processes were left alone, the Mississippi would shift, leaving Baton Rouge and New Orleans along an abandoned and nearly dry channel. Economic and social costs of such a shift are enormous and so the Corps of Engineers has spent several hundred million dollars in damlike river-control structures to keep the Mississippi where it is. Because the potential new path is much shorter and steeper it may be only a matter of time before the shift takes place, regardless of what structures are built. This view is shared by some geologists but does not reflect the opinion of the Corps of Engineers. The river nearly shifted during the 1973 flood when major damage to one of the control structures occurred. Larger floods are likely, and because the two rivers are close together, the capture of the Mississippi River by a shorter route to the Gulf seems very probable, even if the structures do not fail. That is, overflow and channel cutting could occur at other locations, causing the shift (19).

Adjustment: Floodplain Regulation

From an environmental point of view, *the best approach to minimizing flood damage in urban areas* is **floodplain regulation.** The purpose of floodplain regulation is to obtain the most beneficial use of floodplains while minimizing flood damage and cost of flood protection (20). It is a compromise between indiscriminate use of floodplains, which results in loss of life and tremendous property damage, and complete abandonment of floodplains, which gives up a valuable natural resource.

This is not to say that physical barriers, reservoirs, and channel works are not desirable. In areas developed on floodplains, they will be necessary to protect lives and property. We need to recognize, however, that the floodplain belongs to the river system, and any encroachment that reduces the cross-sectional area of the floodplain increases flooding (Figure 5.20). An ideal solution would be to discontinue floodplain development that necessitates new physical barriers. In other words, the ideal is to "design with nature." Realistically, in most cases, the most effective and practical solution will be a combination of physical barriers and floodplain regulations that will result in less physical modification of the river system. For example, reasonable floodplain zoning in conjunction with a diversion channel project or upstream reservoir may result in a smaller diversion channel or reservoir than would be necessary if no floodplain regulations were used.

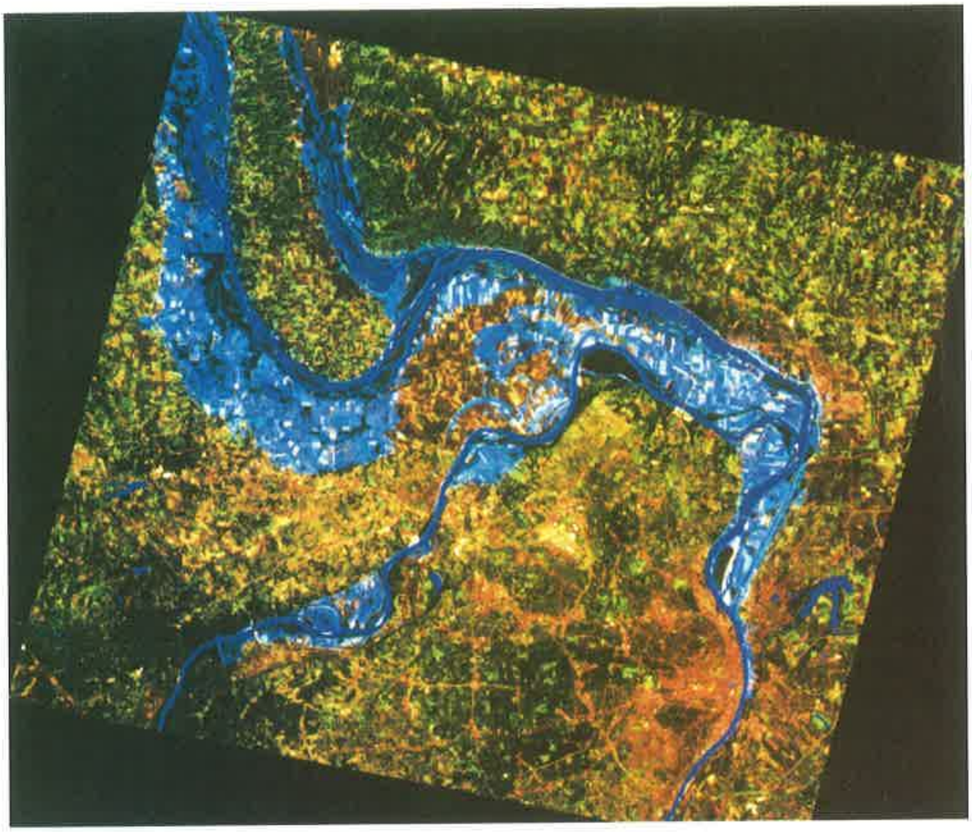


▲ **FIGURE 5.20** Development that encroaches on the floodplain can increase the heights of subsequent floods. (From *Water Resources Council*, Regulation of Flood Hazard Areas, *vol.* 1, 1971)

Flood-hazard Mapping A preliminary step to floodplain regulation is flood-hazard mapping, which is a means of providing information about the floodplain for land-use planning (23). Flood-hazard maps may delineate past floods or floods of a particular frequency, say, the 100-year flood. They are useful in regulating private development, purchasing land for public use as parks and recreational facilities, and creating guidelines for future land use on floodplains (see *Putting Some Numbers On Flood Hazard Analysis* on page 124).

Developing flood-hazard maps for a particular drainage basin can be difficult and expensive. The maps are generally prepared by analyzing stream-flow data from gauging stations over a period of years. However, flow data are not available in many cases, especially for small streams, so alternative data sources must be used to assess the flood hazard. Methods of upstream flood hazard evaluation may involve estimations of flood peak discharges based on physical properties of the drainage basin. A study of streams in central Texas characterized by periodic intense upstream flooding produced a preliminary empirical model to estimate flood-peak discharges by measuring the *stream magnitude* (number of source streams) of a drainage basin and the *drainage density* (total length of all streams in a basin divided by the area of the basin) (28). In other words, the Texas work produced a statistically valid relationship between measured flood-peak discharge and two measured physical parameters, stream magnitude and drainage density, that can be used to predict floods in basins where hydrologic information is unavailable or insufficient for detailed evaluation.

Flood hazard evaluation for downstream areas may also be accomplished in a general way by direct observation and measurement of physical parameters. For example, extensive flooding of the Mississippi River Valley during the summer of 1993 is clearly shown on images produced from satellite-collected data (Figure 5.21). Floods can also be mapped from aerial photographs taken during flood events, and they



▲ **FIGURE 5.21** This image, which is the synthesis of two images, shows the extent of flooding from the 1993 floods of the Mississippi River. The rivers are shown in 1988 under normal flow conditions in dark blue. The river on the lower left and flowing to the center of the photograph is the Missouri River and it joins the Mississippi River. The smaller river coming in from the top is the Illinois River and the large river that flows from the upper left to the lower right is the Mississippi River. In the lower right-hand corner, the river becomes narrow where it flows by the city of St. Louis, Missouri (orange color area in lower right corner). The river is narrow here because flow is constricted by a series of dikes and flood prevention measures constructed to protect the city. The light blue color is the floodwaters of 1993. Notice the extensive flooding upstream of St. Louis, Missouri. The city with its floodworks is a real "bottleneck" to the flow of water. The town of Alton, Illinois, is the first orange area upstream from St. Louis. This city has a notorious history of flooding. The town is just upstream from the confluence of the Missouri and Mississippi rivers. During the 1993 floods, the width of flooding (the light blue area shown here) from Alton across the flooded area is approximately 8 km. This image was constructed by superposition of images from 1988 and 1993. (*Courtesy of* ITD-SRSC/RSI/SPOT *Image, Copyright* ESA/CNES/*Sygma*)

can be estimated from high-water lines, flood deposits, scour marks, and trapped debris on the floodplain, measured in the field after the water has receded (Figure 5.22).

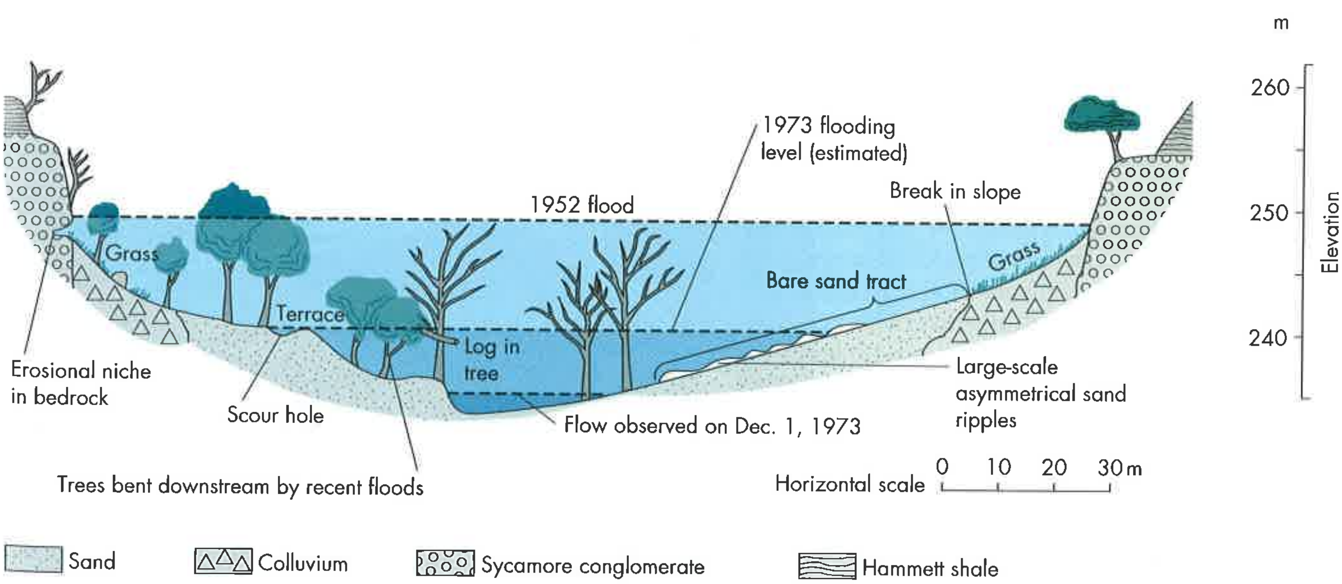
Careful mapping of soils and vegetation can also help evaluate the downstream flood hazard. Soils on floodplains are often different from upland soils, and, with favorable conditions, certain soils can be correlated with flooding of known frequency. A map based on a study of the Colorado River Valley near Austin, Texas (Figure 5.23), shows a fair correlation between soils and the 100-year flood (28). Vegetation type may facilitate flood-hazard assessment because there is often a rough zonation of vegetation in river valleys that may correlate with flood zones. Some types of trees with shallow roots require an abundant supply of water and benefit from frequent submergence. These trees are often found near the banks of perennial streams that frequently flood. Other species of trees are more restricted to well-drained soils that are not subjected to prolonged or frequent flooding. Although zonation of vegetation is helpful in evaluating flood-prone areas, the cause of the zones is complex and not directly caused by flooding. Therefore, use of vegetation, as with soils, should be combined with other methods of flood-hazard evaluation such as satellite data, aerial photographs, historical records, and floodplain features (28).

The primary advantages of evaluating both upstream and downstream flood hazards from direct observation or properties of the drainage basin and river valley are expediency and cost. The Colorado River study showed that these methods could easily distinguish areas with a frequent flood hazard (1- to 4-year recurrence interval) from areas with an intermediate (10- to 30-year) or infrequent (greater than 100-year) hazard (28). The only disadvantage is that of relative

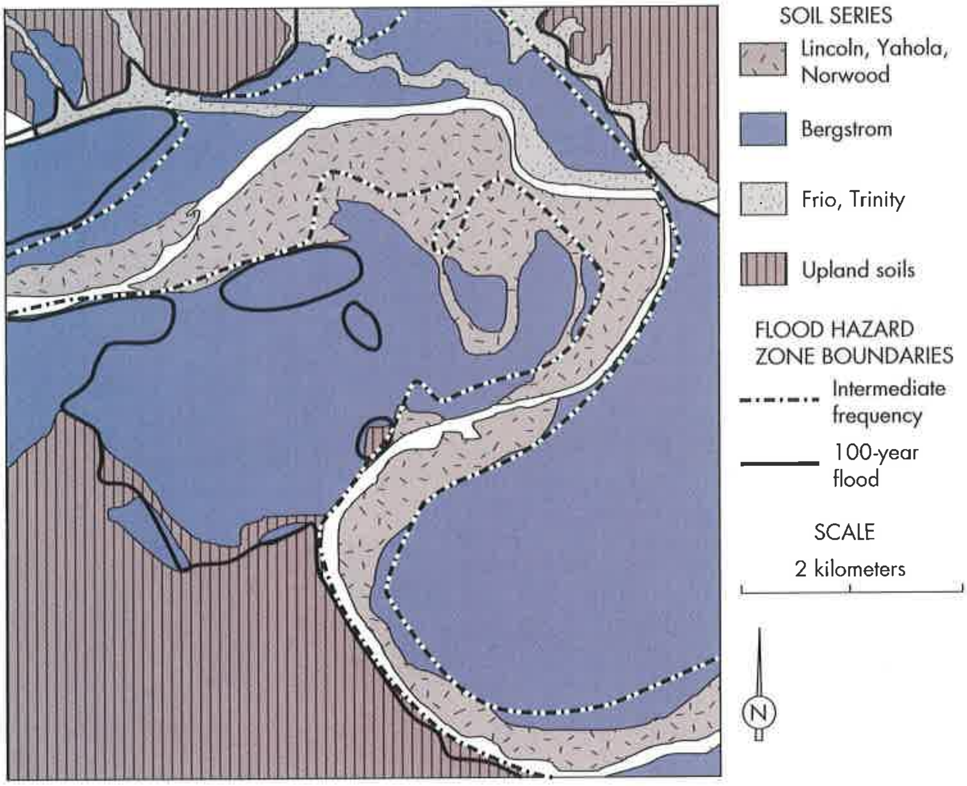
CASE HISTORY Tucson, Arizona

The September 1983 floods in Arizona killed at least 13 people and inflicted more than $416 million in damages to homes (more than 1300 destroyed or damaged), highways, roads, and bridges. During the flood, extensive bank erosion occurred on the Rillito, a tributary of Santa Cruz River in Tucson (Figure 5.D). The damage clearly suggested that those responsible for flood planning were not prepared for such massive bank erosion. Rather than adopting an overall river-management plan to retard erosion, Tucson had piecemeal bank protection that generated greater channel instability than would have occurred without the structures. That is, although existing bank protection structures protected short reaches of the channel, they enhanced the bank erosion in the unprotected reaches immediately downstream (21). In January 1993, there was major flooding again. Flood peaks were similar to 1983 and serious bank erosion occurred once more, in spite of attempts at additional bank stabilization (soil-cement, i.e., covering the bank with a layer of cement). Once again partial protection only made the problem worse. What was learned in the 1983 flood was apparently ignored and the event was repeated (22).

▶ **FIGURE 5.D** Tucson flood damage on the Rillito in 1983. Flow is from bottom to top in the photograph. Note damage to townhouses (center) due to lateral migration of the upstream meander bend that eroded behind and through bank protection (soil cement) emplaced to protect the houses. (*Edward A. Keller*)



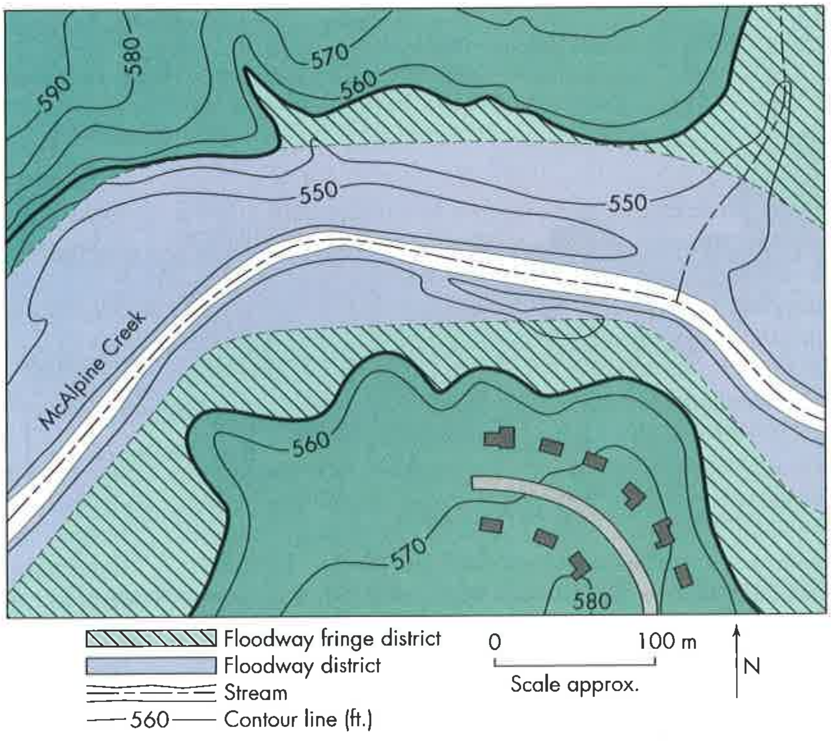
▲ **FIGURE 5.22** Schematic cross section of the Pedernales River Valley, Texas, illustrating floodplain features useful in estimating floods. (*After V. R. Baker, "Hydrogeomorphic Methods for the Regional Evaluation of Flood Hazards,"* Environmental Geology, *vol.* 1, *pp.* 261–81, 1976)



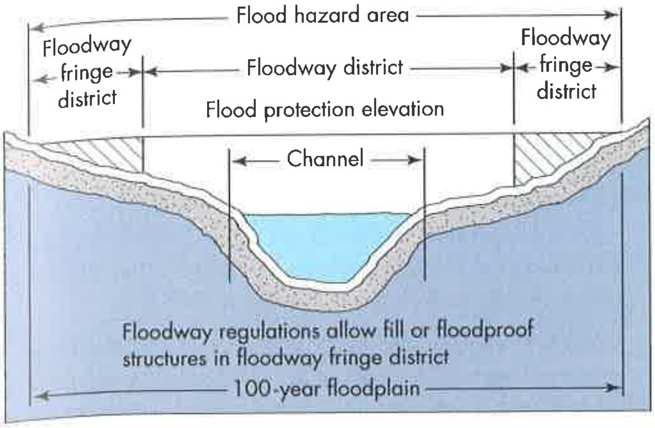
▶ **FIGURE 5.23** Relationship between soils and flooding for a reach of the Colorado River near Austin, Texas. The intermediate frequency floods with a recurrence interval of 10 to 30 years are primarily associated with the Lincoln, Yahola, Norwood, and Bergstrom soils (on the floodplain). The 100-year flood tends to roughly correlate with the lower topographic boundary of the upland soils. (*After V. R. Baker, "Hydrogeomorphic Methods for the Regional Evaluation of Flood Hazards,"* Environmental Geology, *vol. 1, pp.* 261–81, 1976)

accuracy. Flood-hazard evaluation based on sufficient hydrologic (stream flow) data generally provides more accurate prediction of flood events (revisit *Putting Some Numbers On Flood Hazard Analysis*). In urbanizing areas, the accuracy of flood-hazard mapping based entirely on stream flow data is questionable. A better map may sometimes be produced by assuming projected future urban conditions with an estimated percentage of impervious areas. A theoretical 100-year flood map can then be produced.

Floodplain Zoning Figure 5.24 shows how flood-hazard information is used to designate districts with specific



▶ **FIGURE 5.24** Example of a flood hazard map showing the floodway fringe district and the floodway district. (*From County Engineer, Mecklenburg County, North Carolina*) (550 to 580 ft = 168 to 177 m)

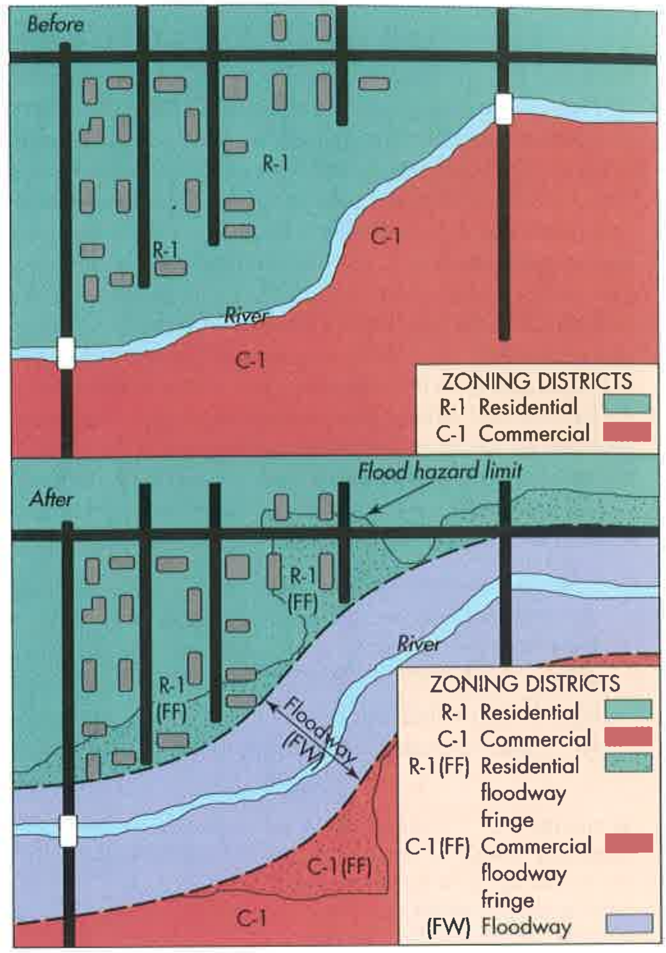


▲ **FIGURE 5.25** Idealized diagram showing a valley cross section and its flood-hazard area, floodway district, and floodway fringe district. (From Water Resources Council, *Regulation of Flood Hazard Areas*, vol. 1, 1971)

permitted uses in a flood-hazard area. Two districts are mapped in the flood-hazard area, the *floodway district* and the *floodway fringe district*. These districts are shown in an idealized cross section in Figure 5.25. Once the districts are established, planners can use them to establish zoning regulations. Figure 5.26 shows a typical zoning map before and after establishment of floodplain regulations.

The **floodway district** is that portion of the channel and floodplain of a stream designated to provide passage of the 100-year regulatory flood without increasing the elevation of the flood by more than 0.3 m. On this land, permitted uses include farming, pasture, outdoor plant nurseries, wildlife sanctuaries and game farms; loading areas, parking areas, rotary aircraft ports, and similar uses, provided they are farther than 8 m from the stream channel; golf courses, tennis courts, and hiking and riding trails; streets, bridges, overhead utility lines, and storm-drainage facilities; temporary facilities for certain specified activities such as circuses, carnivals, and plays; boat docks, ramps, and piers; and dams, if they are constructed in accordance with approved specifications. Other uses of the floodway district, such as open storage of equipment or material, structures designed for human habitation, or underground storage of fuel or flammable liquids, require special permits.

The **floodway fringe district** consists of the land located between the floodway district and the maximum elevation subject to flooding by the 100-year regulatory flood. Permitted uses in this area include any uses permitted in the floodway district; residential accessory structures, provided they are firmly anchored to prevent flotation; fill material that is graded to a minimum of 1 percent grade and protected against erosion; and structural foundations if firmly anchored to prevent flotation. Aboveground storage or processing of any material that is flammable or explosive or that could cause injury to human, animal, or plant life in times of flooding is prohibited on the floodway fringe district.



▲ **FIGURE 5.26** Typical zoning map before and after the addition of flood regulations. (From Water Resources Council, *Regulation of Flood Hazard Areas*, vol. 1, 1971)

The Channelization Controversy

Channelization of streams consists of straightening, deepening, widening, clearing, or lining existing stream channels. Basically, it is an engineering technique, with the objectives of controlling floods, draining wetlands, controlling erosion, and improving navigation (16). Of the four objectives, flood control and drainage improvement are the two most often cited in channelization projects. Thousands of kilometers of streams in the United States have been modified, and thousands more kilometers of channelization are being planned or constructed. Federal agencies alone have carried out several thousand kilometers of channel modification (30). In the past, however, inadequate consideration has been given to the adverse environmental effects of channelization.

Adverse Effects of Channelization Opponents of channelizing natural streams emphasize that the practice is antithetical to the production of fish and wetland wildlife, and that, furthermore, the stream suffers from extensive aesthetic degradation. The argument is as follows:

A CLOSER LOOK History of a River

Philosopher George Santayana observed that "Those who cannot remember the past are condemned to repeat it." Scholars may debate the age-old question of whether or not cycles in human history repeat themselves, but the repetitive nature of natural hazards such as floods is undisputed (29). Better understanding of the historical behavior of a river is therefore valuable in estimating its present and future flood hazards. Consider the Ventura River flood (southern California) of February 1992. With a recurrence interval of approximately 22 years, the flood severely damaged the Ventura Beach RV (recreational vehicle) Resort, which was constructed a few years earlier on an active distributary channel of the delta of the Ventura River (Figure 5.E). Earlier engineering studies suggested that the RV park would not be inundated by flood with a recurrence interval of 100 years. What went wrong?

- It was not recognized that the RV park was constructed on a historically active distributary channel of the Ventura River delta. In fact, early reports did not even mention a delta.
- Engineering models that predict flood inundation are not very good in evaluating distributary channels on river deltas where extensive channel fill and scour as well as lateral movement of the channel is likely.
- Historical documents such as maps dating back to 1855 and more recent aerial photographs that showed the channel were apparently not evaluated. Figure 5.F shows maps rendered from these documents that suggest that the distributary channel was in fact present in 1855 (29).

What went wrong was that the historic behavior of the river was not evaluated as part of the flood-hazard evaluation. If that had been done, it would have been recognized prior to construction of the RV park that a historically active channel was present and the site was unacceptable for development. Nevertheless, necessary permits were issued for development of the park and, in fact, following the flood the park was rebuilt.

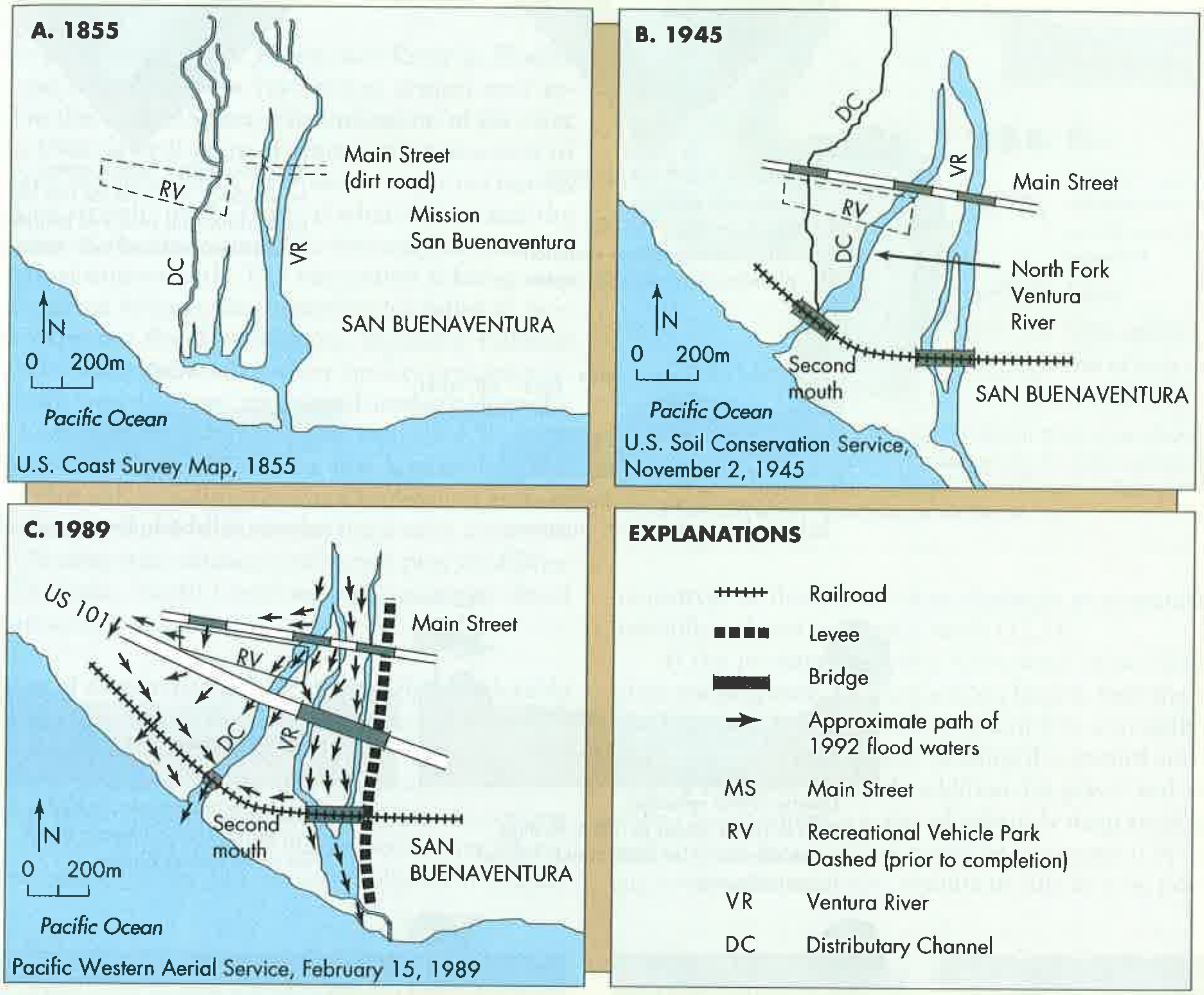
Prior to 1992, the distributary channel carried floodwater during 1969, 1978, and 1982. Following the 1992 flood event, the channel again carried floodwaters in the winters of 1993, 1995, and 1998 (repeatedly flooding the RV park). During the 1992 floods, the discharge increased from less than 25 m^3/s to a peak of 1322 m^3/s in only about 4 hours! This is approximately twice as much as the daily high discharge of the Col-

▶ **FIGURE 5.E** Flooding of the Ventura Beach RV Resort in February 1992. The RV park was built directly across a historically active distributary channel of the Ventura River delta. The recurrence interval of this flood is approximately 22 years. A similar flood occurred again in 1995. Notice that U.S. Highway 101 along the Pacific Coast is completely closed by the flood event. (*Mark J. Terrell/AP/Wide World Photos*)

- Drainage of wetlands adversely affects plants and animals by eliminating habitats necessary for the survival of certain species.
- Cutting trees along the stream eliminates shading and cover for fish, while exposing the stream to the sun, which results in damage to plant life and heat-sensitive aquatic organisms.
- Cutting of bottomland (floodplain) hardwood trees eliminates the habitats of many animals and birds and also facilitates erosion and siltation of the stream.
- Straightening and modifying the streambed destroys the diversity of flow patterns, changes peak flow, and destroys feeding and breeding areas for aquatic life.
- Conversion of wetlands from a meandering stream to a straight, open ditch seriously degrades the aesthetic value of a natural area (16). Figure 5.27 summarizes some of the differences between natural streams and those modified by channelization.

It is commonly believed that channelization increases the flood hazard downstream from the modified channel.

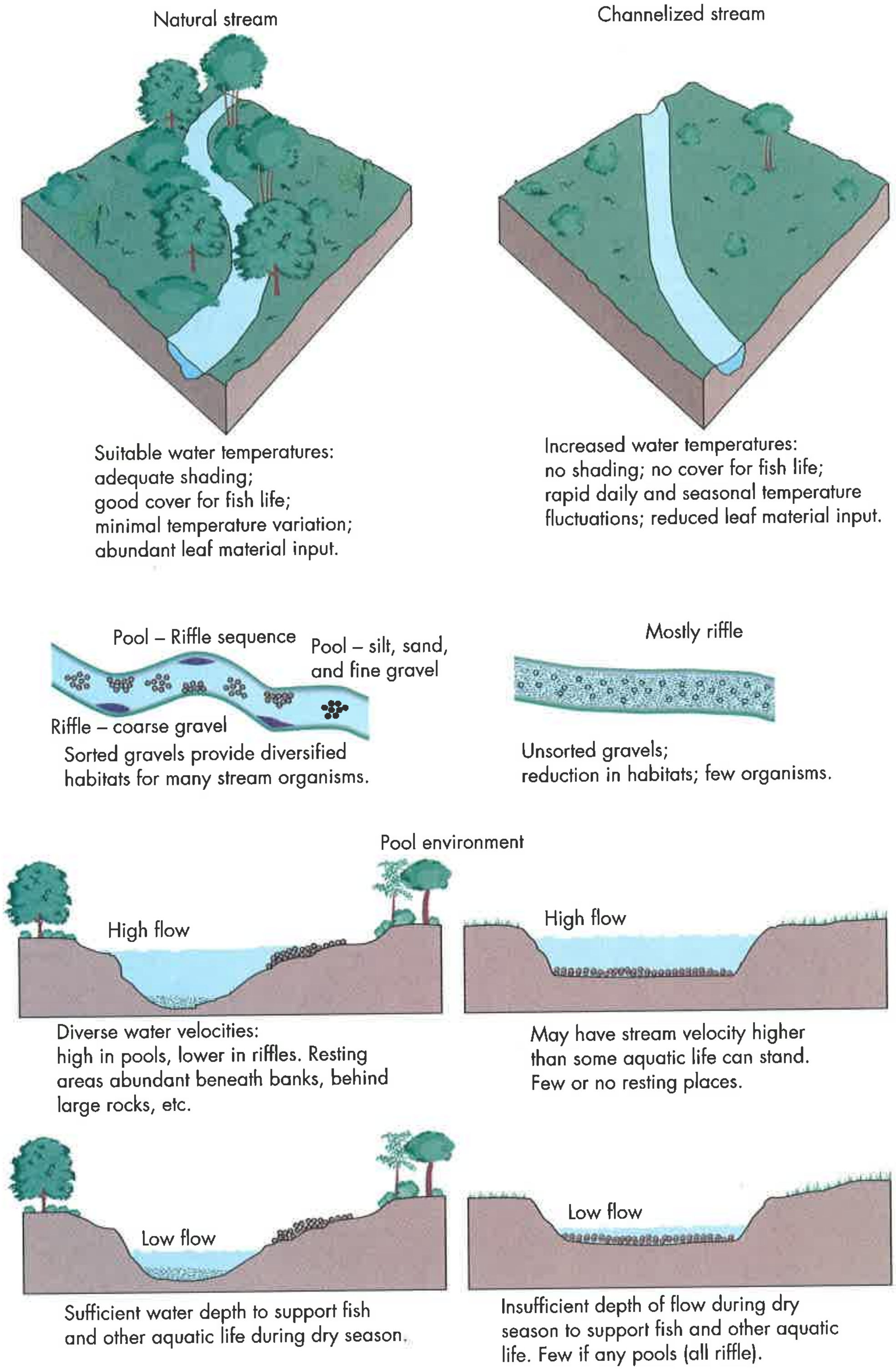
orado River through the Grand Canyon in the summer, when it is navigated by river rafters. This is an incredible discharge for a relatively small river with a drainage area of only about 585 km^2. If the flood of 1992 had occurred during nighttime hours, there may have been many deaths rather than the lone fatality that did occur. The river will flood again! A warning system is being developed for the park, but it remains to be seen how effective it will be, given the potential short response time of the river to precipitation. In other words, the park, with or without the RVs and people, is a "sitting duck." This was dramatically illustrated in 1995 and 1998, when winter floods again swept through the park. Although the warning system worked and the park was successfully evacuated, the facility was again severely damaged. There is now a move afoot to purchase the park and restore the land to a more natural delta environment—a good move!



▲ **FIGURE 5.F** Historical maps of the Ventura River delta showing distributary channel and location of a recreational vehicle park. (*From E. A. Keller and M. H. Capelli, Ventura River flood of February 1992: A lesson ignored?* Water Resources Bulletin 25(5):813–31)

Although in many cases this is true, it is far from the entire story. One study concluded that, on the contrary, increases of normal and peak flows from channelization are not particularly significant, and in some cases the flood peaks are actually reduced (30). This results partly because the contribution of runoff from the modified channels tends to be a small fraction of the total basin runoff; peak runoff from channelized streams may not coincide with basinwide runoff, and thus the quicker flow from a modified stream may pass prior to the natural flood flow from the entire basin, thereby reducing the normal aggregated peak flow; and many streams that are modified have gradients so low that no amount of straightening could significantly increase the downstream flow. However, we emphasize that channel modification, especially straightening, can increase flooding directly downstream from the project, and the problem may be compounded if there are a number of projects in the same basin.

Examples of channel-work projects that have adversely affected the environment are well known. For example, from its initiation in 1910, channelization of the Blackwater River in Missouri resulted in channel erosion (enlarge-



▶ **FIGURE 5.27** A natural stream compared with a channelized stream in terms of general characteristics and pool environments. (*Modified after Corning, Virginia Wildlife, February* 1975)

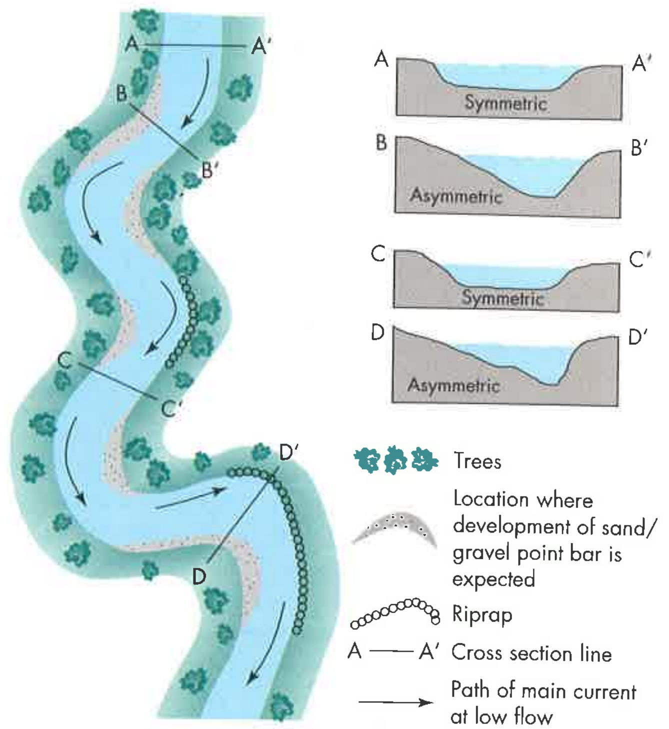
ment locally exceeded 1000 percent, causing bridges to collapse), reduced biologic productivity, and downstream flooding (31).

Benefits of Channelization and Channel Restoration Not all channelization causes serious environmental degradation; in many cases, drainage projects are beneficial. Benefits are probably best observed in urban areas subject to flooding and in rural areas where previous land use has caused drainage problems. In addition, other examples can be cited in which channel modification has improved navigation or reduced flooding and has not caused environmental disruption.

Many streams in urban areas scarcely resemble natural channels. The process of constructing roads, utilities, and buildings with the associated sediment production is sufficient to disrupt most small streams. **Channel restora-**

tion is often needed to clean urban waste from the channel, allowing the stream to flow freely, to protect the banks by not removing existing trees and, where necessary, planting additional trees and other vegetation. The channel should be made as natural as possible by allowing the stream to meander and, where possible, by providing for variable, low-water flow conditions—fast and shallow (riffle) alternating with slow and deep (pool) (32). Where lateral bank erosion must be absolutely controlled, the outsides of bends may be defended with large stones known as **riprap** (Figure 5.28).

River restoration of the Kissimmee River in Florida may be the most ambitious restoration project ever attempted in the United States. Channelization of the river began in 1962; after 9 years of construction at a cost of $24 million, the meandering river had been turned into an 83-km-long straight ditch. Now, at what will exceed the original cost of channelization, the river may be returned to its original sinuous path. The restoration is being seriously considered because the channelization failed to provide the expected flood protection, degraded valuable wildlife habitat, contributed to water-quality problems associated with land drainage, and caused aesthetic degradation. In Los Angeles, California, a group called "Friends of the River" has suggested that the Los Angeles River be restored. This will be a difficult, if not impossible, task, as most of the riverbed and banks are lined with concrete. Figure 5.29 compares a channel restoration project of Briar Creek, Charlotte, North Carolina, with a concrete-lined channel in southern California.



▲ **FIGURE 5.28** Channel-restoration design criteria for urban streams, using a variable cross-channel profile to induce scour and deposition at desired locations. (*Modified after Keller and Hoffman*, 1977, Journal of Soil and Water Conservation, *vol.* 32, *no.* 5.)

The Future of Channelization Although considerable controversy and justifiable anxieties surround channelization, it is expected that channel modification will remain a necessity as long as land-use changes, such as urbanization or conversion of wetlands to farmland, continue. Therefore, we must strive to design channels that reduce adverse effects. Effective channelization can be accomplished if project objectives of flood control or drainage improvement are carefully tailored to specific needs (32,33).

If the primary objective is drainage improvement in areas where natural flooding is not a hazard, then there is no need to convert a meandering stream into a straight ditch. Rather, design might involve cleaning the channel and maintaining a sinuous stream. In addition, for gravel-bed streams with a low gradient, a series of relatively deep areas (pools) and shallow areas (riffles) might be constructed by changing cross-sectional shape, asymmetrically to form pools and

(a)

(b)

▲ **FIGURE 5.29** Concrete channel in Los Angeles River system compared to channel restoration in North Carolina. (*Edward A. Keller*) symmetrically to form riffles, as found in natural streams. Where this is possible, the resulting channel would tend to duplicate nature rather than be alien to it. In addition, cutting trees along the channel bank would be minimized and new growth would be encouraged. This plan would tend to minimize adverse effects by producing a channel that is more biologically productive and aesthetically pleasing (32).

Channel design for flood control is more complicated because natural channels are maintained by flows with a recurrence interval of 1 to 2 years, whereas flood-control projects may need to carry the 25- or even 100-year flood. A 100-year channel cannot be expected to be maintained by a 2-year flood. Such a channel would probably be braided and choked with migrating sandbars. A solution is to construct a pilot channel, a meandering channel designed to be maintained by the 2-year flood and superimposed on the larger flood-control channel. Addition of pools and riffles in the pilot channel, when possible, would help provide fish habitat and better low-flow conditions. The large channel might be vegetated, and the untrained observer might not easily recognize it. This plan will not work in urbanizing areas where sediment production is high and property is not available to be purchased for the pilot channel. However, if sediment is reduced by good conservation practice and the property is available to be purchased, the urban area will benefit from a more aesthetically pleasing and more useful stream.

Perception of Flooding

At the institutional level (government, flood-control agencies, etc.), perception and understanding of flooding is adequate for planning purposes; however, on the individual level, the situation is not as clear. People are tremendously variable in their knowledge of flooding, anticipation of future flooding, and willingness to accept adjustments caused by the hazard.

Progress at the institutional level includes mapping of flood-prone areas (thousands of maps have been prepared), areas with a flash-flood potential downstream from dams, and areas where urbanization is likely to cause problems in the near future. In addition, the federal government has encouraged states and local communities to adopt floodplain management plans (34). Nevertheless, the concept of floodplain management, planning to avoid the flood hazard by not developing on floodplains, or relocating present development to locations off the floodplain needs further consideration and education to be accepted by the general population.

5.6 Mississippi River Flooding, 1973 and 1993

Spring flooding of the Mississippi River in 1973 caused the evacuation of tens of thousands of people as thousands of square kilometers of farmland were inundated throughout the Mississippi River Valley. Fortunately, there were few deaths, but the flooding resulted in approximately $1.2 billion in property damage (18). The 1973 flooding occurred despite a tremendous investment in flood-control dams upstream on the Missouri River. Reservoirs behind these dams inundated some of the most valuable farmland in the Dakotas, and in spite of these structures, the downstream floods near St. Louis were of record-breaking magnitude (35). Impressive as this flood was at the time, it did not compare in magnitude or in the suffering it caused to the flooding that occurred 20 years later.

Flooding of the Mississippi River and its tributaries during the summer of 1993 will likely be remembered as the flood of the century. There was more water than during the 1973 flood, and the recurrence interval exceeded 100 years. The floods lasted from late June to early August, causing 50 human deaths and more than $10 billion in property damages. In all, about 55,000 km^2 of floodplain were inundated, including numerous towns and farmlands (36,37).

The 1993 floods resulted from a major climatic anomaly that covered the upper Midwest and north-central Great Plains, precisely the area that drains into the Mississippi and lower Missouri river systems (38). The trouble started with a wet autumn and a heavy spring snowmelt that saturated the ground in the upper Mississippi River basin. Then, early in June, a high-pressure center became stationary on the East Coast, drawing moist unstable air into the upper Mississippi River drainage basin. This condition kept storm systems in the Midwest from moving east. At the same time, air moving in over the Rocky Mountains initiated unusually heavy rainstorms (38). The summer of 1993 was the wettest on record for Illinois, Iowa, and Minnesota. Cedar Rapids, Iowa, for example, received about 90 cm of rain from April through July—a normal year's rainfall in 4 months (36)! Intense precipitation falling on saturated ground led to a tremendous amount of runoff and unusually high flood peaks during the summer. Floodwaters were high and prolonged, putting tremendous pressure on the levee system that was built in hopes of alleviating flooding.

Prior to construction of the levees, the floodplain of the Mississippi was much wider and contained extensive wetlands. Since the first levees were built in 1718, approximately 60 percent of the wetland in Wisconsin, Illinois, Iowa, Missouri, and Minnesota—all hard hit by the flooding in 1993—have been lost as a result of development and construction of levees. The effect of levees is to constrict the width of the river, which leads to a greater depth of flow and creates a bottleneck that raises the height of floodwaters upstream. In some locations, such as St. Louis, Missouri, levees give way to floodwalls designed to protect the city against high-magnitude floods.

Examination of Figure 5.21, a satellite image from mid-July 1993, shows that the river is relatively narrow at St. Louis, where it is contained by the floodwalls, and very broad upstream near Alton and Portage des Sioux, where extensive flooding occurred. Even so, the rising flood peak came within about 0.6 m of overtopping the floodwalls. Failure of downstream levees partially relieved the pressure and possibly saved St. Louis from flooding. Levee failures (Figure 5.30) were very common during the flood event (39). In fact, something like 80 percent of the private levees along the Mississippi River and its tributaries failed (37). On the other hand, most of the levees built by the federal government survived the flooding and undoubtedly saved lives and property. The problem is that there is not a uniform code for the levees and so some areas' levees are higher or lower than others. Failures occurred as a result of overtopping and breaching, resulting in massive flooding of farmlands and towns (Figure 5.31) (37).

The main lesson learned from the 1993 floods is that construction of levees leads to a false sense of security. It is difficult to design levees to withstand extremely high-magnitude floods for a long period of time. Furthermore, because of loss of wetlands, there is less floodplain space to soak up the floodwaters. The 1993 floods caused such extensive damage and loss of property that many communities along the river are rethinking strategies concerning the flood hazard. Several are considering moving to higher ground! In addition, there is now a FEMA (Federal Emergency Management Agency) program to buy out some floodplain land, with the understanding that homes never be constructed there again. Of course, these adjustments are entirely appropriate. The Mississippi River system flooded riverside communities, including Grafton, Illinois, again in 1995! When will we ever learn?

▲ **FIGURE 5.30** Failure of this levee in Illinois during the 1993 floods of the Mississippi River caused flooding in the town of Valmeyer. (*Comstock, Inc.*)

◀ **FIGURE 5.31** Damage to farmlands during the peak of the 1993 flood of the Mississippi River. (*Comstock, Inc.*)

PUTTING SOME NUMBERS ON Flood Hazard Analysis

We learned earlier in *A Closer Look: Magnitude and Frequency of Floods* that for every flood event we may derive a recurrence interval *(R)*, which provides an estimate of the probable average time period between floods of a particular magnitude. We now return to that theme with the purpose of better understanding how we evaluate the flood hazard and construct flood hazard maps that delineate the land area likely to be inundated by a flood of a particular *R*, say, the 100-year flood. The 100-year flood may also be represented by Q_{100}, which means the 100-year discharge. The units of discharge commonly used in science are cubic meters per second (cms), but in the United States the units most often encountered are cubic feet per second (cfs). As a result, the data presented here will be in cfs.

Steps in flood hazard analysis are:

- Collect stream flow data from a gauging station or set of gauging stations on a particular river.
- Analyze the stream flow data to estimate magnitude and frequency of flows, and in the case of flood hazards, estimate the discharge from the 100-year flood (Q_{100}) or other discharge of interest to a particular project.
- The 100-year flood might also be estimated from a mathematical model if a stream gauging station is not available or stream gauge data are insufficient.
- Use an appropriate mathematical/computer model to predict the stage (elevation of water surface) expected from the Q_{100} at a variety of topographic cross sections, and construct a flood hazard map showing the area inundated by flood waters.

Probably the best way to understand how flood hazards are estimated is to provide an example. Mission Creek near Santa Barbara, California, has a notorious flood history, including damaging floods of 1995. These floods resulted from a long duration storm that exceeded 8 hours and delivered low- to moderate-intensity rainfall totaling approximately 14 cm (5.5 in.). Mission Creek flooded approximately 500 structures and inflicted about $50 million in property damage. The city of Santa Barbara is built upon an alluvial fan, and the resulting floods were typical of those occurring on alluvial fans (24), consisting of breakouts of waters that spread relatively shallow, fast-moving floodwater down the fan surface, ponding near the ocean. Peak discharge from a stream gauge was estimated by local authorities as exceeding 5000 cfs, with a lower estimate of approximately 3800 cfs. The lower estimate is used here in flood hazard analysis as it was based upon a calculation from field measurements, rather than data from a gauging station, where accumulation of debris may have resulted in an observed stage that was anomalously high. Regardless of which discharge measure is used, the flood was large and caused extensive damage. We begin our analysis of Mission Creek by examining the data on Table 5.A, which shows peak annual flows from 1971 to 1995. This is known as the *annual series.* Notice that in the 1980s and 1990s the years of high discharge are related to El Niño events (see discussion of El Niño in Chapter 16). One way to analyze flood frequency is to arrange the peak annual flows into a series based upon their magnitude *(M)* where $M = 1$ is assigned the highest flow, which occurred in 1995. The *R* is then calculated from the equation $R = (N + 1)/M$, where *N* is the number of years of record. That analysis is shown on Table 5.B. Using this technique we then plot on probability paper the discharge and recur-

Table 5.A Mission Creek at Santa Barbara, California, peak annual flows 1971–1995, arranged per year

Year	Peak flow (cfs)	Comment
1971	360	
1972	1420	
1973	2580	
1974	519	
1975	1130	
1976	353	
1977	569	
1978	2500	El Niño event?[a]
1979	667	
1980	1300	
1981	302	
1982	186	
1983	2300	El Niño year
1984	681	
1985	128	
1986	626	El Niño year
1987	626	El Niño year
1988	139	Drought year
1989	168	Drought year
1990	115	Drought year
1991	468	El Niño year
1992	1130	El Niño year
1993	838	El Niño year
1994	207	El Niño year
1995	3800 (est)	(Highest on record)

[a]El Niño events often bring an increase in precipitation to southern California.

Source: U.S. Geological Survey

Table 5.B Annual peak flow data for Mission Creek at Santa Barbara, CA, 1971–1995, arranged by magnitude *M*, where *M* = 1 is largest event. Also shown are average recurrence intervals *R* (yrs).

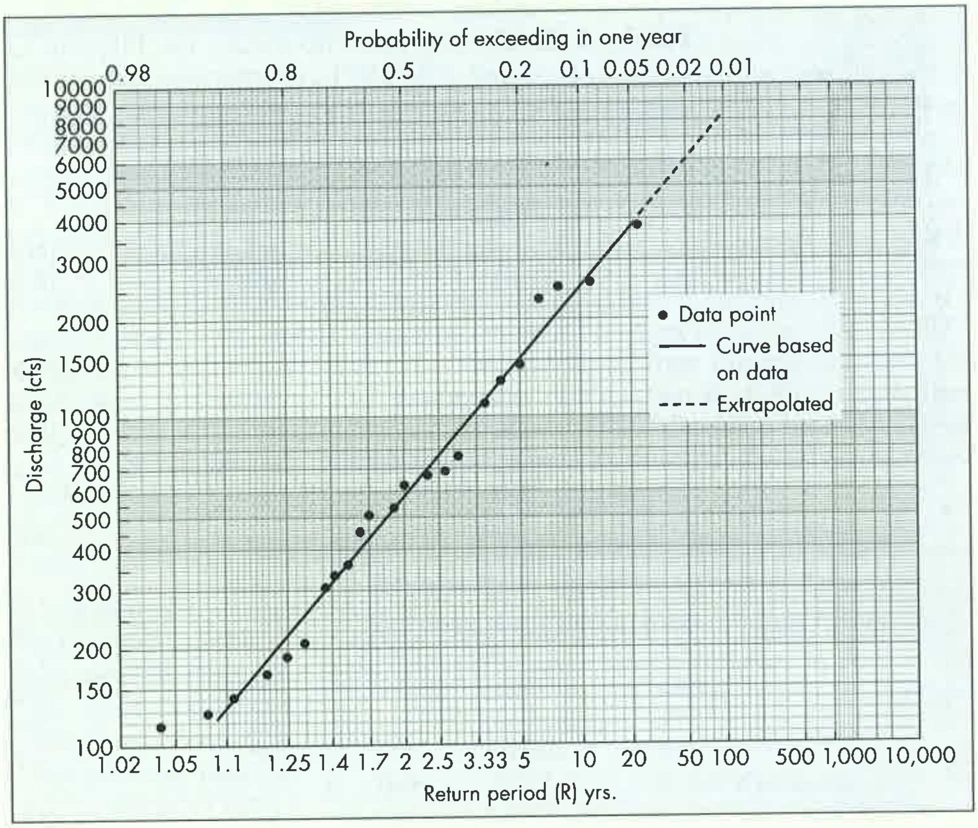
Year	Annual Peak Discharge (cm)	Magnitude (*M*)	(*N* + 1) / *M* (R, yrs)
1995	3800 (estimate)	1	26.00
1973	2580	2	13.00
1978	2500	3	8.67
1983	2300	4	6.50
1972	1420	5	5.20
1980	1300	6	4.33
1975	1130	7.5[a]	3.47
1992	1130	7.5	3.47
1993	838	9	2.89
1984	681	10	2.60
1979	667	11	2.36
1986	626	12.5	2.08
1987	626	12.5	2.08
1977	569	14	1.86
1974	519	15	1.73
1991	468	16	1.62
1971	360	17	1.53
1976	353	18	1.44
1981	302	19	1.37
1994	207	20	1.30
1982	186	21	1.24
1989	168	22	1.18
1988	139	23	1.13
1985	128	24	1.08
1990	115	25	1.04

[a]Ties are averaged.

Source: U.S. Geological Survey

rence interval for each flow as shown on Figure 5.G. Since we only have 25 years of records, we need to extrapolate the curve to estimate higher magnitude events, such as the Q_{50} or Q_{100}. It is best not to extrapolate the record beyond about two times the length of the record, which means that we could extrapolate to the 50-year flood. However we commonly have to estimate the 100-year flood because this is the so-called "project flood" used in flood hazard analysis. The Water Resources Council (25) in the 1960s recommended using the log-Pearson type III distribution for analyzing flood frequency in flood hazard analysis. This method is thought to produce a better prediction of flood discharge than simple application of the formula used above and shown in Table 5.B. The basic equation used that relates the flood peak and return period with the log-Pearson type III distribution is:

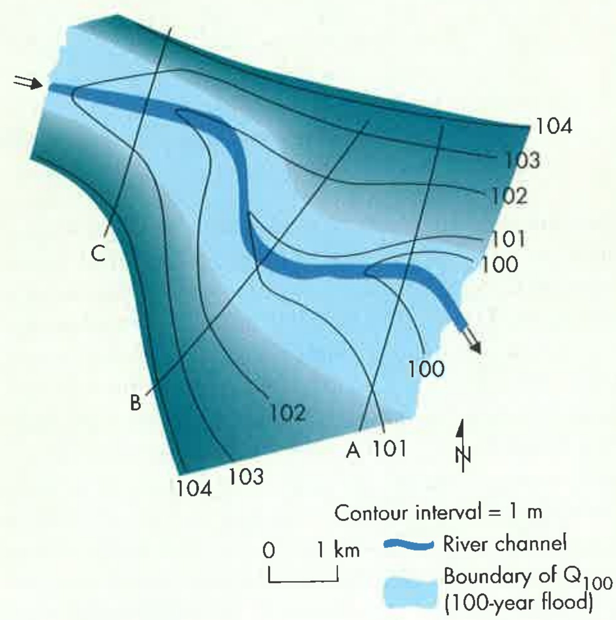
X is equal to $\overline{X} + K\sigma$, where X is the peak discharge at a particular flow frequency of interest (say Q_{100}), $\overline{X}$ is the mean discharge from the set of annual peak flows, K is a frequency factor that increases as R increases, and σ is the standard deviation of the annual peak flows (25). As the name of the distribution implies, logarithms (base 10) are utilized. The method is shown on Table 5.C for the Mission Creek data. We substitute for our general equation above as follows: X is log Q_{100}, $\overline{X}$ is the mean of the logarithmic values of annual peak flows, K is determined from Table 5.D by linear extrapolation, and σ is the standard deviation of the logarithmic values of the annual peak flows. As shown, the last step in the calculation of the



▶ **FIGURE 5.G** Flood frequency of Mission Creek at Santa Barbara, California. Data from Table 5.B.

Q_{100} is to take the antilogarithm of the value to produce the desired discharge, in this case Q_{100} (6393 cfs). Notice that there is a different K value for each return period, but to determine K from the table, you must first calculate the value of G from the equation provided. The G value depends upon the actual distribution of the annual peak floods and accounts for the skewness (a measure of the departure of the distribution from one that is symmetrical on both sides of the mean, that is, a departure from the normal distribution, which is roughly "bell-shaped") (26). For our example we have calculated the Q_{100}. Notice that the value of Q_{100} from log-Pearson type III method is less than that from extrapolating the graph on Figure 5.G, where Q_{100} is about 8000 cfs (227 cms). For Q_{50}, the two methods are in closer agreement—4796 cfs (136 cms) for the log-Pearson type III and about 6000 cfs (170 cms) for extrapolation of the graph (Figure 5.G). As an exercise you may wish to calculate other values, say the Q_{10} and Q_{25}. Compare these values with those that you estimate from the graphing of the data shown on Figure 5.G.

The final step in flood hazard analysis is to produce maps that show areas inundated by a particular flood flow (say, Q_{100}). For the system where a channel and floodplain are present, we construct a series of cross sections across the floodplain and channel, and for each of these estimate the stage (elevation of water) that will occur from the Q_{100}. This is commonly done by using a mathematical computer model that solves basic hydrology equations of flow of water in the channel and on the floodplain. A model commonly utilized is the HEC-2 step-backwater model developed by the Hydrologic Engineering Center, Davis, California, in 1990 (27). Data requirements for the program include survey cross sections along the channel and



▲ **FIGURE 5.H** Idealized diagram illustrating how flood hazard maps map be produced. See text for explanation.

Table 5.C Mission Creek, Santa Barbara, CA, annual peak flows, 1971–1995. Mission Creek Flood Data Log-Pearson type III distribution. Calculations with logarithms to base 10.

Year	*M*	Annual Peak Q (cfs)	Q = log peak	$Q - \bar{Q}$	$(Q - \bar{Q})^2$	$(Q - \bar{Q})^3$
1995	1	3800 (estimate)	3.5798	0.8116	0.6587	0.5346
1973	2	2580	3.4116	0.6434	0.4140	0.2664
1978	3	2500	3.3979	0.6297	0.3966	0.2497
1983	4	2300	3.3617	0.5935	0.3523	0.2091
1972	5	1420	3.1523	0.3841	0.1475	0.0567
1980	6	1300[a]	3.1139	0.3457	0.1195	0.0413
1992	7	1300	3.1139	0.3457	0.1195	0.0413
1975	8	1130	3.0531	0.2849	0.0812	0.0231
1993	9	838	2.9232	0.1550	0.0240	0.0037
1984	10	681	2.8331	0.0649	0.0042	0.0003
1979	11	667	2.8241	0.0559	0.0031	0.0002
1986	12.5	626	2.7966	0.0284	0.0008	0.0000
1987	12.5	626	2.7966	0.0284	0.0008	0.0000
1977	14	569	2.7551	−0.0131	0.0002	0.0000
1974	15	519	2.7152	−0.0530	0.0028	−0.0001
1991	16	468	2.6702	−0.0980	0.0096	−0.0009
1971	17	360	2.5563	−0.2119	0.0449	−0.0095
1976	18	353	2.5478	−0.2204	0.0486	−0.0107
1981	19	302	2.4800	−0.2882	0.0831	−0.0239
1994	20	207	2.3160	−0.4522	0.2045	−0.0925
1982	21	186	2.2695	−0.4987	0.2487	−0.1240
1989	22	168	2.2253	−0.5429	0.2947	−0.1600
1988	23	139	2.1430	−0.6252	0.3909	−0.2444
1985	24	128	2.1072	−0.6610	0.4369	−0.2888
1990	25	115	2.0607	−0.7075	0.5006	−0.3541
Sum:			69.2043		4.5876	0.1174

- M = magnitude; $N = 25$ (number of years of record)
- $\bar{Q} = \dfrac{69.2043}{25} = 2.7682$ (is the mean of the logarithmic values of Q)
- σ = standard deviation $= \sqrt{\dfrac{\Sigma(Q - \bar{Q})^2}{N - 1}} = \sqrt{\dfrac{4.586}{24}} = 0.4372$
- $G = \left(\dfrac{n}{(N-1)(N-2)}\right)\left(\dfrac{\Sigma(Q - \bar{Q})^3}{\sigma^3}\right) = \left(\dfrac{25}{(24)(23)}\right)\left(\dfrac{0.1174}{0.4372^3}\right) = 0.064$
- K for Q_{100}, from Table 5.D (for $G = 0.064$) = 2.373 (by linear extrapolation)
- For Q_{100} (100-year flood)
  $\log Q_{100} = \bar{Q} + K\sigma = 2.7682 + (2.373)(0.4372) = 3.8057$
  $Q_{100} = 6393$ cfs (181 cms)

[a]Ties are averaged.

floodplain, initial stage and discharge of water (say, the Q_{100}) and appropriate coefficients, including roughness and whether the channel is expanding or contracting between typical cross sections. An idealized diagram showing the area inundated by the 100-year flood for a hypothetical stretch of river with three cross sections is shown in Figure 5.H. The computer model begins calculations and estimation of flood stage for the downstream cross sections first and then works upstream. Using this method, the area inundated by a flood of a particular frequency may be estimated and mapped. This has been done for thousands of streams and rivers across the United States and is the basic data necessary for evaluating flood hazard and floodplain zonation. This method does have limitations. For example, it doesn't work well for lower Mission Creek because flooding on an alluvial fan may be in multiple distributary channels, and is different from a river with a well-defined floodplain that the HEC-2 model assumes.

Table 5.D Values of *K* for log-Pearson Type III Distribution

	Return Period, Years						
G	2	5	10	25	50	100	200
3.0	–0.396	0.420	1.180	2.278	3.152	4.051	4.970
2.8	–0.384	0.460	1.210	2.275	3.114	3.973	4.847
2.6	–0.368	0.499	1.238	2.267	3.071	3.889	4.718
2.4	–0.351	0.537	1.262	2.256	3.023	3.800	4.584
2.2	–0.330	0.574	1.284	2.240	2.970	3.705	4.444
2.0	–0.307	0.609	1.302	2.219	2.912	3.605	4.298
1.8	–0.282	0.643	1.318	2.193	2.848	3.499	4.147
1.6	–0.254	0.675	1.329	2.163	2.780	3.388	3.990
1.4	–0.225	0.705	1.337	2.128	2.706	3.271	3.828
1.2	–0.195	0.732	1.340	2.087	2.626	3.149	3.661
1.0	–0.164	0.758	1.340	2.043	2.542	3.022	3.489
0.8	–0.132	0.780	1.336	1.993	2.453	2.891	3.312
0.6	–0.099	0.800	1.328	1.939	2.359	2.755	3.132
0.4	–0.066	0.816	1.317	1.880	2.261	2.615	2.949
0.2	–0.033	0.830	1.301	1.818	2.159	2.472	2.763
0.0	0.0	0.842	1.282	1.751	2.054	2.326	2.576
–0.2	0.033	0.850	1.258	1.680	1.945	2.178	2.388
–0.4	0.066	0.855	1.231	1.606	1.834	2.029	2.201
–0.6	0.099	0.857	1.200	1.528	1.720	1.880	2.016
–0.8	0.132	0.856	1.166	1.448	1.606	1.733	1.837
–1.0	0.164	0.852	1.128	1.366	1.492	1.588	1.664
–1.2	0.195	0.844	1.086	1.282	1.379	1.449	1.501
–1.4	0.225	0.832	1.041	1.198	1.270	1.318	1.351
–1.6	0.254	0.817	0.994	1.116	1.166	1.197	1.216
–1.8	0.282	0.799	0.945	1.035	1.069	1.087	1.097
–2.0	0.307	0.777	0.895	0.959	0.980	0.990	0.995
–2.2	0.330	0.752	0.844	0.888	0.900	0.905	0.907
–2.4	0.351	0.725	0.795	0.823	0.830	0.832	0.833
–2.6	0.368	0.696	0.747	0.764	0.768	0.769	0.769
–2.8	0.384	0.666	0.702	0.712	0.714	0.714	0.714
–3.0	0.396	0.636	0.660	0.666	0.666	0.667	0.667

Source: U.S. Soil Conservation Service

SUMMARY

Streams and rivers form a basic transport system of the rock cycle and are a primary erosion agent shaping the landscape. The region drained by a stream system is termed a *drainage basin*. Erosion and deposition of sediments are determined in part by the stream's velocity and stream power at any point, which are determined by the stream's slope, cross-sectional area and shape, and discharge. A river generally maintains a dynamic equilibrium between the work done (sediment transported) and the load imposed (sediment received). A land-use change that affects the amount of water or sediment entering the stream results in a change in the channel's slope and cross-sectional shape and in the velocity of the water.

Sediments deposited by lateral migration of meanders in a stream and by periodic overflow of the stream banks form a floodplain. The magnitude and frequency of flooding are inversely related and are functions of the intensity and distribution of precipitation, the rate of infiltration of water into the soil and rock, and topography. Upstream floods are produced by intense, brief rainfall over a small area. Downstream floods in major rivers are produced by storms of long duration over a large area that saturate the soil, causing increased runoff from thousands of tributary basins. Urbanization has increased flooding in small drainage basins by covering much of the ground with impermeable surfaces such as buildings and roads, increasing the runoff of storm water.

River flooding is the most universally experienced natural hazard. Loss of life is relatively low in developed countries with adequate monitoring and warning systems, but property damage is much greater than in preindustrial societies because floodplains are often extensively developed. Factors that control damage caused by flooding include land use on the floodplain, magnitude and frequency of the flooding, rate of rise and duration of the flooding, the season, the amount of sediment deposited, and the effectiveness of forecasting, warning, and emergency systems.

Environmentally, the best solution to minimizing flood damage is floodplain regulation, but in highly urban areas it will remain necessary to use engineering structures to protect existing development. These include physical barriers such as levees and floodwalls; structures that regulate the release of water, such as reservoirs; and modification of natural channels to accommodate more water (channelization). The realistic solution to minimizing flood damage involves a combination of floodplain regulation and engineering techniques. The inclusion of floodplain regulation is critical because engineered structures tend to encourage further development of floodplains by producing a false sense of security. The first step in floodplain regulation is mapping the flood hazards, which can be difficult and expensive. Planners can then use the maps to zone a flood-prone area for appropriate uses.

Channelization is the straightening, deepening, widening, cleaning, or lining of existing streams. The most commonly cited objectives of channel modification are flood control and drainage improvement. Channelization has often caused environmental degradation, so new projects are closely evaluated. Novel approaches to channel modification that use natural processes are being practiced, and in some cases channelized streams are being restored.

An adequate perception of flood hazards exists at the institutional level; however, on the individual level, more public-awareness programs are needed to help people perceive the hazard of living in flood-prone areas.

Flooding of the Mississippi River Valley in 1993 was of a magnitude that exceeded the 100-year event. The loss of life and extensive damage to crops and property has led some communities to consider moving to higher ground.

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KEY TERMS

floodplain (p. 98)
stream power (p. 99)
discharge (p. 100)
competency (p. 100)
capacity (p. 100)
channel pattern (p. 102)
braided channels (p. 102)
meandering (p. 103)
point bar (p. 104)
riverine environment (p. 104)
pool (p. 104)
riffle (p. 104)
upstream floods (p. 105)
downstream floods (p. 105)
recurrence interval (p. 108)
floodplain regulation (p. 113)
floodway district (p. 117)
floodway fringe district (p. 117)
channelization (p. 117)
channel restoration (p. 120)

SOME QUESTIONS TO THINK ABOUT

1. You are a planner working for a community that is expanding into the headwater portion of a drainage basin. You are aware of the effects of urbanization on flooding and wish to make recommendations to avoid some of these effects. Outline a plan of action.
2. You are aware that at the institutional level the perception of flooding is adequate. However, at the individual level the situation is not so clear. How could you develop a plan to communicate the potential of flood hazard to people in your community?
3. You are working for a county flood-control agency that has been channelizing streams for many years. The preferable method has been to use bulldozers to straighten and widen the channel. Recently your agency has been criticized for causing extensive environmental damage. You have developed new plans of channel restoration that you wish to have implemented for a stream maintenance program. Describe what you might do (devise a plan of action) to convince the official in charge of the maintenance program that your ideas will improve the urban stream environment and help reduce the potential of flood hazard.