Many small government and private boats rescued people from flooded homes

6



APPLYING the 5 fundamental concepts Houston Floods of 2017

1

Science helps us predict hazards.

Flooding is a serious and costly natural hazard, one that more people experience than any other natural hazard. Fortunately, flooding is usually linked to meteorological phenomena that can be used to provide some advance warning about the potential for flooding, as was the case in 2017.

2

Knowing hazard risks can help people make decisions.

Following the 2017 Houston floods, the risk of damage to land and property from the flood is being studied in the context of population increase, land-use planning and long-term trends and climate change. However, for Houston and many other regions knowing the risk may not prevent people from living and working in flood-prone areas.

Flooding

Houston Flood of 2017

In a period spanning a few days, as much as 125 cm (~50 in.) of rain from Hurricane Harvey fell on the city of Houston, Texas, producing the largest and most serious urban flood in U.S. history. Total damages will probably approach $200 billion. The flood caused immense human suffering to the urban population (see opening photograph). Houston is the fourth largest city in the U.S., with about 6.5 million people spread over 1500 square kilometers (6000 square miles, two-thirds the area of Maryland). The city is sufficiently inland from the Gulf Coast to avoid storm surge from hurricanes, but it is sited on low-lying land with numerous streams (some, called bayous, are mostly very slow-moving water courses with abundant plants) which flow south through Houston to the sea. The result of the unprecedented amount of rain was catastrophic flooding which inundated much of the city and surrounding areas with several feet of water. Freeways and streets became rivers (Figure 6.1). The floodwaters displaced about 1 million people and damaged about 200,000 homes and several hundred thousand automobiles. Many thousands of people were rescued by boat and helicopter (Figure 6.2) and spent time in emergency shelters. Evacuation of the city was not an option because massive traffic jams would have trapped people in cars on flooding streets and perhaps have caused many more deaths than those which occurred to people sheltering in their homes.

< Rescue Operation in Houston
Elderly woman being rescued from floodwaters at her home in Houston during the 2017 flood. Many hundreds of people were rescued as people helped people. *(Joe Readle/Getty)*

Flooding is the most universally experienced natural hazard. Floodwaters have killed more than 10,000 people in the United States since 1900. For the past decade, property damage from flooding has averaged more than $4 billion per year. Flooding is a natural process that will remain a major hazard as long as people live and work in flood-prone areas.

After reading this chapter, you should be able to:

LEARNING Objectives

LO:1 Explain basic river processes.

LO:2 Compare and contrast flash floods, downstream floods, and megafloods and know why the differences are important.

LO:3 Summarize regions at risk from flooding and the global impact.

LO:4 Differentiate between the effects of flooding and the linkages with other natural hazards.

LO:5 Describe the benefits of periodic flooding.

LO:6 Discuss how human activity can significantly affect river processes and flooding.

LO:7 Summarize why being proactive with flood hazards is, in the long term, more significant in reducing the flood hazard than being reactive after a flood.

LO:8 Evaluate the adjustments we can make to minimize flood deaths and damage.

LO:9 Summarize how people perceive flooding.

3

Linkages exist between natural hazards.

Flooding is linked to several other natural hazards; in the case of Pakistan, it was linked to severe weather and climate, as well as waterborne disease.

4

Humans can turn disastrous events into catastrophes.

With a population that has grown dramatically in recent decades, the 2017 Houston flood illustrates that densely populated flood-prone areas are becoming more vulnerable to large events with the potential to cause catastrophes.

5

Consequences of hazards can be minimized.

When we return to the 2017 Houston flood, you will learn about the challenges faced by governments with minimal resources to minimize future flood hazards through prediction, land-use planning, and engineering.



FIGURE 6.1 Aerial View of 2017 Houston Flood
Thousands of homes were damaged and roads were covered by floodwaters. *(David J. Phillip/AP)*



FIGURE 6.2 Flood Victims Were Rescued by Boats
Private and government boats of many types joined together to rescue people from floodwaters. *(ABC News.Go.Com chron.com)*

Years before the Houston flood of 2017, concerns and warnings were voiced about the risk and impact of flooding as a result of the rapid increase in Houston's urban population (increasing exposure to flooding), drainage problems (increasing vulnerability of flooding) as the land was paved over, and poor land-use planning (increasing exposure to flooding) that allowed increased development with more people living in areas that were becoming more susceptible to flooding over time. After the flood, people reported that this was the first flood they had experienced, and few had flood insurance. Concern was also raised about emerging long-term trends linked to climate change which, with increase in intensity of storms, would likely increase the risk and damage from flooding.

The response to the flood (people helping people) as it emerged over a week of prolonged, intense rain was a heartwarming aspect of the catastrophic urban flood. Private citizens from far and near in all sorts of small boats, along with military support, moved through flooded areas, rescuing people from homes and stranded cars and moving them to shelters. Around the country, millions of dollars were donated from fellow Americans to assist those in need. Houston-area deaths from the flood numbered about 30 people. Swift responses and rescues saved lives. While Houston was being flooded, unusually strong seasonal (monsoon) rains in India, Nepal, and Bangladesh (South Asia) flooded cities and surrounding areas, killing over 1,000 people (about 40 million people were affected by the flooding). As in Houston, the city of Mumbai, India's richest city with an urban population of about 22 million, was brought to a standstill by flooding (Figure 6.3). The geography, topography, and climate is very different in Houston compared to Mumbai, but the risk of urban flooding in both cities is high due to similar circumstances (high population, potential of prolonged intense rainfall, and poor land-use planning). Flooding is the most widespread and common natural hazard in the world today. Major U.S. cities that have a significant urban flood hazard include New York, Boston, New Orleans, Miami, and Los Angles.

Flood disasters are becoming more common in large urban areas, suggesting that a new approach to mitigating floods, such as reducing exposure and vulnerability and, thus, risk (see the discussion of risk in Chapter 1) through restricting development on floodplains and better control, using engineering of floodwaters, is necessary. An urban flood control dam failed to control runoff in Houston, requiring release of water that flooded downstream areas. Links to climate change must also be carefully considered in future flood hazard evaluation as storms become more intense. We will return to the Houston flood in more detail at the end of the chapter when we discuss the event with respect to the fundamental concepts of this book.



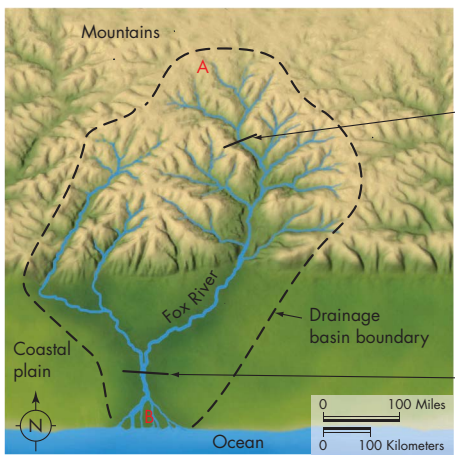
FIGURE 6.3 People Wading through Floodwater
While Houston was being flooded, so was the city of Mumbai, India's richest city with an urban population of about 22 million. *(newGettyimages 840507052)*

6.1 An Introduction to Rivers

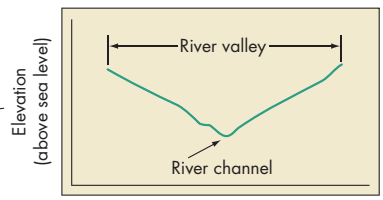
The range of drainage area, sediment size and volume, water, climate, and human use make each river and each flood unique. Nevertheless, an understanding of basic river processes greatly improves the understanding of floods, which are the most commonly experienced natural hazard, whether you live in a rural area, small town, or large urban area. Streams and rivers are part of the water or hydrologic cycle, and *hydrology* is the study of this cycle (see Chapter 1). In the hydrologic cycle, water evaporates from Earth's surface (primarily from the oceans) into the atmosphere, then precipitates back onto Earth's surface, and eventually returns to the oceans by flowing underground and across the land surface. Water that falls on the land as rain and snow will infiltrate into the ground, evaporate from the land surface, or drain off the land, following a course determined by the local topography.

Surface drainage, referred to as *runoff*, finds its way to small streams, which may merge as *tributaries* to form a larger stream or **river**. Streams and rivers differ only in size; that is, streams are small rivers. Local usage varies as to what constitutes a creek, brook, and river. Geologists, however, commonly use the term *stream* for any body of water that flows in a channel. The region drained by a single stream or river is variously called a **drainage basin**, *watershed*, river basin, or catchment (Figure 6.4a). Thus, each stream has its own drainage basin or watershed that collects rain and other precipitation. A large river basin, such as the Susquehanna River basin in the northeastern United States, is made up of hundreds of small drainage basins, commonly called watersheds, which catch the precipitation that drains into the smaller tributary streams and rivers. Except for the very few who live right next to the river, most people who live on land that drains into the Susquehanna live in a watershed of one of its tributaries. In fact, virtually everyone lives in a watershed that is a part of a larger drainage basin.

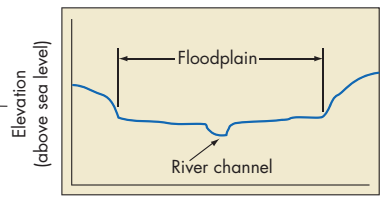
One important characteristic of a river is the slope of the land over which it flows. Referred to as the *gradient*, this slope is determined by calculating the vertical drop in elevation of the channel over some horizontal distance. Gradient is commonly given in meters per kilometer or feet per mile. Also used is meter (drop) per meters in channel length or foot (drop) per feet of channel length. If a river falls 2 feet per mile, the slope is 2/5280 or 0.0004 (0.04 percent). The gradient of a river is steepest at higher elevations and levels off as the



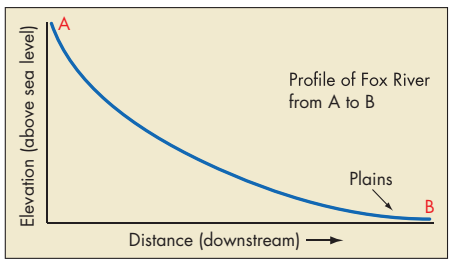
(a) Map (plan view)



(c) Cross section across river valley near headwaters



(d) Cross section across river valley near base level



(b) Longitudinal profile

< FIGURE 6.4 Drainage Basin and River Profile

Idealized diagram of the Fox River showing (a) its drainage basin outlined by the black dashed line, that is, the area where surface runoff drains into the river or its tributaries. (b) The longitudinal profile from point A at the river's head to point B at the river's mouth; note that the vertical scale on this diagram is greatly exaggerated. (c) The V-shaped cross-section of the river valley near its headwaters where the valley floor is mainly the channel. (d) Cross-sectional profile across the Fox River valley on the coastal plain where the valley floor is mainly the floodplain.

river approaches its base level. The *base level* of a river is the lowest elevation to which it may erode. Most often, this elevation is at or close to sea level, although a river may have a temporary base level such as a lake. Rivers, thus, flow downhill to their base level, and a graph showing the downstream changes in a river's elevation is the *longitudinal profile* (Figure 6.4b).

A river usually has a steeper-sided and deeper valley at high elevations near its *headwaters* (Figure 6.4c) than closer to its base level where a wide floodplain may be present (Figure 6.4d). This happens because, at higher elevations, the steeper river gradient increases flow velocity, which, in turn, increases erosional down-cutting by the river.

EARTH MATERIAL TRANSPORTED BY RIVERS

Rivers not only move water but also transport a tremendous amount of visible and invisible material. The quantity of this material, called the *total load*, is generally subdivided into bed load, suspended load, and dissolved load, based on how the river carries the material. The bed load of most rivers consists of sand and gravel particles that slide, roll, and bounce along the channel bottom in rapidly moving water. The bed load commonly makes up less than 10 percent of the total load. In contrast, the suspended load is composed mainly of small silt and clay particles that are carried above the streambed by the flowing water. The suspended load accounts for nearly 90 percent of the total load and makes rivers look muddy, especially during a flood. Finally, the dissolved load consists of electrically charged atoms or molecules, called *ions*, which are carried in chemical solution. Most dissolved load is derived from chemical weathering of earth materials in the drainage basin. In some places, ions from discharging underground springs, wastewater, and chemical pollution are a significant part of the dissolved load.

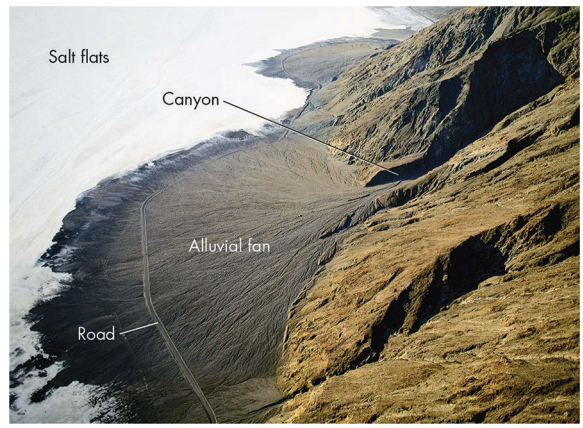
RIVER VELOCITY, DISCHARGE, EROSION, AND SEDIMENT DEPOSITION

Rivers are the basic transportation system of that part of the rock cycle involving erosion and deposition of sediment. They are a primary erosion agent in the sculpture of our landscape, removing and carrying sediment from one site and depositing it in another. The velocity, or speed, of water in a river varies along its course, affecting both erosion and deposition of sediment. Hydrologists combine measurements of flow velocity and channel area (capacity) to determine discharge, a more useful indicator of stream flow.

Discharge (Q) is the volume of water moving through a cross-section of a river per unit time. In this case, a cross-section is the side-to-side view of the river that you would have if you took a huge knife and sliced across the valley from top to bottom at right angles to each riverbank. Once the topographic cross-section is completed with survey equipment, a hydrologist can determine the cross-sectional area that is occupied by water by simply measuring the water depth. Mean velocity is measured with a current meter. Discharge is then calculated by multiplying the cross-sectional area of the water in the channel (A) and the velocity of flow (V) and is reported in either cubic meters per second (cms) or cubic feet per second (cfs).

If there were no additions or deletions of flow along a given length of river, then its discharge would not change. Where the cross-sectional area of flow decreases, the velocity of the water must increase for discharge to remain constant. You can prove this to yourself with a garden hose. Turn on the water and observe the velocity of the water as it exits the hose. Then put your thumb partly over the end of the hose, reducing the area where the water flows out of the hose, and observe the increase in the velocity. This explains why velocity is higher where a river flows through a narrow channel in a canyon than where it spreads out and expands into a larger area downstream of the narrow channel.

Stream flow expands and slows down as a river goes from mountains onto plains or from a channel into an ocean, lake, or pond. At these points, the river commonly forms a fan-shaped deposit on land known as an *alluvial fan* (Figure 6.5) or a triangular or irregularly



▲ FIGURE 6.5 Alluvial Fan in Death Valley
Along the western foot of California's Black Mountains, this alluvial fan formed where a stream leaves a canyon and expands outward into Death Valley. The bent line in the lower left is a road that cuts across the lower part of the fan. Infrequent floods on this fan drain into the white salt flats of Death Valley, seen in the upper and lower left. *(Michael Collier)*

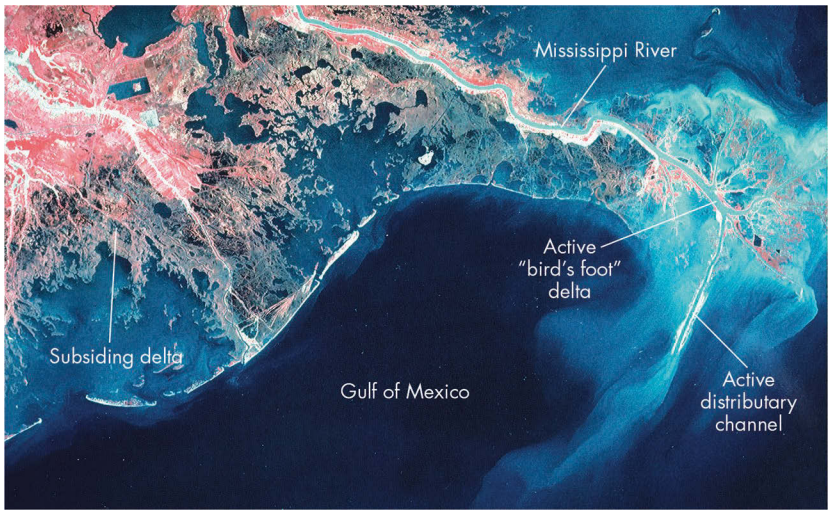


FIGURE 6.6 Mississippi Delta
In this false-color satellite image of the Mississippi River Delta, living vegetation appears red, sediment-laden waters are white or light blue, and deeper water is darker blue because it contains less suspended sediment. The main active distributary is the light-blue channel that starts in the top-left center and slopes toward the middle right. In the far-right center, the main distributary branches into several channels that make the shape of a "bird's foot." This shape indicates that river flow is stronger than the wave and current action in the Gulf of Mexico. Distance across the image is about 180 km (~112 mi.). *(University of Washington Libraries Special Collections SL-23–40-H)*

shaped deposit known as a *delta* if it extends into a larger body of water (Figure 6.6).

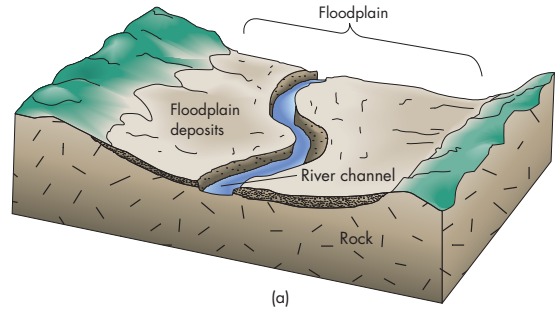
River flow on alluvial fans and deltas is different from flow in a river valley and its adjacent area. Rivers reaching base level and entering an alluvial fan or delta often split into a system of *distributary channels*. That is, the main river divides into several channels that carry floodwaters and sediment to different parts of the fan or delta. Furthermore, these channels may change position rapidly during a high-flow event or from one flow event to the next, creating a system and channels that are difficult to predict.

CHANNEL PATTERNS AND FLOODPLAIN FORMATION

Most physical features of rivers and floodplains result from the interaction of flowing water and moving sediment. Such features include various forms of sediment accumulation and the river channel itself.

A bird's-eye view of a stream channel as seen from an airplane reveals that streams and rivers develop distinctive **channel patterns**. The most common patterns are *meandering*, a single-thread channel similar to the curves of a moving snake, and *braided*, a multithread channel where there are two or more channels that unite and divide as the river flows downstream.

Meandering Pattern Many rivers have curving channel bends called *meanders* that migrate back and forth across the **floodplain** (relatively flat land adjacent to a river that is produced by river processes). Floodplains are a major river landform that develop over a period of years to decades and much longer (Figure 6.7). It is interesting that although the



(a)

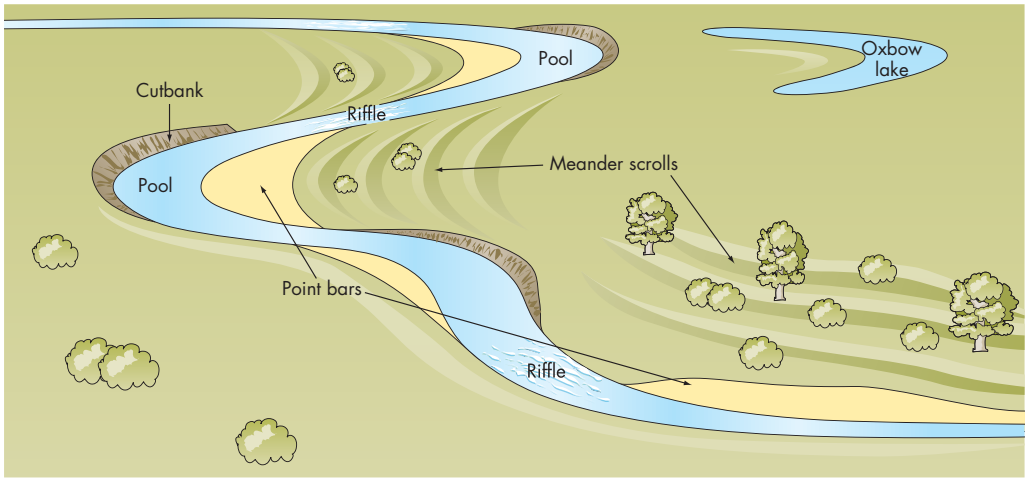


(b)

FIGURE 6.7 Floodplain
(a) Diagram illustrating the location of a river's floodplain. Most floodplains have deposits that are finer grained than those found in, and immediately adjacent to, the channel. (b) Floodplain of the Rio Grande near its headwaters in Colorado. *(Edward A. Keller)*

meandering behavior of rivers has been studied for nearly a century by many hydrologists, geologists, engineers, and physicists, including Albert Einstein, we don't know for sure why rivers meander. We do, however, know a great deal about how water flows in a meandering stream.

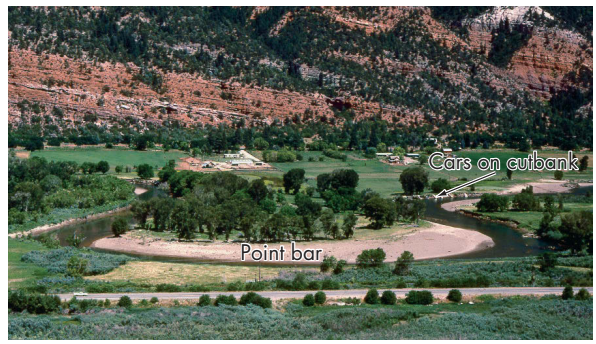
Canoeists have long known that water moves faster along the outside of a meander bend during low to relatively high flows. The fast-moving water erodes the riverbank on the outside of the bend to form a steep or near-vertical slope known as a *cutbank* (Figure 6.8). In contrast, slower water on the inside of a meander bend deposits sand and sometimes gravel to form a *point bar*. Continual erosion of the cutbank and deposition on the point bar cause each meander bend to migrate laterally in a different direction. This process is important in constructing and maintaining some floodplains (see Figure 6.7). Floodplains are also built during *overbank flow*, a condition that develops when rising water spills over the riverbank onto the floodplain. Flow that expands out of its channel is slowed and then deposits fine sediment, such as very fine sand, silt, and clay, which builds up the floodplain. Much of the sediment transported in rivers is



(a)



(b)



(c)

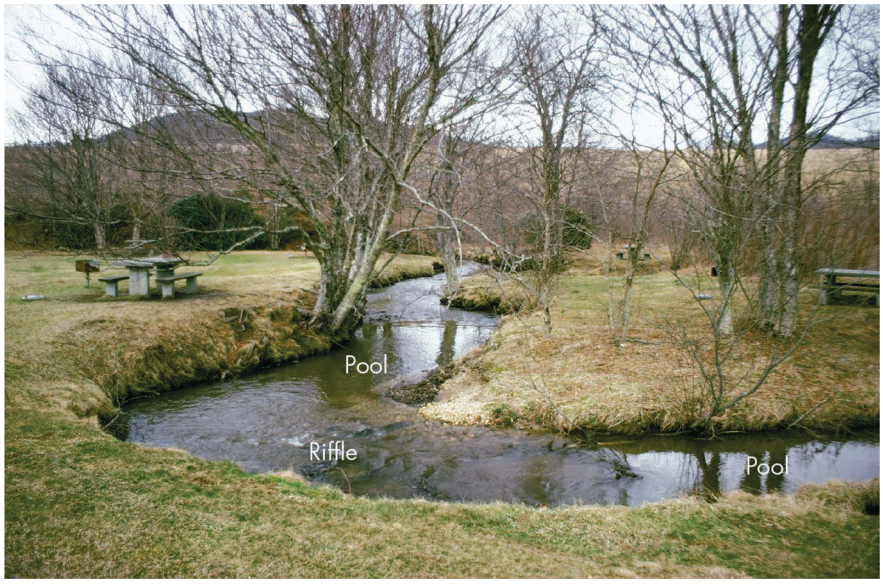
▲ FIGURE 6.8 Characteristics of a Meandering River

(a) Idealized diagram of a meandering stream showing important features. Historical migration of meander bends is commonly indicated by low, curving, vegetation-covered ridges called meander scrolls. The scrolls on the point bar in the left center of the diagram indicate that it migrated from right to left. (b) Animas River north of Durango, Colorado, at high flow with brown muddy water filling the channel. The dark-blue abandoned channels that form oxbow lakes in the lower right indicate that the river has meandered back and forth across the valley to build its floodplain. In contrast to the river, the lakes have little suspended sediment in the water. *(Robert H. Blodgett)* (c)The sandy point bar on the left side of (b) exposed at low flow. A farmer has placed junked cars on the cutbank of a meander bend in the right center to slow the erosion of his pasture. *(Robert H. Blodgett)*

periodically stored by deposition in the channel and on the adjacent floodplain.

Meandering channels often contain a series of regularly spaced pools and riffles (Figure 6.9). *Pools* are deep areas produced by scour, or erosion, at high flow, and *riffles* are shallow areas formed by sediment deposited at high flow. At low flow, pools have relatively deep, slow-moving water while riffles have shallow, fast-moving water. These changes in water depth and velocity along a stream create different *habitats*, that is, environmental conditions in which organisms live. The variety of environmental conditions found in these habitats increases the diversity of aquatic life. For example, fish may feed in riffles and seek shelter in pools. Also, pools have different types of insects than are found in riffles.

Braided Pattern Overall, braided channels (Figure 6.10) tend to be wide and shallow compared to meandering channels. During a raft trip down the braided Chilkat River in Alaska, for example, the raft may frequently run aground on gravel bars despite the



< FIGURE 6.9 Pools and Riffles
Well-developed pool and riffle sequence in Sims Creek near Blowing Rock, North Carolina. Deep pools lie under the smooth, reflective water surface in the center and lower right; shallow riffles lie under the rough, nonreflective water in the far distance and left foreground. *(Edward A. Keller)*



(a)



(b)

^ FIGURE 6.10 Braided Rivers
(a) The braided pattern of the North Saskatchewan River, Alberta, Canada, is formed by shallow channels flowing around and across numerous sand and gravel bars and islands. Coarse bed-load sediment of the river comes from melting glaciers in the Canadian Rocky Mountains. *(University of Washington Libraries Special Collections KC9330)* (b) Surface view of a braided channel near Granada, southern Spain, with subdividing channels, a steep gradient, and coarse gravel. Distance near the channel in the foreground is about 7 m (~23 ft.). *(Edward A. Keller)*

guide's best efforts. When that occurs, the guide may yell "shuffle," and the passengers bounce up and down until the raft floats back into the main channel. Rivers similar to the Chilkat are likely to have a braided pattern where the stream has a steep gradient and abundant, coarse bed-load sediment. These conditions are often found in areas where tectonic processes are rapidly uplifting the land surface and where rivers receive water and sediment from melting glaciers.

River Systems A drainage basin with the sediment and water it transports makes up a **river system** that consists of three distinct zones, each with different channel characteristics[1] (Figure 6.11):

- Zone 1: The zone of water and sediment production, also called the zone of production. This is generally in the upper parts of the system where topography is steeper and more precipitation falls. Water velocity is fast, and downcutting and erosion occur. Channels may be in steep-sided, V-shaped valleys with waterfalls and rapids controlled by hard rocks.
- Zone 2: The zone of transport, where water and sediment are conveyed by a river with a broad valley and floodplain, created as the river moves laterally rather than downcutting a steep valley. Sediment is frequently deposited in river bars or on the floodplain, but such deposition is temporary in the history of a river. The channel pattern may be braided or meandering or some combination of both.
- Zone 3: The zone of deposition, where water velocity slows near base level and sediment is deposited. This may be an alluvial fan, lake, or, more commonly, a delta.

Understanding the characteristics of these three zones is basic to evaluating a river system. Life is very different in each of the zones; where you live does make a difference.

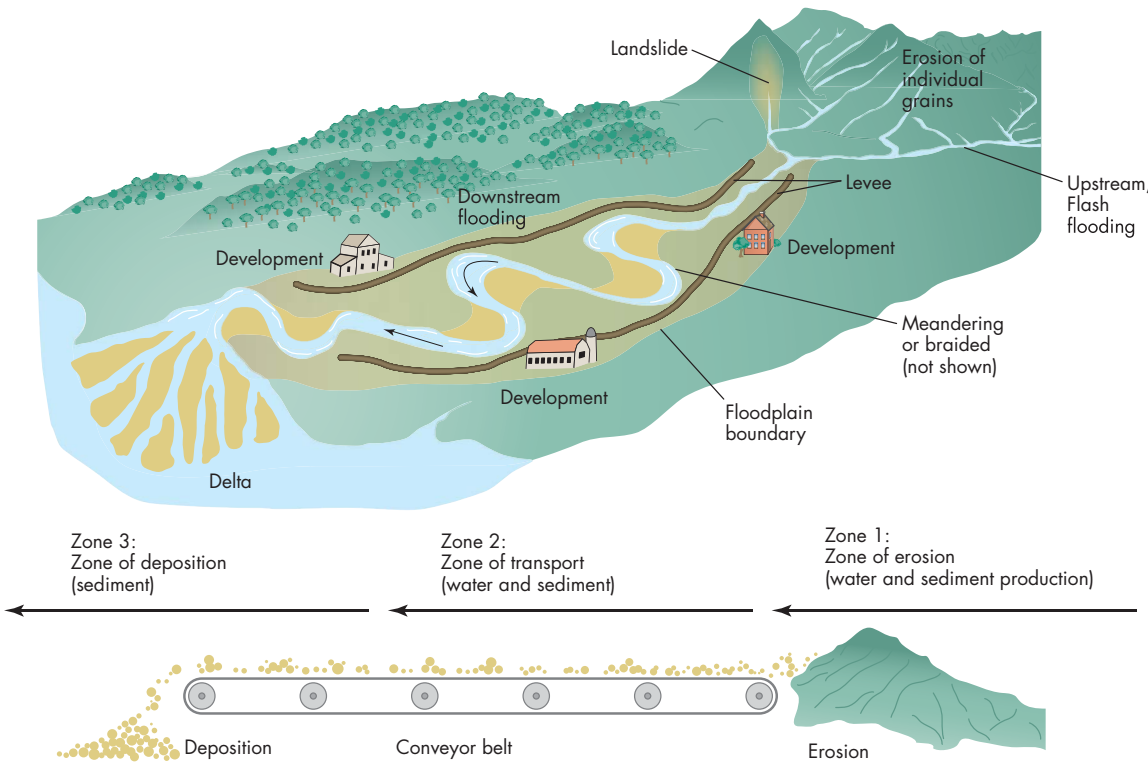


FIGURE 6.11 Idealized Diagram of the River System
A river system consists of three zones: water and sediment production, transport of water and sediment, and deposition of sediment. *(Schumm, S. A. 1977.* The fluvial system. New York: John Wiley & Sons; *Kondolf, M. G. 1994. "Geomorphic and Environmental Effects of Instream Gravel Mining,"* Landscape and Urban Planning *28: 225–43)*

Stream channels flowing through sediment, such as sand, gravel, or mud, rarely stay fixed in the same place for a long period of time. Either erosion or deposition causes the stream channel to shift position. These shifts can be continual or they can be abrupt, such as when a channel shifts to an entirely new location during a flood. In abrupt changes, a stream may abandon part of its existing channel and form a new one nearby. This process, known as *avulsion*, can have unexpected consequences for people living in a stream valley.

Having presented some of the characteristics and processes of the flow of water and sediment in rivers, we turn to the process of flooding in greater detail.

6.1 CHECK your understanding

1. What is a drainage basin?
2. What is the difference between dissolved load, suspended load, and bed load?
3. Define alluvial fan and delta.
4. What are the two main channel patterns? How and why do these differ?
5. Describe the three zones of a river system.

6.2 Flooding

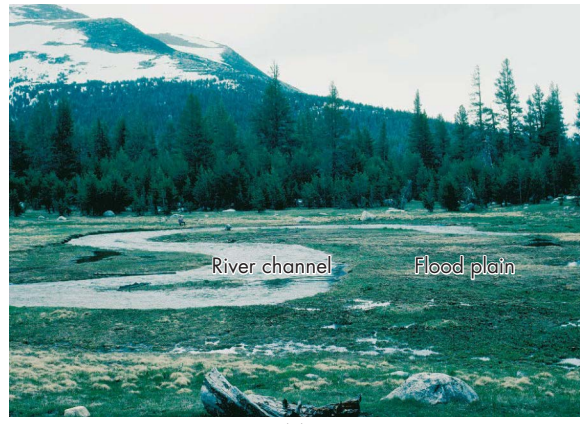
INTRODUCTION

The natural process of overbank flow is termed **flooding** (Figure 6.12). Most river flooding is related to the amount and distribution of precipitation in the drainage basin, the rate at which the precipitation infiltrates (soaks) into the earth, and how quickly surface runoff from that precipitation reaches the river.

The amount of moisture in the soil at the time the precipitation starts also plays an important role in flooding. Water-saturated soil is similar to a wet sponge that cannot hold any additional moisture. If significant precipitation falls on a saturated drainage basin, flooding will occur. If the same amount of precipitation falls on a dry basin, the soil may be able to absorb considerable moisture and, thus, help prevent flooding.

In mountainous areas (zone 1; see Figure 6.11) and in locations at higher latitudes, such as Alaska, Canada, and the northern contiguous United States, floods are common during early spring and midwinter thaws. Rain falling on frozen ground or accumulated snow, or the rapid melting of ice and snow, can cause flooding. In these areas, large masses of floating ice can create ice jams across rivers that temporarily dam their flow. Floodwaters can back up behind the ice jams or the jams can break apart abruptly, causing flooding downstream. For example, an ice jam on the Winooski River in Vermont in 1992 threatened to flood Montpelier, the state capital, which was located upstream of the jam. Flooding can also occur in zones 2 or 3 (see Figure 6.11), downstream of zone 1. Large downstream floods may last weeks to months and be regional in extent.

A flood can be characterized in several ways. One is the *flood discharge*, defined as the discharge of the stream

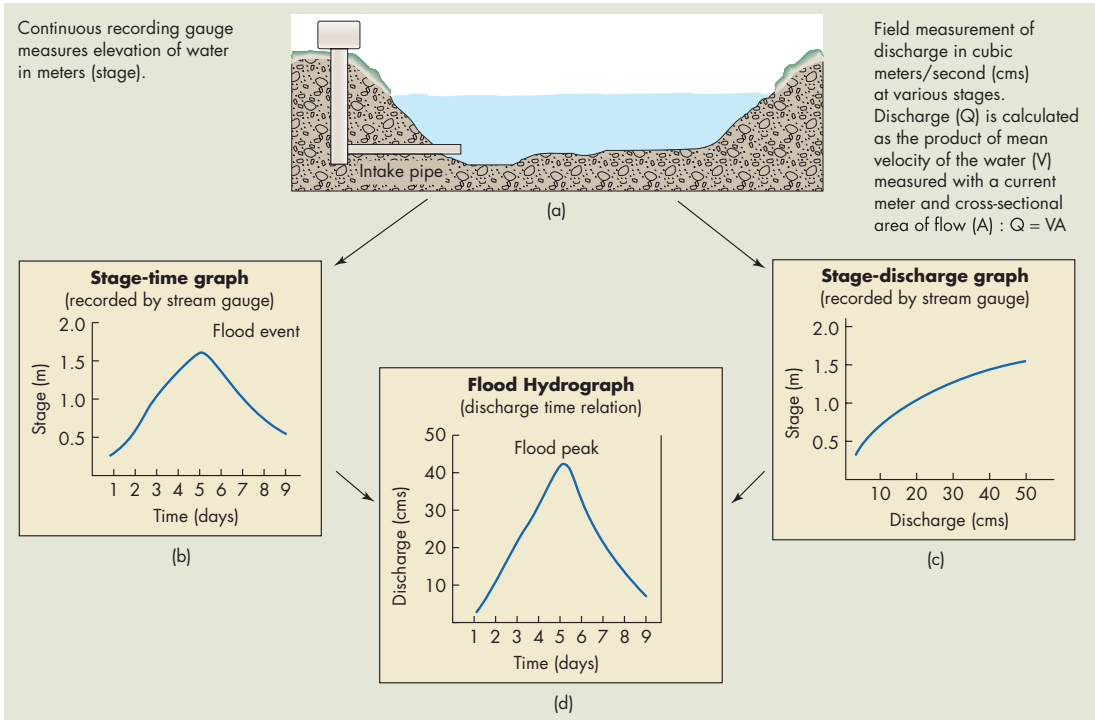


(a)



(b)

▲ FIGURE 6.12 Floodplain Flooding from Snowmelt
Gaylor Creek, Yosemite National Park, California, during spring snowmelt. (a) In the morning, water stays within the stream channel. *(Edward A. Keller)* (b) In the afternoon, during daily peak snowmelt, overbank flow covers the floodplain. *(Edward A. Keller)*



▲ FIGURE 6.13 How to Produce a Hydrograph

Field data (a) consists of a continuous recording of the water level, or stage, which is used to produce a stage-time graph (b). Field measurements at various flows also produce a stage-discharge (c). Graphs (b) and (c) are combined to produce the final hydrograph (d).

at the point where water overflows the channel banks. Floods can also be defined by the height of water in the river, referred to as the *stage* of the river. A graph showing changes in stream discharge, water depth, or stage over time is called a *hydrograph*.

The term *flood stage* is frequently used to indicate that the elevation of the water surface has reached a level likely to cause damage to personal property. This definition is based on human perception, so the elevation that is considered flood stage depends on human use of the floodplain.[2] Therefore, the size of a flood (total discharge) may or may not coincide with the extent of property damage. The relationships among the stage, discharge, and recurrence interval of floods are described and illustrated in the following discussion.

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 that occur more frequently. All flow events can be measured or estimated from stream-gauging stations to produce hydrographs (Figure 6.13) and arranged in order of their magnitude of discharge, generally measured in cubic meters per second (Figure 6.14). This list of annual peak (largest) flows can be plotted on a discharge-frequency curve by deriving the recurrence interval R for each flow from the relationship.

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

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 within the recorded years (Figure 6.14).[3] For example, the highest flow for 9 years of data for the Patrick River is approximately 280 m^3 (~9900 $ft.^3$) per second, and that flow has a rank $M = 1$.[4] The recurrence interval of this flood is

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

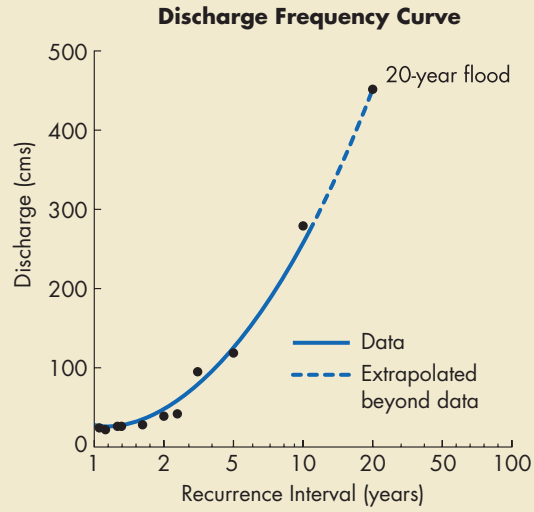
which means that a flood with a magnitude equal to or exceeding 280 m^3 (~9900 $ft.^3$) per second can be

Patrick River
Stream Gauge Data
Peak Annual Flow

Year	Discharge (cms)	M	R (yrs)
1995	30	5	2
1996	280	1	10
1997	45	4	2.5
1998	28	6	1.7
1999	120	2	5
2000	26	7	1.4
2001	100	3	3.3
2002	23	8	1.3
2003	20	9	1.1

M = Magnitude where M = 1 is the highest flow on record

R = Recurrence Interval in years; calculated by $R = \frac{N+1}{M}$; for Patrick River N = 9



▲ FIGURE 6.14 Example of a Discharge-Frequency Curve
To make a discharge-frequency graph for the Patrick River, nine years of discharge measurements in cubic meters per second (cms) were ranked (1 though 9) on the basis of the size (magnitude) of the largest flow each year. The recurrence interval, or frequency, of the largest annual flow was then calculated using the formula shown in the text. Data from the table on the left were then plotted on the graph on the right. The curve was then extended (extrapolated) to estimate the discharge of the 20-year flood, which was 450 m^3 (~15,900 $ft.^3$) per second. *(Based on Leopold, L. B., U.S. Geological Survey Circular 554, 1968)*

expected about every 10 years; we call this a 10-year flood. The probability that the 10-year flood will occur in any one year is 1 ÷ 10 or 0.1 (10 percent). Likewise, the probability that the 100-year flood will occur in any year is 1 ÷ 100 = 0.01, or 1 percent.

Extending, that is, extrapolating, the discharge-frequency curve is risky. The curve shouldn't be extended much beyond twice the number of years for which there are discharge records. Studies of many streams and rivers show that channels are formed and maintained by *bankfull discharge*, defined as a flow with a recurrence interval of 1.5 to 2 years. Applying this concept to the Patrick River (Figure 6.14), the bankfull discharge with an interval of 1.5 years was a discharge of 27 m^3 (~950 $ft.^3$) per second. Bankfull is the flow that just fills the channel. 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.

As longer flow records are collected, we can more accurately predict floods. However, designing structures for a 10-year, 25-year, 50-year, or even 100-year flood, or, in fact, any flow, is a calculated risk, since predicting such floods is based on a statistical probability. For many streams, the flow record is far too short to accurately predict the magnitude and frequency of large floods. 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] Finally, very large but not unprecedented floods may not have occurred during the period of stream flow record. As a result, the flow frequency analysis may not be of much use in dealing with the "so called extreme events." To consider these flows we need to look to the historic and prehistoric record that is often present in old news stories and the sediment record the Earth provides. The flood record in the sediment in a valley or on a floodplain is the real deal – never fake news. The Earth does not lie. What is needed is better science to incorporate extreme floods (too often neglected in flood hazard analysis as unprecedented) into our flood hazard analysis. The 2017 Houston flood that opened this chapter was considered unprecedented with a recurrence interval of the precipitation of hundreds of years or more. It was not unprecedented, similar

rainfall events have occurred in Texas several times in past 100 years, often associated with tropical storms (hurricanes) that stall and dump 100 cm (~40 in.) of rain in a few days. What was unprecedented in 2017 was the horrific damages as a result of increasing population, urbanization, and poor land-use practices.

FLASH FLOODS OF ZONE 1

Floods can be characterized by where they occur in a drainage basin (see zones 1, 2, and 3 in Figure 6.11). **Flash floods** typically occur in the upper part of a drainage basin (zone 1) and in some small drainage basins of tributaries to a larger river. They are generally produced by intense rainfall of short duration over a relatively small area. If these floods are sudden and of relatively great volume, peak discharge can be reached in less than 10 minutes. Flash flooding is most common in arid and semiarid environments, in areas with steep topography or little vegetation, and following breaks of dams, levees, and ice jams (see Case Study 6.1: Survivor Story).

Although flash floods do not generally cause flooding in the larger streams, they can join downstream and may be quite severe locally. For example, a high-magnitude flash flood occurred in July 1976 in the Front Range of the Rocky Mountains in Colorado. This flood was caused by a complex system of thunderstorms that swept through several canyons west of Loveland and delivered up to 25 cm (~10 in.) of rain in a few hours. The flash flooding killed 139 people and inflicted more than $35 million in damages to highways, roads, bridges, homes, and small businesses. Most damage and loss of life occurred in Big Thompson Canyon, where hundreds of residents, campers, and tourists were caught with little or no warning. Although the storms and flood were rare events in the Front Range canyons, comparable floods have occurred in the past.[6–8] Flash floods returned to the Front Range of Colorado in September 2013. Record rainfall over a short time produced record floods in many streams, including Boulder Creek in Boulder, Colorado. The area of flooding covered several thousand square kilometers (square miles).

Over 1,500 homes were destroyed (17,000 were damaged), many bridges were washed out, and cars were washed into creeks and rivers (Figure 6.15). Many people who die during flash floods are in automobiles. Deaths occur when people attempt to drive through shallow, fast-moving floodwater. A combination of buoyancy and the strong lateral force of the water sweeps automobiles off the road into deeper water, trapping people in sinking or overturned vehicles. Most automobiles will be carried away by 0.6 m (~2 ft.) of water. More than ten thousand people were evacuated during the 2013 Colorado flash floods, and about 1,000 were airlifted to safety. Eight people were killed as a direct result of flooding, and damages will likely exceed $100 million.

DOWNSTREAM FLOODS OF ZONE 2

It is the large **downstream floods** in zone 2 that often make national television and newspaper headlines. In 2004, heavy rains from a series of hurricanes and



(a) (b)

▲ FIGURE 6.15 Heavy Rain and Flooding in Colorado

(a) Three vehicles crashed into a creek after the road washed out from beneath them in Broomfield, Colorado, September 12, 2013, in heavy flooding. *(Andy Cross/The Denver Post via Getty Images)* (b) A road crew works on a stretch of highway washed out by flooding along the South Platte River in Weld County, Colorado, near Greeley, Saturday, September 14, 2013. *(AP Photo/John Wark)*

Flash Flood

6.1 Survivor Story

CASE study

Jason Lange and his four companions were all set for a leisurely canoe trip down Santa Elena Canyon in Big Bend National Park in southwestern Texas. And there wasn't any reason to suspect it would be anything but that. The five University of Wisconsin–Whitewater students were in Big Bend during their spring break, and as Lange says, "it was supposed to be the dry season."

They set off on their planned two-day trip on March 20, and for the first day the waters were quiet, as is typical for early spring. Oftentimes, the water was so shallow that they were forced to carry their boats, and Lange estimated that it never got much deeper than 1 m (~3 ft.).

They had stopped for lunch on the second day about a quarter of a mile from the entrance to Santa Elena Canyon when, without warning, the group saw a "wall of water coming down the river" more than 2 m (~7 ft.) high.

"It literally sounded like a train coming," Lange said. "It immediately made the river explode. The river was casually running along, and all of the sudden it was whitewater."

The area where the group had stopped was quickly being consumed by the rising water level, and they had no choice but to get in their canoes and enter the canyon (Figure 6.1.A).

The students would later learn that the flash flood that caught them unprepared had originated in Mexico and caused a 6 m (~20 ft.) depth gauge to overflow, leading park officials to estimate that it was more than 7 m (~23 ft.) tall and had boasted Class V rapids. "The canoes we were in were not set up for those kinds of rapids whatsoever," Lange said.

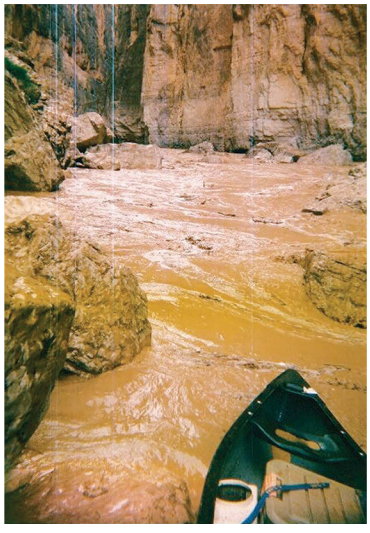
Once in the water, the group quickly ran into trouble. Almost immediately one of Lange's companions, Nick Gomez, capsized in his one-person canoe. After joining Lange and one of their other companions, the five set off again down the rapids in a pair of two-person canoes.

After a second boat flipped on an unexpected drop, the group stopped at a gravel bar to regroup. Repose, however, was brief; the very land beneath their feet quickly disappeared under the rising water. Within minutes, both remaining boats had capsized, and the five students were scattered.

Amazingly, Lange's original partner in his canoe, Lisa Chowdhury, managed to cling to one canoe all the way down the river. The remaining four were split into two groups, battling hypothermia through the night. A hiker finally spotted one party the next morning, and park rangers rescued the group, using spotter planes and jet boats.

Once all the students had learned that their companions were safe, Lange said the entire experience was thrilling beyond belief. "Once everyone got rescued, it was the most insane rush," he said. And, what's more, they want to go back.

—CHRIS WILSON



< FIGURE 6.1.A Flash Flood on the Rio Grande

Lange was able to snap a quick photograph as he and his companions were tossed into the rockslide rapids. The rocks pictured and his canoe were submerged within 2 minutes. This is a photograph of the Rio Grande in Santa Elena Canyon, Big Bend National Park, Texas-Mexico border. *(Jason Lange/Big Bend National Park)*



FIGURE 6.16 Downstream Flooding on the Ohio River
Marietta, Ohio, experienced its worst flooding in 40 years from the Ohio River because of heavy rains from the remnants of Hurricane Ivan in 2004. The town used snowplows to clear the mud deposited by the floodwaters. *(AP Photo/The Marietta Times, Mitch Casey)*

tropical storms in the eastern United States caused record and near-record flooding. Major downstream flooding occurred because the ground remained saturated as one storm after another crossed the same drainage basins. In Pennsylvania, the Susquehanna River crested 2.5 m (~8 ft.) above flood stage for one of the five greatest floods in history. Downstream flooding on the Ohio River in Marietta, Ohio, was the worst in 40 years (Figure 6.16), and flooding in Atlanta, Georgia, set all-time records.

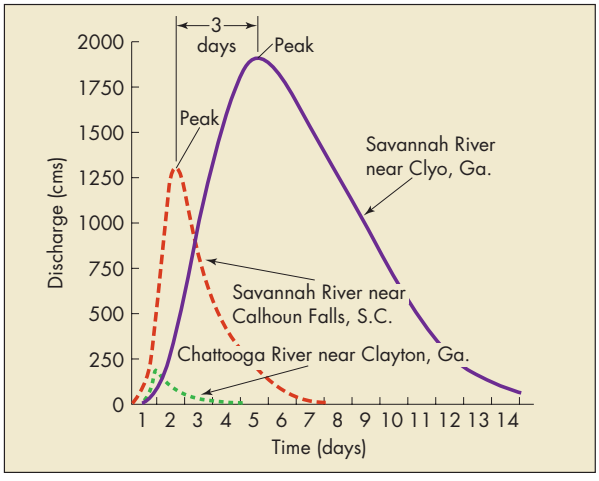
Downstream floods of zone 2 are often associated with inundation of the floodplain. Zone 2 floods may cover a wide area and are usually produced by storms of long duration that saturate the soil and produce increased runoff. Although flooding in small tributary drainage basins is generally limited, the combined runoff from thousands of tributary basins produces a large flood downstream. This kind of flood is characterized by the downstream movement of the flood crest (the peak height of the floodwaters) with a large rise and fall of discharge at a particular location.[9] An example of a downstream flood comes from the Chattooga and Savannah Rivers of Georgia and South Carolina (Figure 6.17a). As a flood crest on this river system migrated 257 km (~160 mi.) downstream, it took a progressively longer time for the water to rise and fall (Figure 6.17b). The hydrograph of the flood at the downstream gauging station in Clyo, Georgia, shows that the floodwaters took five days to reach their peak of more than 1700 m^3 (~60,000 $ft.^3$) per second.[10] Another way of looking at a flood is to examine the volume of discharge per unit area of the drainage basin (Figure 6.17c). This approach eliminates the effect of downstream increases in discharge and better illustrates the shape and form of the flood peak as it moves downstream.[11]

6.2 CASE study Mississippi River Floods of 1973–2008: Zone 2 Floods

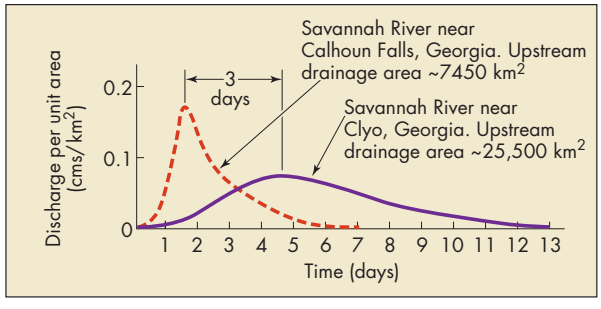
In 1973, spring flooding of the Mississippi River caused the evacuation of tens of thousands of people, as thousands of square kilometers of farmland were inundated throughout the Mississippi River Valley.



(a)



(b)



(c)

< FIGURE 6.17 Downstream Movement of a Flood Crest
Floodwaters, as they moved downstream along the Savannah River on the state line between South Carolina and Georgia. The distance from Clayton to Clyo is 257 km (~160 mi.). (a) Map of the area. (b) Volume of water passing Clayton, Calhoun Falls, and Clyo each second; the discharge increases as tributaries add more water. (c) Volume of water per unit area at the same points; flooding at Clyo lasts much longer than flooding in Clayton because of the addition of water from thousands of small tributaries. *(Based on data from Hoyt, W. G. and Langbein, W. B.,* Floods, *Princeton, NJ: Princeton University Press, 1955)*

Fortunately, there were few deaths, but the flooding resulted in approximately $1.2 billion in property damage.[12] The 1973 floods occurred despite a tremendous investment in upstream flood-control dams on the Missouri River, the largest tributary to the Mississippi. Reservoirs behind these dams inundated some of the most valuable farmland in the Dakotas, and despite these structures, the flood near St. Louis was record breaking.[13] As impressive as this flood was at the time, it did not compare—either in magnitude or in the suffering it caused—with the flooding that occurred 20 and 35 years later.

During the summers of 1993 and 2008, the land around the Mississippi River and its tributaries experienced two of the largest floods in the last hundred years. There was more water, in both 1993 and 2008, than during the 1973 flood, which had a magnitude of flow expected on average once in 100 years.

The 1993 flood resulted from rainstorms from April through July in the region of Cedar Rapids, Iowa, where low-pressure areas produced about 90 cm (~35 in.) of rain. Flooding lasted from late June to early August and caused 50 deaths and more than $15 billion in property damage. In all, about 55,000 km^2 (~21,000 $mi.^2$), including numerous towns and farmlands, were inundated with water.[14–16]

The 2008 floods resulted from winter to late spring storms that in June dumped as much as 25.5 cm (~10 in.) of rain in a 24-hour period in Indiana. Flood defenses again failed, about 24 people died, and the damage totaled around $9 billion.

The 1993 floodwaters were high for a prolonged time, putting pressure on the flood defenses of the Mississippi River, particularly **levees**, which are earthen embankments constructed parallel to the river to contain floodwaters and reduce flooding (Figure 6.18). Levees in the St. Louis region on the Mississippi, Missouri, and Illinois Rivers are shown in Figure 6.19. Notice that levees completely circle some areas on the floodplains.

Before construction of the levees, the Mississippi River's floodplain was much wider and contained extensive wetlands. Since the first levees were built in 1718, approximately 60 percent of the wetlands in Wisconsin, Illinois, Iowa, Missouri, and Minnesota—all hard hit by the flooding in 1993—have been lost. In some urban areas, such as St. Louis, Missouri, levees have been replaced with flood walls designed to protect the city against high-magnitude floods. The effects of these flood walls can be seen in a satellite image taken in mid-July 1993 (Figure 6.20). This image shows that the river is narrow at St. Louis, where it is contained by the flood walls, and broad upstream near Alton, Illinois, where extensive flooding occurred.

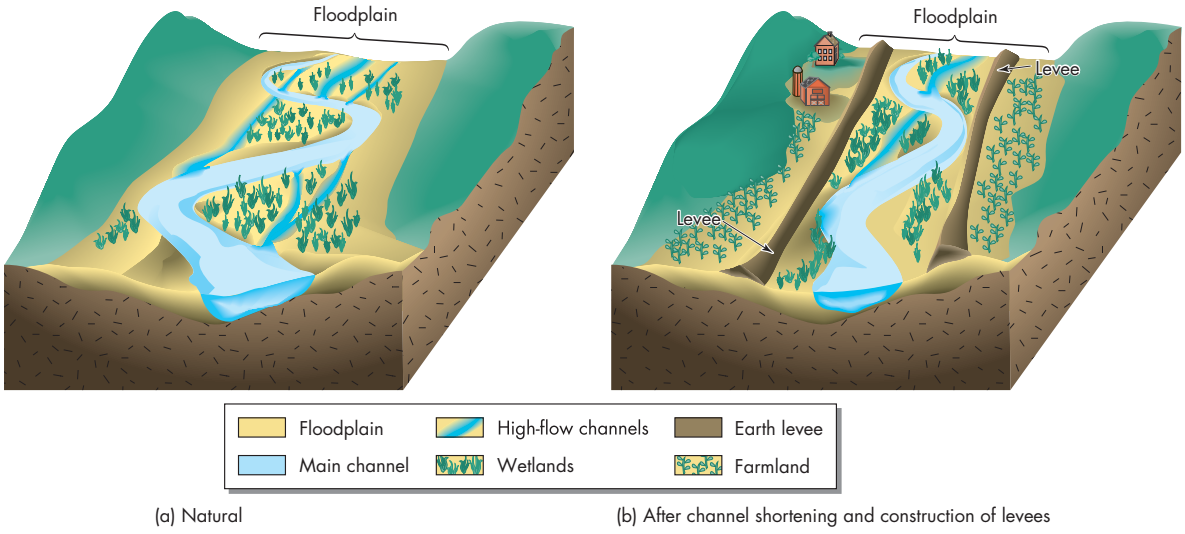


FIGURE 6.18 Floodplain With and Without Levees
Idealized diagram of (a) natural floodplain with wetlands. (b) Floodplain after channel is shortened and levees are constructed. Land behind levees is farmed, and wetlands are generally confined between the levees. *(Edward A. Keller)*

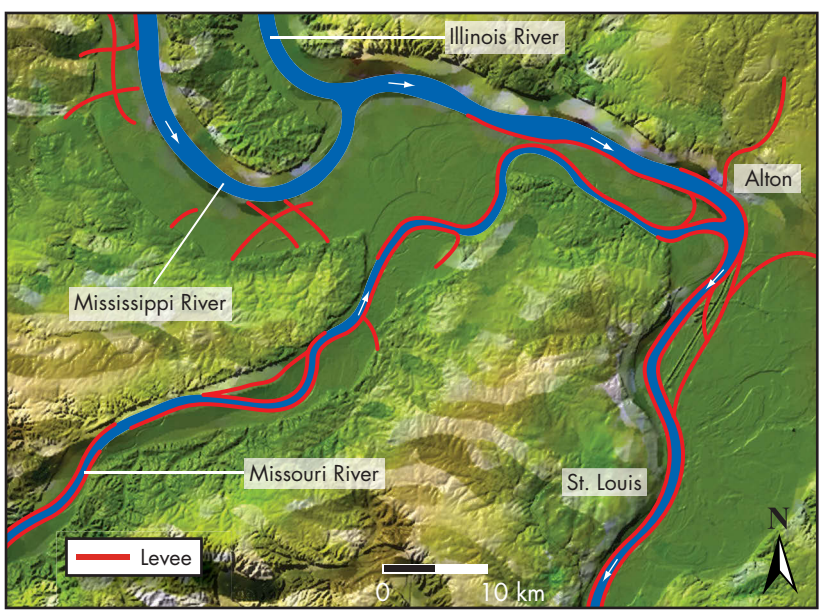


FIGURE 6.19 Levees Near St. Louis
Levees (red lines) almost completely enclose the Mississippi River near the cities of Alton and St. Louis, Missouri. *(Data from R. E. Criss and T. M. Kusky (eds.),* Finding a Balance between Floods, Flood Protection and River Navigation, *pp. 34–40. St. Louis, MO: Saint Louis University Center for Environmental Science. 2009. www.ces.slu.edu)*

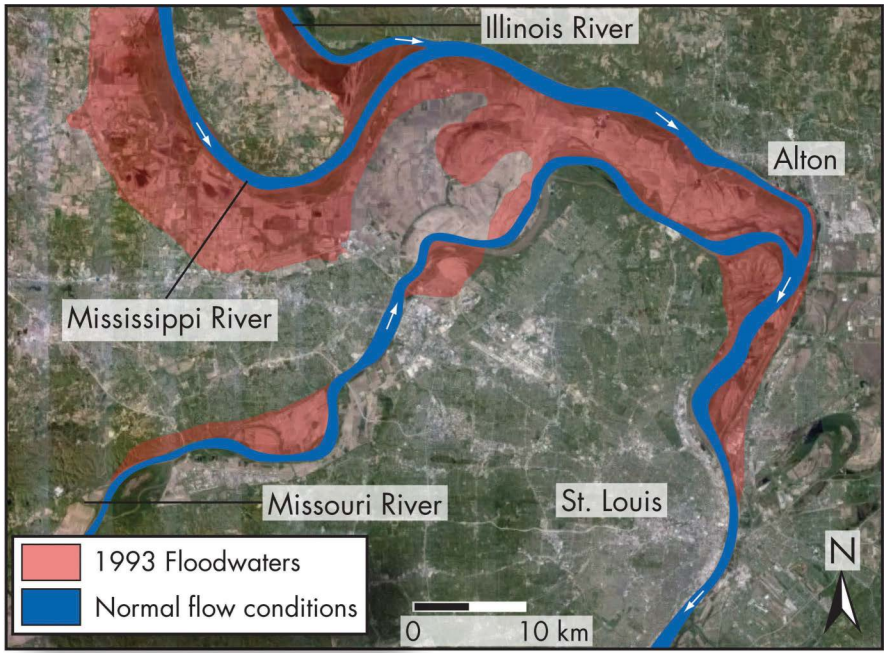
The flood walls produce a bottleneck effect—they force floodwater through a narrow channel between the walls and cause it to back up while waiting to get through. This effect contributed to the 1993 flooding upstream of St. Louis.

Despite the high walls constructed to prevent flooding, the rising flood peak came to within about 0.6 m (~2 ft.) of overtopping the flood walls at St. Louis. As the floodwaters in 1993 rose to record levels, these flood walls began to leak and required round-the-clock efforts to keep them from failing. Failure of levees downstream from St. Louis partially relieved the pressure, possibly saving the city from flooding. Levee failures were common during the flood event (Figure 6.21). In fact, the vast majority of the private levees, that is, levees built by farmers and homeowners, along the Mississippi River and its tributaries failed.[15–18] However, most of the levees built by the federal government survived the flooding and undoubtedly saved lives and property. Unfortunately, there is no uniform building code for levees, so some areas have levees that are higher or lower than others. Failures occurred as a result of overtopping and breaching, or rupturing, resulting in massive flooding of farmlands and towns (Figure 6.21).[15,17]

In addition to flood walls, other engineering structures designed to control the Mississippi have actually increased the long-term flood hazard.[19] For example, river-control structures designed to optimize the movement of loaded riverboats and barges during normal flow conditions can increase flooding at high flow. When floods overtop these structures, the floodwaters slow down and begin to back up, increasing flood height in a manner similar to the bottleneck effect created by the flood walls in St. Louis.[20]

Of course, building houses, industrial plants, public buildings, and farms on a floodplain invites disaster; too many 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, in fact, produced by the process of flooding (see Figure 6.7). If the floodplain and its relation to the river are not recognized, flood control and drainage of wetlands, including floodplains, become prime concerns.

An important lesson learned from the 1993 and 2008 floods is that construction of levees provides a false sense of security. Construction of a levee does not remove land from the floodplain, nor does it eliminate the flood risk. It is difficult to design levees to withstand extremely high-magnitude floods for a long period of time. Furthermore, by constructing a levee, the result is less floodplain space to "soak up" the floodwaters.[18] The 1993 floods caused extensive damage and loss of property; in 2008, floodwaters of the Mississippi River system inundated floodplain communities once again. National trends show that flood-control expenditures and damages have increased since the mid-twentieth century. Total flood losses have dramatically increased, in spite of the



< FIGURE 6.20 Mississippi River Flood of 1993

Satellite view of the extent of flooding in 1993 where the Illinois and Missouri Rivers join the Mississippi. The 1993 floodwaters are shown in light red, and dark blue shows normal river flow. In the lower right, a series of flood walls built to protect St. Louis constricts the Mississippi. This bottleneck to the flow caused widespread flooding upstream, including in the town of Alton, Illinois, on the east bank of the river near the right center edge of the image. Alton has a notorious history of flooding.





< FIGURE 6.21 Levee Failure
(a) A breach of this levee in Illinois during the 1993 floods of the Mississippi River caused flooding of the town of Valmeyer. Rapidly flowing whitewater can be seen rushing through the breach in the lower half of this grass-covered earthen levee. *(©Getty Images/Chicago Tribune/Contributor)* (b) Damage to farmlands during the peak of the 1993 flood of the Mississippi River. *(© Getty Images/Win McNamee/Staff)*

ever-increasing cost of flood-control structures.[21] The increase is partly due to changing frequency of high-intensity, high-volume storms. Since about 1950, the extreme participation index, defined as a two-day precipitation event (total participation) that is exceeded only once in a five-year period, in the U.S. (not including Hawaii and Alaska) has increased by about 40 percent.[22] The occurrence of extreme participation events are becoming more common. The increase is consistent with global warming, insofar as warming oceans impart more energy into the atmosphere, increasing storm intensity.

In the first six to seven years after the 1993 flood, the federal government bought out many homeowners in the floodplain upstream from St. Louis.[22] Now, real estate interests have reversed the trend, and local governments are allowing floodplain development behind levees.[22] Weak floodplain regulations and government subsidies have allowed the construction of more than 25,000 new homes and other buildings on the floodplain behind new, higher levees.[23] Fortunately, not all communities along the river are shortsighted and have reevaluated their strategies concerning the flood hazard—they have moved to higher ground! Of course, this is exactly the adjustment that is appropriate.

DOWNSTREAM FLOODS OF ZONE 3: ALLUVIAL FANS AND DELTAS

Floods on alluvial fans and deltas (zone 3) are particularly hazardous because of uncertain and changing flow paths.[24] The main channel of a fan or delta during one flood may not be the same channel in a subsequent flood. Fans and deltas have distributary channels that developed as the fan or delta formed. For example, the Mississippi River Delta has had numerous distributary channels over the past several thousand years (see Figure 6.6). The present channel passes New Orleans, giving much of the charm to the riverfront city. Upstream, a potential distributary channel is closer to the Gulf of Mexico, and only a system of barriers keeps the river from moving there and inundating New Orleans. One day, the barriers may fail.

CASE study 6.3

Flooding on the Delta of the Ventura River

In 1905, the philosopher George Santayana said, "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.[25,26] Better understanding of the historical behavior of a river is, therefore, valuable in estimating its present and future flood hazards. Consider the February 1992 Ventura River Flood in southern California. The flood severely damaged the Ventura Beach Recreational Vehicle (RV) Resort, which had been constructed a few years earlier on an active distributary channel of the Ventura River Delta (Figure 6.22). Although the recurrence interval for the 1992 flood is approximately 22 years, earlier engineering studies had suggested that the area of the RV park had a 100-year flood recurrence interval.[27] What had gone wrong?

- Planners did not recognize 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 inaccurate when evaluating distributary channels on river deltas where extensive channel filling and scouring, as well as lateral movement of the channel, are likely to occur.
- Historical documents, such as maps dating back to 1855, and more recent aerial photographs showed that the channels were apparently not evaluated. Maps rendered from these documents suggest that the distributary channel passing through the RV park was, in fact, present in 1855 (Figure 6.23).

Clearly, the historic behavior of the river was not evaluated as part of the flood-hazard assessment. If it had been, the site would have been recognized as unacceptable for development, given that a historically active channel was present. Nevertheless, necessary permits were issued for development of the park, and, in fact, the park was rebuilt after the flood.

Records show that the distributary channel carried water during 1969, 1978, and 1982. Following the 1992 flood event, the channel carried floodwaters in the winters of 1993, 1995, and 1998, again flooding the RV park. During the 1992 floods, the discharge increased from less than 25 m^3 per second (~880 $ft.^3$ per second) to a peak of 1,322 m^3 per second (~46,670 $ft.^3$ per second) in only about 4 hours! This rate of flow is approximately twice as much as the daily high discharge of the Colorado River through the Grand Canyon in the summer, when river rafters navigate it. This volume is an immense discharge for a relatively small river with a drainage area of only about 585 km^2 (~226 $mi.^2$). The flood occurred during daylight, and one person was killed. However, if the flood had occurred at night, the death toll would likely have been much higher.[27]

A warning system developed for the park has, so far, been effective in providing early warning of an



< FIGURE 6.22 Flooding of California's 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. On the left, U.S. 101, the Pacific Coast Highway, is completely closed by the flood event. *(AP Photo/Mark J. Terrell)*

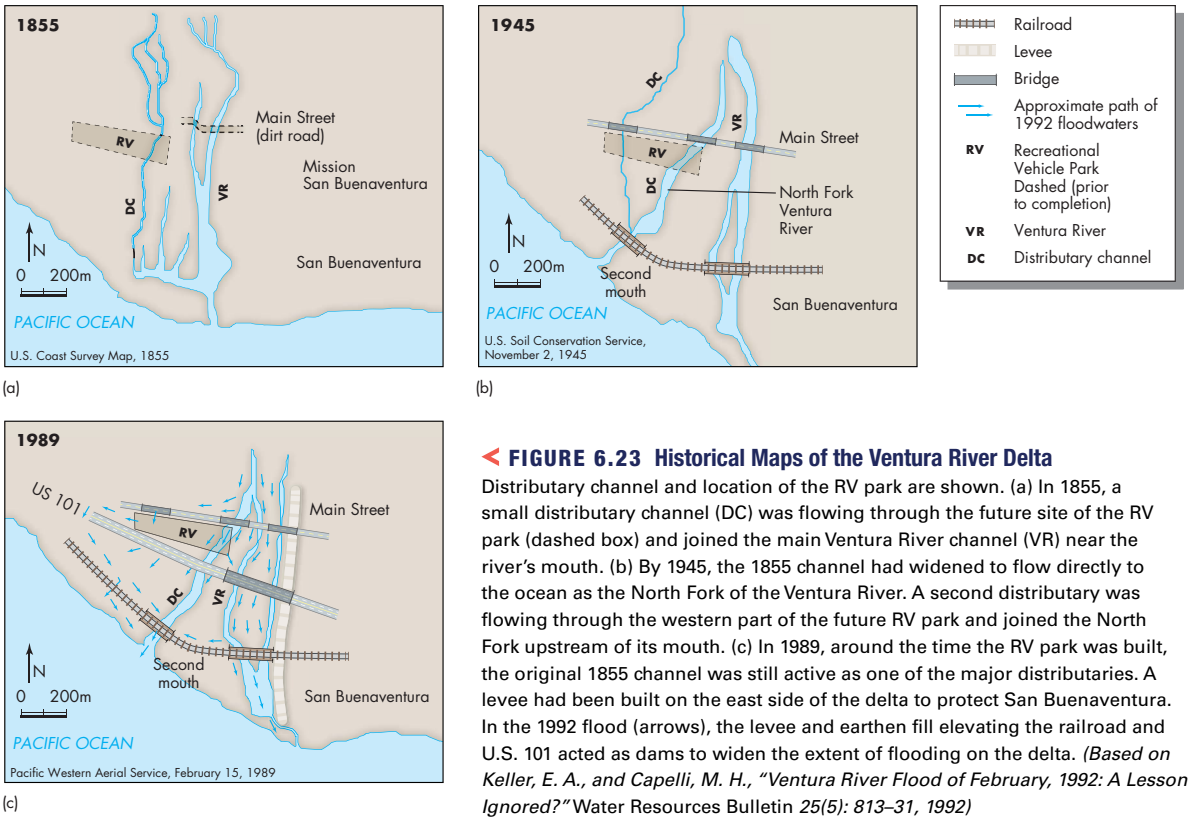


FIGURE 6.23 Historical Maps of the Ventura River Delta

Distributary channel and location of the RV park are shown. (a) In 1855, a small distributary channel (DC) was flowing through the future site of the RV park (dashed box) and joined the main Ventura River channel (VR) near the river's mouth. (b) By 1945, the 1855 channel had widened to flow directly to the ocean as the North Fork of the Ventura River. A second distributary was flowing through the western part of the future RV park and joined the North Fork upstream of its mouth. (c) In 1989, around the time the RV park was built, the original 1855 channel was still active as one of the major distributaries. A levee had been built on the east side of the delta to protect San Buenaventura. In the 1992 flood (arrows), the levee and earthen fill elevating the railroad and U.S. 101 acted as dams to widen the extent of flooding on the delta. *(Based on Keller, E. A., and Capelli, M. H., "Ventura River Flood of February, 1992: A Lesson Ignored?"* Water Resources Bulletin *25(5): 813–31, 1992)*

impending flood. The park, with or without the RVs and people, is a "sitting duck." This situation was dramatically illustrated in 1995 and 1998, when winter floods again swept through the park.[27] Although the warning system worked and the park was successfully evacuated, the facility was again severely damaged. A move is now afoot to purchase the park and restore the land to a more natural delta environment—a good move but, as of 2017, not yet a reality.

MEGAFLOODS

Disasters resulting from natural hazards occur frequently over the surface of the Earth. Often, these disasters are local to regional in extent and cause up to several billions of dollars of property loss, as well as loss of human life. Less frequently, **megafloods** may cause tens to hundreds of billions of dollars of damage and loss of human life that goes into the thousands or even the hundreds of thousands. Southern California from Los Angeles to Santa Barbara receives on average 38–51 cm (~15–20 in.) of rain annually, with more to the north, which could be plus or minus about 400 percent for a given year. Much of the rainfall in a given winter often comes in a few storms where it might rain 13 to 18 cm (~5 to 7 in.) over several days. Less frequently, it may rain for a week at a time. The so-called "Pineapple Express," moist air coming across the Pacific from the Hawaiian Islands, would occasionally make landfall in southern California, causing intense and sometimes prolonged rains (see Chapter 10). In the late 1990s, scientists discovered atmospheric rivers that were, in fact, discrete zones of high moisture that could move, as do rivers, for thousands of kilometers (Figure 6.24).[28] Recently, it was learned that the amount of moisture is truly astounding, as some of the larger atmospheric rivers contain as much water as the Amazon or 10 to 20 times as much water as carried by the Mississippi River. Furthermore, these atmospheric rivers carry high winds, and when they reach high mountains, the storms are forced upward, increasing precipitation even more.[28]

Several atmospheric rivers arrive in southern California each year; most are moderate in extent and bring welcome precipitation. However, we have

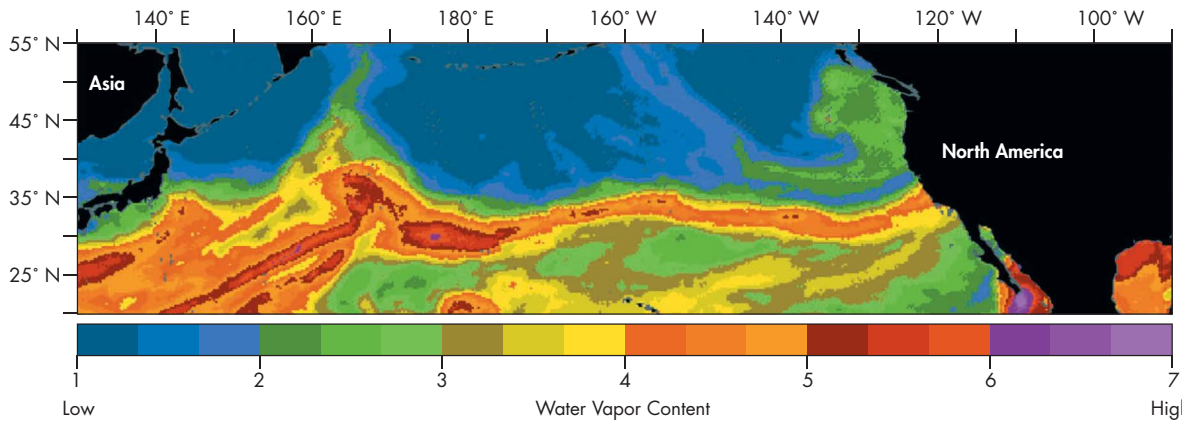


FIGURE 6.24 Atmospheric River
A relatively narrow band of concentrated moisture in the atmosphere forms a conceptual river of water flowing from western Pacific to the West Coast of North America bringing heavy precipitation. *(NOAA)*

recently learned that sometimes a series of atmospheric rivers will arrive over a period of a month or longer, bringing prolonged moderate to intense rainfall that can cause catastrophic flooding. When this occurs, the term that meteorologists and hydrologists now use is *megaflood*.

As we learn more about meteorology and what drives climate and link the science to the geologic record, we find that what were considered extremely rare, one-time-only events are, in fact, not nearly as singular as we thought. Megafloods, for example, occur in southern California every 200 years or so, and the last one struck during the winter of 1861–62. Stories about these floods are almost mythical in nature.[29] These atmospheric rivers and resulting storms and flooding caused havoc from San Diego to well north of San Francisco. Rainfall in the foothills of the Sierra Nevada Mountains and the Sacramento area was intense and prolonged, lasting over one month. Sacramento was flooded, and the state capital had to be moved to San Francisco for several months while Sacramento dried out. What happened in the Great Valley of California is difficult to imagine. Because the precipitation from the Sierra Nevada Mountains and the runoff were very high, part of the valley literally became a lake that extended for as much as 480 km (~300 mi.) along the valley, with widths exceeding 32–97 km (~20–60 mi.).[28]

Extensive flooding in 1861–62 occurred along the Ventura River, and much of the town of Ventura was flooded. Ventura in 1881 was strung out along the river delta area, which today is protected by a levee. However, a repeat of the 1861–62 event would probably threaten that levee, as well as other flood protection normally in place for large floods.[29]

The looming question becomes how likely is it that we will see a repeat of the 1861–62 floods. The more we learn about natural hazards and their long-term return period, the more we realize that these events, while rare, are not unexpected. This holds true for earthquakes, tsunamis, landslides, and other natural hazards. What do we know now about megafloods that could strike California and other regions in the future?

The Santa Barbara Channel is a natural collecting ground for sediment from runoff from streams and rivers. That sediment has been extensively studied for various reasons, including trying to discern past climate. A recent study on megaflood deposits in the channel found that, since approximately 107 B.C. to the present, there has been periodic deposition of massive flood deposits in the channel. The three most recent occurred in 1532, 1761, and 1861 (the flood for which we have most knowledge). The only time there were fewer floods was during the medieval warming period from about A.D. 950 to 1250, when Earth's surface was considerably warmer than what climatologists today call normal.[28]

Reading personal accounts of the megaflood in northern California, along with extensive references to southern California as well, provides sobering thoughts about what might occur in the future. The problem is that our flood programs simply are not designed for the type of flood that occurred in 1861–62. Such a flood was considered an unimaginable event that is unlikely to occur again. Unfortunately, it is likely that such floods will occur, even though the return period between events may be several hundred years.[29]

The U.S. Geological Survey, in conjunction with many other agencies and people, is working on storm scenarios for events such as the one in 1861–62. This approach allows us to work through a trial event and test our emergency response. Some people say that it is impossible to plan for a megaflood that might have total damages in excess of $500 billion. The actual megaflood scenario run for planning purposes is quite a bit smaller than the 1861–62 event. The scenario is based on a 23-day storm period in which two major storms caused by atmospheric rivers strike southern California: a 10-day storm, then a reprieve for about five days, followed by another eight-day storm. Keep in mind that, while two-thirds of the water resources in California are in the northern part of the state, three-fourths of the people live in southern California. The scenario suggests that initial damages directly to property would be on the order of $400 billion, of which less than 10 percent could be recovered by public and commercial insurance companies. The report states that if business interruptions, evacuations, and so on are taken into account, total damages could be on the order of $700 billion, about three times the predicted losses for a large earthquake on the San Andreas fault that impacts the Los Angeles area.

So, what does all this doom-and-gloom news mean? It means that extreme events are likely rather than unlikely—only the time frame may be long between such events. Realizing this, it would be prudent to think about the consequences of a future megaflood. In many cases, an option is to look more closely at flood-proofing (discussed in more detail in Section 6.7). Flood walls can be decorative and built around critical facilities such as airports, train stations, and other vulnerable places. Individual companies can also consider flood-proofing buildings with specially designed flood doors that can be closed to keep floodwaters out for a period of time. So far, scientists think that the number of megafloods will not increase significantly due to climate change, but the intensity may increase because warmer seawater would mean more water vapor, which can be translated into more rainfall.

6.2 CHECK your understanding

1. Define flooding.
2. What are flash floods and where are they likely to occur?
3. Why are downstream zone 2 floods potentially so dangerous?
4. Contrast the alluvial fans and delta flows of zone 3 with zone 2 river flows.
5. What are atmospheric rivers and megafloods?

6.3 Geographic Regions at Risk for River Flooding

Water covers about 70 percent of Earth's surface and is critical to supporting life on the planet. However, water can also cause a significant hazard to human life and property in certain situations, such as a flood. Analysis of the global impact of flooding from 1980 to 2012 suggests annual losses worldwide of about 6,000 lives lost and economic losses of $23 billion.[30] Although the number of floods and the number of people killed or affected, along with economic loss, is highly variable from region to region (e.g., Asia compared to the Americas, Europe, or Africa), the greatest losses of life and property, as well as people affected, is in Asia. This number reflects the very large populations in Asia that live along rivers in areas with a climate characterized by intense precipitation. As a result, both exposure (people and property at risk) and vulnerability (degree of loss due to exposure) are high, resulting in a relatively high risk.

At the global level, the vulnerability from 1990 to 2010 to flooding declined. This is in spite of the fact that total global impacts of flooding remain very significant and, in many cases, is rising in particular areas. Rising incomes worldwide in the past several decades has reduced vulnerability to flooding, resulting in fewer deaths and direct economic losses. Vulnerability (recall that vulnerability is the degree of loss due to exposure) has been historically high in developing countries, compared to developed countries, but that is changing. Vulnerability of developing countries compared to developed countries (high income countries) is converging (especially since about 2000) as a result of developing countries (low income countries) successfully lowering their vulnerability through a mixture of structural and nonstructural flood control and other adaptation measures. The number of lives lost as a percent of exposed population in low income countries compared to high income countries has converged since about 1995. The rate of deaths in 1995 was much higher in developing countries than in developed countries. Death rates remain higher today in developing countries, but differences are much less.[30]

Floods in the United States were the number one disaster during the twentieth century; on average, 80 lives are lost each year from river flooding. Tragically, developing countries suffer much greater losses because of a lack of monitoring facilities, warning systems, adequate infrastructure and transportation systems, and effective disaster relief.

Virtually all areas of the United States are vulnerable to floods. A single flood can cause billions of dollars of property damage and hundreds of lives to be lost (Table 6.1). Not listed in Table 6.1 are the hundreds of

TABLE 6.1 Selected River Floods in the United States

Year	Month	Location	Number of Lives Lost	Property Damage (Millions of Dollars)
1937	Jan.–Feb.	Ohio and lower Mississippi River basins	137	418
1938	March	Southern California	79	25
1940	August	Southern Virginia and Carolinas and eastern Tennessee	40	12
1947	May–July	Lower Missouri and middle Mississippi River basins	29	235
1951	June–July	Kansas and Missouri	28	923
1955	December	West Coast	61	155
1963	March	Ohio River basin	26	98
1964	June	Montana	31	54
1964	December	California and Oregon	40	416
1965	June	Sanderson, Texas (flash flood)	26	3
1969	Jan.–Feb.	California	60	399
1969	August	James River basin, Virginia (flash flood)	154	116
1971	August	New Jersey	3	139
1972	June	Rapid City, South Dakota (flash flood)	242	163
1972	June	Eastern United States	113	3,000
1973	March–June	Mississippi River	0	1,200
1976	July	Big Thompson River, Colorado (flash flood)	143	35
1977	July	Johnstown, Pennsylvania	76	330
1977	September	Kansas City, Missouri, and Kansas	25	80
1979	April	Mississippi and Alabama	10	500
1983	September	Arizona	13	416
1986	Winter	Western states, especially California	17	270
1990	Jan.–May	Trinity River, Texas	0	1,000
1990	June	Eastern Ohio (flash flood)	21	Several
1993	June–Aug.	Mississippi River and tributaries	50	15,000
1997	January	Sierra Nevada, Central Valley, California	23	Several hundred
2001	June	Houston, Texas, Buffalo Bayou (coastal river)	22	2,000
2004	Aug.–Sept.	Georgia to New York and the Appalachian Mountains	13	400
2006	June–July	Mid-Atlantic (Virginia to New York)	16	1,000
2008	June	Mississippi River System	24	9,000
2010	May	Cumberland and other rivers (Nashville, Tennessee region)	24	1,500
2013	September	Colorado Front Range (flash flood)	8	Several hundred
2015	Late May	Houston, Texas area (flash flood)	6	45
2015	September	Utah-Arizona border area (flash flood)	20	Not evaluated
2016	August	Louisiana	13	10,000
2017	August	Houston, Texas area (long duration high intensity rainfall)	~50	100,000
2018	May	Ellicot City Maryland (flash flood)	2	Several million
2018	August	Hawaii Islands (flooding Hurricane Lane)	4	Prop damage >3 billion (3,000 million)

small drainage basins that experienced flooding during the time period covered by the table. For example, central Texas had six major episodes of flash flooding during the five-year period, with damage totals exceeding $10 million.[31] By realizing how many more areas are at risk, we can recognize how serious the flood hazard can be and how the hazard might be minimized.

6.3 CHECK your understanding

1. Why are flood losses so great in Asia?
2. Examine Table 6.1. Which flood caused the most deaths? Which caused the greatest economic loss? Can you make any generalizations about zone 1 and zone 2 floods?

6.4 Effects of Flooding and Linkages between Floods and Other Hazards

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 because of the flood.[11] Primary effects include injury, loss of life, and damage caused by swift currents, debris, and sediment to farms, homes, buildings, railroads, bridges, roads, and communication systems. Erosion and deposition of sediment during a flood may also involve considerable loss of soil and vegetation.

Secondary effects may include short-term pollution of rivers, hunger and disease, and displacement of persons who have lost their homes. Failure of wastewater ponds, treatment plants, sanitary sewers, and septic systems often contaminate floodwaters with disease-causing microorganisms. For instance, in June 1998, flooding from record rainfall in southern New England caused partially treated sewage to float into Boston Harbor, and many areas of Rhode Island's Narragansett Bay were closed to swimming and shell fishing because of sewage-contaminated floodwaters.

Several factors affect the damage caused by floods:

- Land use on the floodplain
- Depth and velocity of floodwaters
- Rate of rise and duration of flooding
- Season of the year in which flooding takes place
- Quantity and type of sediment transported and deposited by floodwaters
- Effectiveness of forecasting, warning, and evacuation.

In general, commercial and residential properties may experience more damage than land used for farming, ranching, or recreation. On the other hand, long-duration flooding during the growing season may completely destroy crops, whereas the same flooding of cropland during winter months may be less damaging. For downstream floods, accurate flood forecasts by the National Weather Service sometimes provide the warning time needed to build temporary levees, remove property, or evacuate residents from the hazard area.

Floods can be a primary effect of hurricanes (Chapter 10) and a secondary effect of earthquakes (Chapter 3) and landslides (Chapter 7). Although it may seem counterintuitive, floods may also cause fires in urban areas. Floodwaters may produce shorts in electric circuits and erode and break natural gas mains, resulting in dangerous fires.[11] For example, the 1997 flood in Grand Forks, North Dakota, caused a fire that burned part of the city center. Floods may also contribute to coastal erosion, especially in estuaries and deltas where high water levels may allow storm waves to reach further inland (Chapter 11). River processes in general may also lead to landslides where stream banks are eroded.

6.4 CHECK your understanding

1. What are the major factors that influence the damage a flood causes?
2. Differentiate, with examples, the primary and secondary effects of flooding.

6.5 Natural Service Functions of Floods

Although flooding is considered to be a natural hazard and sometimes a disaster, it is important to remember that "flooding" is no more than the natural process of overbank flow. It becomes a hazard only when people live or build structures on the floodplain or try to cross a flooding river. In fact, there are many benefits to periodic flooding. Floods provide water resources, transport fertile sediment for farming, benefit aquatic ecosystems, and, in some cases, help keep land above sea level.

WATER RESOURCES AND FLOODING

Water security for humans and ecosystems is one of the major environmental concerns of the twenty-first century. Surface water in the form of rainfall and snow

supplies much of the runoff that fills our reservoirs and infiltrates the land to renew groundwater resources. Runoff (especially in the southwestern USA) often comes from high-intensity rainfall that produces high-flow events (floods) or snowmelt that also produces high amounts of spring and summer runoff. Thus, the process of flooding upstream of reservoirs is an important source of water that is controlled and released for agriculture and of water for human consumption. Water from reservoirs may be released to flow down river valleys to support fisheries and augment groundwater resources as it seeps into the river channel. Water supply is intimately related to the concept of the **Water–Energy–Food Nexus** that consists of the complex linkages between water, energy, and agriculture (Figure 6.25). Water supply from runoff to rivers is stored in reservoirs where it provides a number of services, such as helping provide the water supply for human consumption, energy for power, and water to irrigate crops. Increasing human population in a changing climate is raising concerns about water, energy, and food security. The water–energy–food nexus is proving to be a useful concept in the discussion of resource use from the regional to global scale. The nexus is linked to the flood hazard because as we plan the use of water for energy production, urban water supply, and agriculture, the level of flood control from reservoirs is constantly changing. If a reservoir is managed primarily for flood control, then the water for other uses such as agriculture will be impacted as lake level is kept low to accommodate storage space for unexpected upstream floodwater or change in snow runoff. If the reservoir is managed for agriculture, then storage space may be reduced early in the season to provide late season water for irrigation, which lowers the flood protection aspect.

FERTILE LANDS

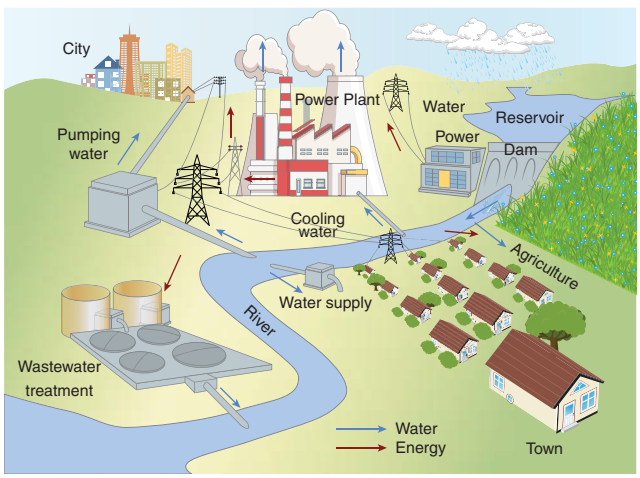
Floodplains are built by floods. As the river overflows its banks, the velocity of flow decreases, and fine sand, silt, clay, and organic matter are deposited on the floodplain. These periodic deposits explain why floodplains are some of the most fertile and productive agricultural areas in the world. Recognizing the value of floods, the ancient Egyptians planned their farming around regular flooding of the Nile. They learned that the higher the flood, the better that year's harvest would be, and even referred to flooding as "The Gift of the Nile." Unfortunately, with completion of the Aswan Dam in 1970, the river's annual floods in Egypt have effectively been stopped. Now farmers must use fertilizer to successfully grow crops on what was once naturally fertile land.

RIPARIAN AND AQUATIC ECOSYSTEMS

Riparian (of the river) refers to the banks and other landforms that are heavily influenced by a river. The riparian area along a stream or river has different vegetation and animals than adjacent upland areas. Floods form and maintain stream banks and, thus, the riparian zone. Floods help flush out stream channels, scouring pools and debris, such as boulders, logs, and tree branches that may have accumulated. Such events generally have a positive effect on stream and riparian ecosystems. Floods also sweep nutrients and other food supplies downstream, potentially improving the environment for downstream aquatic organisms.

SEDIMENT SUPPLY

In some cases, flooding is needed simply to keep the elevation of a landmass above sea level. For example, the Mississippi River Delta in southeastern Louisiana is built



< FIGURE 6.25 Water–Energy–Food Nexus
Linkages between stored river water and service function that help produce water, energy and food security. *(Modified from US DOE)*

up of sediment deposited as the Mississippi River repeatedly overflowed its banks through time. Construction of levees along the Mississippi has all but eliminated flood sedimentation, with the result that much of the delta is now slowly subsiding (see Chapter 8). Some areas, such as the city of New Orleans, are beneath sea level and are regularly threatened by hurricanes that cause both coastal and river flooding (see Chapter 10).

6.4 CASE study Experimental Floods on the Colorado River

The Grand Canyon of the Colorado River (Figure 6.26) provides a good example of the natural service functions provided by periodic flooding and delivery of sediment. In 1963, the Glen Canyon Dam was built upstream from the Grand Canyon (Figure 6.27). Construction of the dam drastically altered both the natural pattern of flow and channel processes downstream—from a hydrologic viewpoint, the Colorado River was tamed.



FIGURE 6.26 The Colorado River in the Grand Canyon at Marble Canyon *(National Park Service)*

Before the Glen Canyon Dam was built, the river reached maximum flow in May or June during the spring snowmelt, and flow receded during the remainder of the year, except for occasional flash floods caused by upstream rainstorms. During periods of high discharge, the river had a tremendous capacity to transport sediment and vigorously scour its channel. This competence was evident when the river moved large boulders from the rapids. Shallow areas in the river, which become rapids, develop where the river flows over an alluvial fan or debris flow deposits delivered from tributary canyons. As the summer low flow approached, the river was able to carry less sediment and deposited sand and gravel along the channel to form large bars and terraces, known as *beaches* to people who raft the river.

After the dam was built, the mean annual flood, determined by averaging the highest flow each year, was reduced by about 66 percent, and the 10-year flood was reduced by about 75 percent. The dam also trapped sediment, greatly reducing the sediment load immediately downstream from the dam. The sediment load farther downstream is less reduced because tributary channels continue to add sediment to the channel.[32]

The Colorado River's changed flow conditions in the Grand Canyon have greatly altered both the channels and the banks. Rapids may be becoming more dangerous because large floods are no longer moving many of the boulders from shallow areas of the channel. In addition, some of the large sandbars are disappearing because the river is deficient in sediment below the dam. The river is eroding this valuable habitat.

Changes in the river flow, mainly the loss of high flows, have also shifted vegetation. Before the dam was built, three nearly parallel belts of vegetation were present on the slopes above the river. Adjacent to the river and on sandbars, plant growth was scoured by yearly spring floods. Above the high waterline of the annual floods were clumps of thorned trees, such as mesquite and acacia, mixed with cactus and Apache plume. Higher yet was a belt of widely spaced brittlebush and barrel cactus. For the first 20 years following its completion, the dam significantly reduced the spring floods. The absence of high, scouring flows allowed plants not formerly found in the canyon, including tamarisk (salt cedar) and indigenous willow, to become established in a new belt along the riverbanks.

In June 1993, a record snowmelt in the Rocky Mountains forced the release of about three times the normal amount of water from the dam. This release was about the same volume as an average spring flood before the dam was built. The resulting flood scoured sediment from the riverbed and riverbanks, which replenished the sandbars, and it scoured out or broke off some of the tamarisk and willow trees. This large



< FIGURE 6.27 The Colorado River Basin

Glen Canyon Dam, just south of the Arizona-Utah state line, divides the Colorado River basin (shaded areas) in half for management purposes. Flaming Gorge Reservoir in Wyoming and Lake Powell in Utah store runoff in the Upper Basin, and Lake Mead on the Nevada–Arizona state line stores runoff in the Lower Basin. The delta, at the head of the Gulf of California, was once a large wetland area in Mexico. Today, it is severely degraded because of the diversion of Colorado River water for other uses in the United States.

release of water was, thus, beneficial to the river, and it emphasizes the importance of large floods in maintaining the system in a more natural state.

Three years later, a "test flood" was released from the dam as an experiment to redistribute the sand supply. The experimental flood formed 55 new beaches and added sand to 75 percent of the existing beaches. It also helped rejuvenate marshes and backwaters, which are important habitats for native fish and some endangered species. The experimental flood was hailed a success, although a significant part of the new sand deposits subsequently eroded away.

Although the 1996 test flood distributed sand from the channel bottom and banks to sandbars, tributary streams added little new sand, since they were not in flood. The sand scoured from the river below the dam is a limited, nonrenewable source that cannot resupply sandbars on a sustainable basis. Two additional experimental floods were run down the canyon in 2004 and 2008 to learn more about river processes and sand supply. Evaluation of the hydrology of the Colorado River and tributaries suggests that the opportunity to replenish sand on the beaches occurs periodically, but high flow releases must be carefully timed to restore or recreate river flow and sediment transport conditions which are as close as possible to those that existed prior to the construction of Glen Canyon Dam.[33,34]

One final effect of the Glen Canyon Dam has been to increase the number of people rafting through the Grand Canyon. Although rafting is now limited to about 20,000 people annually, the rafters' long-range impact on canyon resources is bound to be appreciable. Prior to 1950, fewer than 100 explorers and river runners had made the trip through the canyon.

We must concede that the Colorado River is a changed river. Despite the three experimental floods that reversed some of the changes, river restoration efforts cannot be expected to return the river to what it was before construction of the dam.[33–35] On the other hand, better management of the flows and sediment transport will improve and help maintain the river ecosystem.

6.5 CHECK your understanding

1. What are the main natural service functions of flooding?
2. River flow contributes to our water resources, but also causes damaging flooding. Discuss the implications of this dichotomy.
3. What is the water–energy–food nexus, and why is it important to understanding the flood hazard?
4. What were the main purposes of the three experimental floods through the Grand Canyon?

6.6 Human Interaction with Flooding

Unlike some other natural hazards, human activity can significantly affect river processes, including the magnitude and frequency of flooding. Land-use change and dam construction may affect a stream's sediment supply, which can, in turn, alter its gradient and the shape of its channel. Urbanization, with its addition of paved areas, buildings, and storm sewers, greatly affects the flood hazard of an area.

LAND USE CHANGES

Streams and rivers are open systems that generally maintain a rough *dynamic equilibrium*, that is, an overall balance between the work that the river does transporting sediment and the load that it receives. Sediment is supplied from tributaries and from earth material that moves down hillsides to the stream. A stream tends to have the gradient and cross-sectional shape that provide the flow velocity needed to move its sediment load.[35]

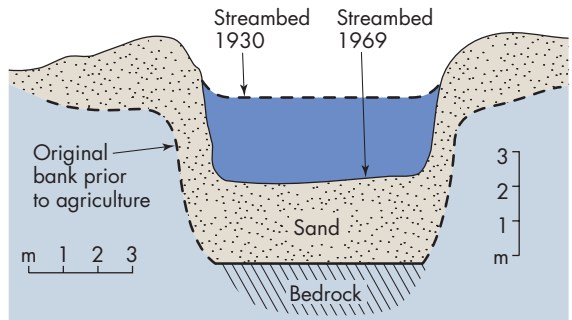
An increase or decrease in the amount of water or sediment received by a stream usually brings about changes in its gradient or cross-sectional shape, effectively changing the velocity of the water. The change in velocity may, in turn, increase or decrease the amount of sediment carried in the system. Therefore, land-use changes that affect a stream's sediment or water volume may set into motion a series of events that results in a new dynamic equilibrium.

Consider, for example, a land-use change from forest to an agricultural row crop, such as corn. Because croplands have higher erosion rates, they provide more sediment to the stream. At first, the stream will be unable to transport the entire load and will deposit sediment, increasing the channel gradient. The new, steeper slope of the channel will increase the velocity of water and allow the stream to move more sediment. If we assume that the base level remains constant, this process will continue until the stream is flowing fast enough to carry the new load. A new dynamic equilibrium may be reached, provided the rate of sediment accumulation levels off and the channel gradient and shape can adjust before another land-use change occurs. Suppose the reverse situation now occurs; that is, farmland is converted to forest. The sediment supply to the stream will decrease, and less sediment will be deposited in the channel. Erosion of the channel will eventually lower the gradient, which, in turn, will lower the velocity of the water. The predominance of erosion over deposition will continue until equilibrium is again achieved between sediment supply and work done.

The sequence of change just described occurred in parts of the southeastern United States during the past two and a half centuries. On the Piedmont, an area of rolling hills between the Appalachian Mountains and the Atlantic Coastal Plain, most forests were cleared for farming by the 1800s. The land-use change from forest to farming accelerated soil erosion and subsequent deposition of sediment in local streams. This caused the channel that existed before farming to begin to fill with sediment. After 1930, the land reverted to pine forests, and this change, in conjunction with soil conservation measures, reduced the quantity of sediment delivered to streams. Thus, by 1969, formerly muddy streams choked with sediment had cleared and eroded their channels (Figure 6.28).

DAM CONSTRUCTION

Dams and their accompanying reservoirs often have multiple purposes, including water for urban and agricultural areas, recreation, generation of electricity, and flood control. It is difficult to maximize different uses at the same time. Reservoir storage is important for flood control. A full reservoir provides no flood control. A reservoir that lowers storage for flood control water may not be optimal for agriculture. There are about 8,000 large dams in the United States; California alone has several hundred large dams. Almost all dams in the United States are over 50 years old, and, thus, dams are part of the aging, deteriorating infrastructure of the United States. Dam failures are rare events that are often linked to the geology of the dam site. Examples are

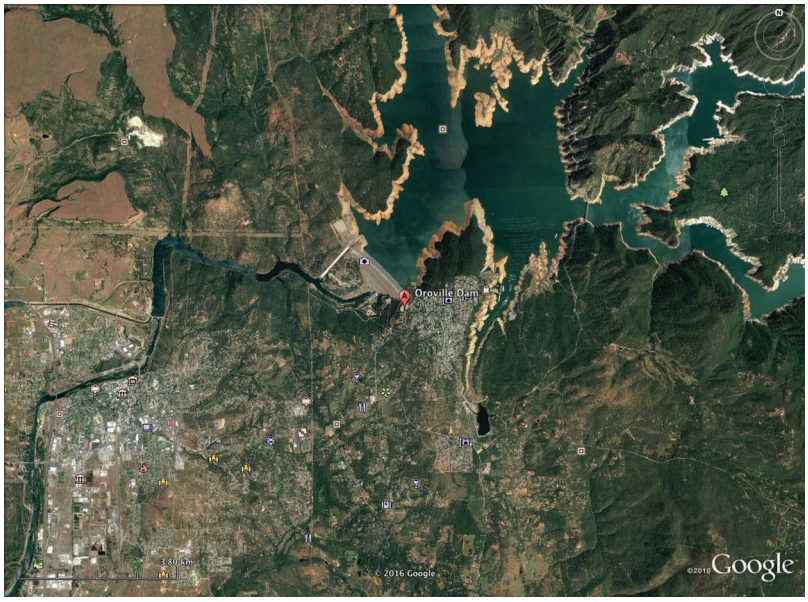


▲ FIGURE 6.28 Changes in a Streambed from Changes in Land Use

Cross-section of a stream at the Mauldin Millsite, Georgia, in 1969 showing changes in channel position through time. Land use changed from natural forest to agriculture, which increased stream sedimentation until 1930, and then back to woodland, which increased stream erosion. *(Trimble, S. W.,* Culturally Accelerated Sedimentation on the Middle Georgia Piedmont. *Master's thesis, Athens, Georgia: University of Georgia, 1969. Reproduced by permission of author.)*

the St. Francis Dam failure in 1928, 50 km (30 mi.) northwest of Los Angeles in San Francisquito Canyon, a tributary of the Santa Clara River. The floodwaters rushed down the Santa Clara River, killing about 500 people and washing many out to the ocean. Constructed as part of the water supply from the Sierra Nevada to Los Angeles, the concrete dam was about 60 m (200 ft. high). The geology of the dam site included landslide-prone schist and sedimentary rocks that could dissolve when wet, both separated by a fault zone with water-soluble minerals. Another example is the Teton Dam, which failed in 1976, just as it was nearly filled. The earthfill dam, consisting of layers of compacted soil, was about 90 m (300 ft. high), and failure was linked to the geology of the foundation which consisted of fractured volcanic rock that had the potential to transmit water beneath the dam. There were significant geologic studies of the site prior to construction. The St. Francis Dam failure was remembered, and detailed geologic evaluations were completed. Some adverse geologic conditions were recognized before and during construction, but the decision to proceed to build the dam was given. Failure, when it occurred, was swift; the dam collapsed, and a wall of water rushed down the Teton River Valley, killing 11 people and causing about $2 billion in damages.

Significant safety issues of dams (under normal operation) are water containment and control of water that is released. Dams have gates and spillways to lower lake levels in times of upstream runoff (floods) that can quickly fill some reservoirs. Dams also have emergency features (secondary spillways) to safely lower reservoir water levels when necessary. When a lot of water has to be released, downstream flooding may occur. Unfortunately, many cities are sited downstream of dams, presenting a potential flood hazard. The worst dam failure in U.S. history occurred in 1889 when floodwaters from a collapsed dam roared through Johnstown, Pennsylvania, killing about 2,000 people. The private earthfill dam had an inadequate, partly plugged emergency spillway that could not handle the heavy runoff that fell prior to the failure. The dam filled, and water overtopped the structure, quickly eroding it and causing the dam to collapse. Alarms had been sounded about the safety of the dam, and an inspection that revealed major flaws was completed. Unfortunately, the results of the inspection were ignored! This is an all too common decision that was repeated in 2017 when a major flood disaster was narrowly avoided in Oroville, California. The Feather River runs through the Oroville area, and there has been major development downstream of the Oroville Dam (Figure 6.29), an aging structure constructed in 1968. The dam is an earthfill structure and is the highest dam (235 m; 770 ft.) in the United States. The Oroville Dam is designed for water supply, agriculture, flood control, and electrical power. A multiple-year drought ended for Northern California in the winter of 2016–17. Intense, long-duration storms from the Pacific Ocean filled reservoirs. When Lake Oroville is nearly filled, water flows down a concrete spillway, lowering the lake level. Rock strength and the state of erosion were not evaluated when the spillway was constructed decades go, and the concrete and, in large areas under the spillway, highly weathered and fractured metamorphic rock was not anchored to fresh, strong



< FIGURE 6.29 Oroville, California Dam Site

The spillway is the white bar just northwest of the dam. Notice the extensive development along the Feather River downstream of the dam. *(2016 Google Earth Image)*

rock. Fresh rock is intact and relatively unweathered; it is the desired substrata for dams and spillways. If weathered rock is present, it must be treated or scraped off, exposing strong, competent rock. Fortunately, this was done for the dam foundation. There is also an emergency spillway with a 10 m (30 ft.) high concrete wall at the top (to protect the spillway). The emergency spillway is not lined and flows over the same highly fractured, weathered weak rock that is under the main concrete-lined spillway (Figure 6.30). Concern over the viability of the emergency spillway was raised in 2005, but no action was taken (the same all too common decision that led to the Johnstown flood). Suddenly, in early 2017, the main spillway failed when a growing hole in the concrete opened and began eroding. A large portion of the spillway failed, and a decision was made to use the emergency spillway. The main dam was not threatened. When the emergency spillway began eroding much faster than expected, it was feared that if the protective wall at the top eroded, a large volume of water would be released downstream, causing serious flooding. Urgent repairs to the emergency spillway were attempted by dropping large rocks below the concrete wall at the top of the emergency spillway. Fearing that a large, damaging flood might be imminent, 200,000 people were quickly evacuated downstream of the dam. A disaster was avoided, but, perhaps, by a narrow margin. Following the emergency, repairs have started on both spillways. If proper repairs had been taken, both the Johnstown flood and the Oroville emergency could have been avoided. Repairs as of 2018 are expected to exceed $1 billion.

URBANIZATION AND FLOODING

Human activities increase both the magnitude and the frequency of floods in small urban drainage basins of a few square kilometers. The rate of increase is determined by the percentage of the land that is covered with roofs, pavement, and cement, referred to as *impervious cover* (Figure 6.31), and the percentage of the area served by storm sewers. In most urban areas, storm sewers start at drains along the sides of streets and carry runoff to stream channels much more quickly than in natural settings. Therefore, impervious cover and storm sewers are collectively a measure of the degree of urbanization. An urban area with 40 percent impervious cover and 40 percent of its area served by storm sewers can expect to have about three times more floods of a given magnitude than before urbanization (Figure 6.32). This ratio applies to floods of small and intermediate frequency. However, as the size of the drainage basin increases, large floods with frequencies of approximately 50 years are less affected by urbanization.

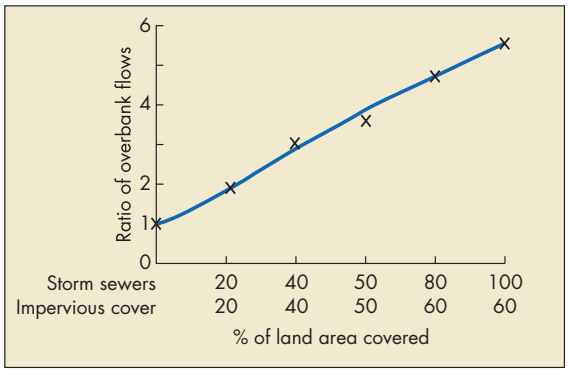
Floods are a function of the relationship between rainfall and runoff, which is significantly changed by urbanization. One study showed that urban runoff from larger storms is nearly five times that of pre-urban conditions.[36] However, the extent of urban flooding is related not only to the peak discharge of a flood but also to the condition of the drainage system. For example, long periods of only moderate precipitation can also cause flooding if storm drains become blocked with sediment and storm debris. In this case, water begins to pond behind a debris dam, causing flooding in low areas. An analogy is water rising in a bathtub when the drain becomes partly blocked by soap.



FIGURE 6.30 Orville Dam Main Spillway Damaged by Erosion
Large holes were eroded in the concrete spillway. The spillway was poorly bonded to the blue and rust-red colored metamorphic rock when the spillway was constructed decades ago. The rust-red rock is more highly weathered and weaker than the blue rock. Both are highly fractured. *(California Department of Water Resource)*

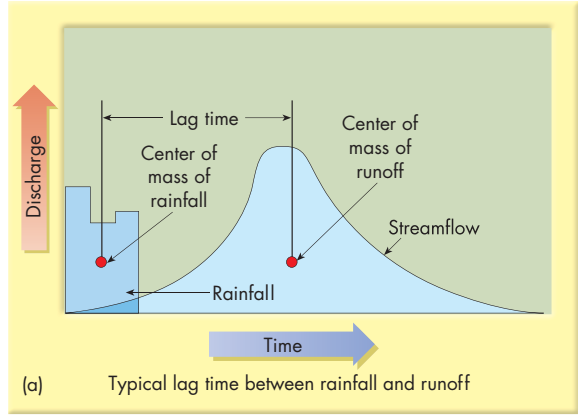


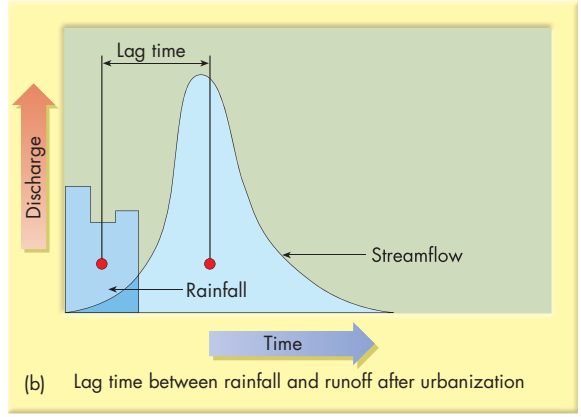
FIGURE 6.31 Urbanization Increases Impervious Cover
Aerial view of Santa Barbara, California, which, like most other U.S. cities, has much of its land surface covered by paved streets, sidewalks, parking lots, and buildings. This impervious land cover blocks the infiltration of water and increases surface runoff. *(Edward A. Keller)*



▲ FIGURE 6.32 Overbank Flooding Before and After Urbanization

Relationship between the ratio of overbank flows (after urbanization compared to before urbanization) and the primary measures of urbanization: the percentage of area with impervious cover and storm sewers. For example, a ratio of 3 to 1, or simply 3, means that after urbanization there are three floods for every one that took place before urbanization, or that flooding is three times as common after urbanization. Note that the percentage of the land area with impervious cover typically reaches its maximum of 60 percent when about 80 percent of the urban area has storm sewers. The percentage of impervious cover then stays the same as the storm sewer system is completed for the community. This graph shows that as the degree of urbanization increases; the number of overbank flows per year also increases. *(Based on Leopold, L. B., "Hydrology for Urban Landplanning—A Guidebook on the Hydrologic Effects of Urban Land Use," U.S. Geological Survey Circular 554, 1968)*



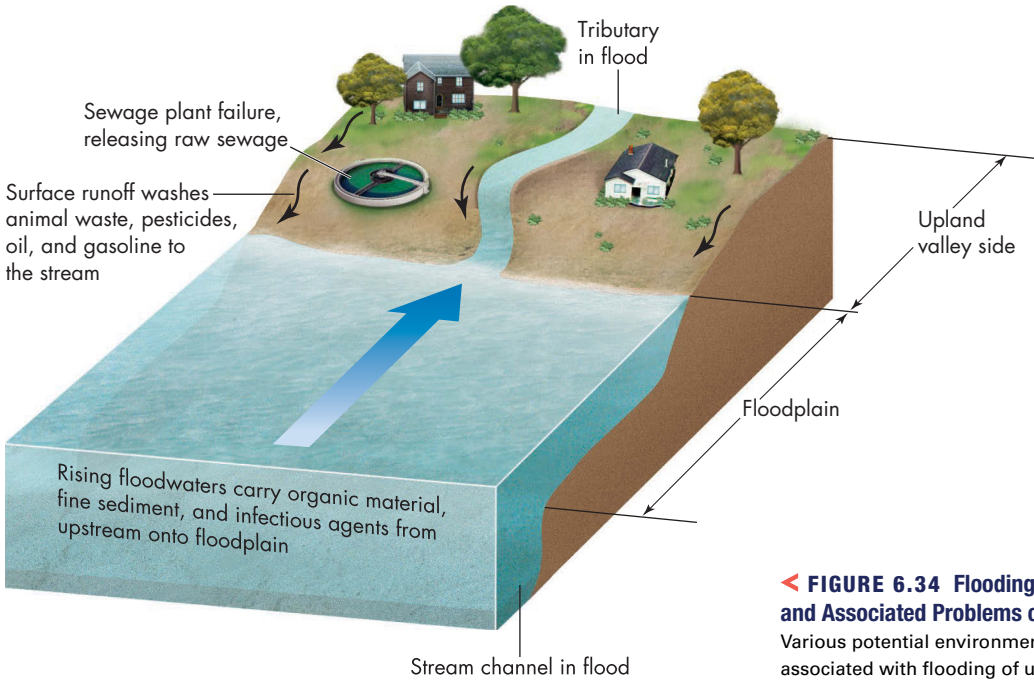


▲ FIGURE 6.33 Urbanization Shortens Lag Time

Generalized hydrographs. (a) Hydrograph shows the typical lag between the time when most of the rainfall occurs and the time when the stream floods. (b) Here, the hydrograph shows the decrease in lag time and an increase in discharge because of urbanization. *(Based on Leopold, L. B., U.S. Geological Survey Circular 559, 1968; modifed after Tarbuck, E. J., and Lutgens, F. K.,* Earth: An introduction to physical geology, *8th ed. Upper Saddle River, NJ: Pearson Prentice Hall, 2005)*

Besides increasing runoff and flooding frequency, urbanization affects how rapidly floods develop. Before urbanization, a considerable delay, or *lag time*, existed between when most rainfall occurred and the subsequent flooding (Figure 6.33a). A comparison of hydrographs before and after urbanization shows that there is a significant reduction in lag time after urbanization (Figure 6.33b). Short lag times, referred to as *flashy discharge*, are characterized by rapid rise and fall of floodwater. Urbanization also affects stream discharge by greatly reducing stream flow during the dry season. Normally, urban streams continue to flow during dry periods because groundwater seeps into the channel. However, because urbanization significantly reduces infiltration into the drainage basin, less groundwater is available to seep into streams. This reduced flow affects both water quality and the appearance of a stream. Very low discharge effectively concentrates pollutants in the water.[4] Some of these pollutants, such as nitrogen and phosphorus from fertilizers, can cause the growth of large amounts of algae and harm aquatic life.

During periods of surface runoff and flooding, pollutants from urban lands may enter streams as fine sediment, and wastewater treatment plants may be overwhelmed and fail (Figure 6.34). Impervious cover and storm sewers are not the only forms of construction that can increase flooding. Some flash floods occur because bridges built across small streams block the passage of floating debris, which then forms a temporary dam. When the debris breaks loose, a wave of water moves downstream. This sequence of events has been repeated in many flash floods around the world. All too often, the supports for bridges are too close together or drainage pipes under roads, referred to as culverts, are too small to allow large debris to pass through; instead, they become temporary dams that either cause flooding upstream or, when they fail, cause flash flooding downstream.



< FIGURE 6.34 Flooding in Urban Areas and Associated Problems or Hazards
Various potential environmental problems are associated with flooding of urban streams.

Flooding in streams and rivers flowing through large cities in poor countries, where high concentrations of people are living in substandard housing (shanties) and encroaching on a floodplain, can result in a catastrophe. The combination of population pressure and poor land-use choices in Manila, the capital of the Philippines, resulted in a catastrophic event in late September 2009 when a tropical storm produced about 44 cm (~18 in.) of rain in a 12-hour period.[37] Swirling floodwaters inundated poor urban areas. Flooding also occurred in middle-class areas, as well as in some commercial areas. The population of Manila had grown to more than 11 million by the time the flooding occurred, with about one-fifth of the people living in crowded shantytowns on a wide floodplain with little or no infrastructure. They had no protection when the Marikina River flooded. Hundreds of people were killed, drowned in their houses and cars and in shopping malls (Figure 6.35).



> FIGURE 6.35 Flood Damage
Urban flooding east of Manila in the Philippines was devastated by floodwaters in late September 2009. The combination of a high-magnitude storm in a densely populated city with many thousands of people living on a floodplain produced a catastrophe. *(Pat Roque/AP Images)*

6.6 CHECK your understanding

1. How does changing land use from forest cover to cropland affect stream channel sediment balance?
2. Why might a stream channel erode below a dam?
3. Why do impervious covers and storm sewers define the degree of urbanization?
4. What are the main effects of the urbanization of small drainage basins on flooding?

6.7 Minimizing the Flood Hazard: Structural Control to Floodplain Management

Historically, particularly in the nineteenth century, humans have responded to floods by attempting to prevent them by modifying streams and rivers. Physical barriers, such as dams and levees, have been created, or the shape of the stream has been changed by widening, deepening, or straightening the channel. The channel shape is changed so that a stream will drain the land more efficiently. Every new flood-control project has the effect of luring more people to the floodplain in the false hope that the flood hazard is no longer significant. We have yet to build a dam or channel capable of controlling the heaviest runoff, and, when the water finally exceeds the capacity of the structure, flooding may be extensive.[11,38]

THE STRUCTURAL APPROACH

Physical Barriers Measures to prevent flooding include construction of physical barriers, such as earthen *levees* and concrete flood walls (Figure 6.36). Unfortunately, the potential benefits of these physical barriers are often lost because of increased development on the floodplains that they are supposed to protect. Also, older levees are often in poor condition and subject to failure during floods. Levee failures can damage agricultural land by creating high-energy flows that erode topsoil and deposit a layer of sand and gravel on otherwise fertile soil in the floodplain.

Capture and control of storm water runoff is an important strategy for reducing urban flooding. For example, specially designed parking lots can temporarily store runoff that is released slowly, reducing the rate of runoff to storm sewers and urban streams. Storm water retention basins of variable size (Figure 6.37) may be constructed that temporarily store urban runoff that is slowly released to reduce flooding. In addition, ground level planters may be constructed and planted with trees and other plants that capture runoff to be released slowly to streams, thus reducing flooding. Concrete can be made pervious, so water will infiltrate the ground rather than runoff. Rooftops of urban areas may have plants and soil that capture and delays runoff.[39]

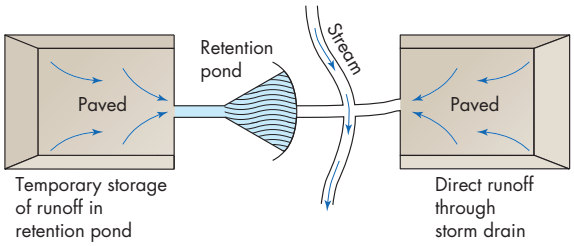


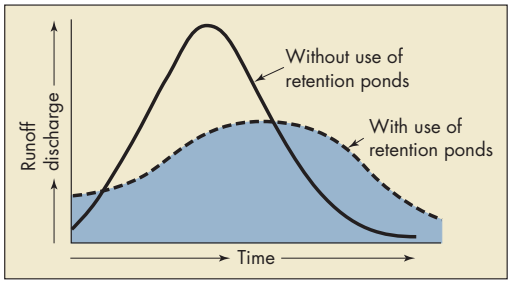
▲ FIGURE 6.36 Mississippi River Levee at Baton Rouge Bike Path
Levee tops are sometimes used as bike paths. Levee is protecting development. *(U.S. Army Corps of Engineers Vicksburg District Levee Safety Program)*

Channelization Straightening, deepening, widening, clearing, and/or lining existing stream channels are all methods of **channelization**. Objectives of this engineering technique include controlling floods and erosion, draining wetlands, and improving navigation. Thousands of kilometers of streams in the United States have been modified without adequate consideration of the adverse effects of channelization.

Opponents of modifying natural streams emphasize that the practice is antithetical to the production of fish and wetland wildlife and causes extensive aesthetic degradation. 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 other areas, channel modification has improved navigation or reduced flooding and has not caused environmental disruption.

Engineering solutions to reduce flooding will remain an important aspect of flood control in areas where previous high-value development is present. However, engineering is not the only option. Alternatives include flood insurance and controlling the land use on floodplains. Planners, policy makers, and hydrologists generally agree that no one adjustment is best in all cases. Rather, an integrated approach





(a)



(b)

▲ FIGURE 6.37 Retention Ponds Reduce Flood Discharge
(a) Comparison of runoff from a paved area, which goes directly through a storm drain to a stream, with runoff that is stored temporarily in a retention pond before draining to a stream. The graph shows that the use of a retention pond reduces peak discharge and the likelihood that the runoff will contribute to flooding of the stream. (b) A nearly dry retention pond near Santa Barbara, California; retention ponds also capture sediment that reduces pollution levels and sedimentation in streams. *(Edward A. Keller)*

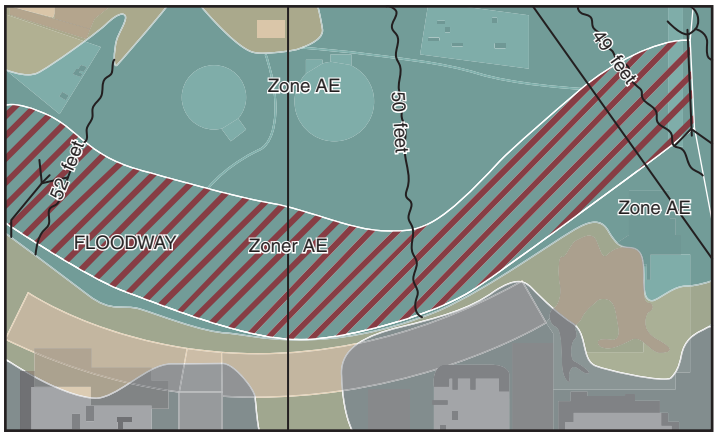
to minimizing the flood hazard is more effective, especially if it incorporates adjustments that are appropriate for a particular situation.

Flood Insurance In 1968, the federal government took over the **flood insurance** business when private companies became reluctant to continue to offer policies. Congress established the U.S. National Flood Insurance Program to make flood insurance available at subsidized rates. Administered by the Federal Emergency Management Agency (FEMA), this program requires the mapping of special flood hazard areas, defined as those areas that would be inundated by a 100-year flood. Flood hazard areas are designated along streams, rivers, lakes, alluvial fans, and deltas and along low-lying coastal areas susceptible to flooding during storms or very high tides.

New property owners in flood hazard areas must buy insurance at rates determined by the risk. Basic risk evaluation depends on identifying the area that would be inundated by the 100-year flood. The insurance program is intended to provide short-term financial aid to victims of floods and to establish long-term land-use regulations for the nation's floodplains. As part of this program, building codes have been revised to limit new construction of nonresidential buildings in a flood hazard area (floodplain) to flood-proofed buildings. The floodway is defined as the channel and parts of the adjacent floodplain that are reasonably necessary to carry the floodwater of a stream or river. No development is allowed in the floodway. Figure 6.38 shows an idealized FEMA Map (Zone AE is the 100-year floodplain). For a community to join the National Flood Insurance Program, it must have FEMA-prepared maps of the 100-year floodplain. The 100-year flood is the flood that has a 1 percent chance of being equaled or exceeded in a given year. Using probability rules, the chance of the 100-year flood occurring once in the 30-year period of a mortgage is 1 in 4 (25 percent). Communities must also adopt minimum standards of land-use regulation within the flood hazard areas. Nearly all U.S. communities with a significant flood risk have basic flood hazard maps and have initiated some form of floodplain regulation. Several million property owners in the United States presently have flood insurance policies.

A problem with flood insurance using the 100-year flood is that it is often based on precipitation and stream flow data that may only be available for 20 years or so and the data may be from years ago. Many people were flooded during the 2017 Houston floods that were well outside of the mapped 100-year flood. The scientific problem is to somehow plan for extreme events that are often not included in flood hazard mapping but are not unprecedented. When we apply standard engineering flood frequency probability equations and modeling to extreme events with long return periods we get answers but those answers are often wrong.

By the early 1990s, policy makers and flood-control professionals recognized that the insurance program



< FIGURE 6.38 Idealized FEMA Flood Hazard Map
The floodway and Zone AE are defined as areas subject to 1 percent annual chance flood (100-year flood). *(FEMA Flood Map Map Service Center* https://msc.fema.gov*)*

was in need of reform. This prompted Congress to pass the National Flood Insurance Reform Act of 1994. Provisions of the act encourage additional opportunities to mitigate flood hazards, such as flood-proofing, relocations, and buyouts of properties likely to be frequently flooded.[40]

Flood-Proofing This is the addition of structural changes to buildings or around buildings that are designed to reduce flooding. Several methods of **flood-proofing** are currently available:

- Raising the foundation of a building above the flood hazard level, using piles or columns or by extending foundation walls or earth fill.
- Constructing flood walls or earthen mounds around buildings to isolate them from floodwaters.
- Using waterproofing construction, such as waterproofed doors, basement walls, and windows.
- Installing improved drains with pumps to remove incoming floodwaters.

Other modifications to buildings are designed to minimize flood damage while allowing floodwaters to enter a building. For example, ground floors along expensive riverfront properties in some communities in Germany are designed so that they are not seriously damaged by floodwaters and may easily be cleaned for reuse following a flood.[43]

Floodplain Regulation From an environmental point of view, the best adjustment to the flood hazard in urban areas is **floodplain regulation**. The objective of floodplain regulation is to obtain the most beneficial use of floodplains while minimizing flood damage and the cost of flood protection. This approach is a compromise between the indiscriminate use of floodplains, which results in loss of life and tremendous property damage from floods, and the complete abandonment of floodplains, which means giving up a valuable natural resource.

There are circumstances, however, when physical barriers, reservoirs, and channelization works are required. Structural controls may be necessary to protect lives and property in areas where there is extensive development on floodplains. 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. 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, the most effective and practical solution is a combination of physical barriers and floodplain regulations that results in less physical modification of the river system. For example, reasonable floodplain zoning in conjunction with a floodwater diversion channel or upstream reservoir may result in a smaller channel or reservoir than would be necessary without the zoning regulations.

A preliminary step toward floodplain regulation is flood hazard mapping, which is a means of providing information about the floodplain for land-use planning.[40] Flood hazard maps may delineate past floods or floods of a particular frequency, for example, the 100-year flood. Such maps 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.

Flood hazard evaluation may be accomplished in a general way by direct observation and measurement of physical parameters. For example, the extensive flooding of the Mississippi River Valley during the summer of 1993 was mapped in detail, using imagery from



< FIGURE 6.39 Scour Marks Indicate Flood Height
Floodwaters of the San Gabriel River in Los Angeles County, California, removed bark from the roots and lower trunks of these trees. Hydrologists measured the elevation of the top of the scour marks to determine the height of the 2005 flood on this segment of the river. *(Theresa Modrick, Ph.D., P.E./Hydrologic Research Center)*

satellite and aircraft (see Figure 6.20). Flooding can also be estimated from the field measurement of high waterlines, flood deposits, scour marks (Figure 6.39), and the distribution of trapped debris in the channel banks or on the floodplain after water has receded.[41] Once flood hazard areas have been established, planners can modify zoning maps, regulations, and building codes.

Relocating People from Floodplains: Examples from North Carolina and North Dakota For several years, local, state, and federal governments have been selectively purchasing and removing homes damaged by floodwaters in order to reduce future losses. In September 1999, nearly 50 cm (~19 in.) of rain from Hurricane Floyd flooded many areas of North Carolina. The flooding damaged approximately 700 homes in Rocky Mount, North Carolina, population 60,000. The state and federal governments subsequently decided to spend nearly $50 million to remove 430 of these homes, the largest single-home buyout ever approved. Following the purchase, the homes were demolished, and the land was preserved as open space. Following Hurricane Matthew in 2016, a buyout program is being considered for about 50 homes damaged by flooding associated with the hurricane.

At Churchs Ferry, North Dakota, a wet cycle since 1993 caused nearby Devils Lake to rise approximately 8 m (~26 ft.). With no natural outlet and flat land surrounding its shore, the lake more than doubled in area. The swollen lake inundated the land around Churchs Ferry, and by late June 2000, the town was all but deserted; the population had shrunk from approximately 100 to 7 people. Most residents took advantage of a voluntary federal buyout plan and moved to higher ground, many to the town of Leeds, approximately 24 km (~15 mi.) away. The empty houses left behind will be demolished or moved to safer ground.

This lucrative $3.5 million buyout plan seemed to be assured. Those people who participated were given the appraised value of their homes plus an incentive; most considered the offer too good to turn down. There was also recognition that the town would eventually have come to an end as a result of flooding. Nevertheless, there was some bitterness among the town's population, and not everyone participated. Among the seven people who decided to stay were the mayor and fire chief. The buyout program for Churchs Ferry demonstrated that the process is an emotional one; it is difficult for some people to make the decision to leave their homes, even though they know the homes are likely to be destroyed by floodwaters in the relatively near future. The story of Churches Ferry is full of anxiety, fear, and anger, as well as hope. The details of people lives, chronicled in three articles in *The Atlantic* are well worth a read.[42–44]

Forest and Flood Management Forested land may serve as a giant sponge that traps precipitation and releases it slowly into streams and rivers, reducing flooding and augmenting low stream flow during dry times. Thus, maintaining and restoring forests may be

considered a flood control strategy. This strategy is more attractive to developing countries that may lack funding for expensive flood control programs. Forested lands are most effective for flood control of small to moderate-sized drainage basins. Large catastrophic floods resulting from high intensity (extreme event) storms in large drainage basins may not be much affected by the presence of forested land. This is because high volumes of rainfall in a short period of time may overwhelm other variables such as forest cover. Nevertheless, deforestation of as little as 10 percent of native forest increases the frequency of floods by 4–28 percent and lengthens flood duration by 4–8 percent. Thus, protecting and restoring forests can help reduce both the frequency and the duration of flooding.[45]

SOCIAL MEDIA AND FLOOD DAMAGE MEDIATION

The 2011 Bangkok flood was Thailand's worst flood in 50 years. The flooding came in three stages over several months of prolonged rainfall. Flooding occurred in spite of two dams that were thought to be able to mitigate severe flooding. Over the greater Bangkok Metropolitan Area, deaths during the first stage totaled about 60, and several hundred thousand homes and businesses were damaged. The relatively low number of deaths was due, in part, to the fact that people in flood-prone areas of Bangkok have adjusted to floods for centuries. Homes and other buildings are often constructed on stilts or they have two-story housing so they can move possessions to the second story during floods. Flood risk in Thailand has increased in recent decades as a result of expansion of agriculture that caused deforestation and increase in population that exposes more people and urban resources to flooding. Furthermore, urban growth has reduced the ability of the land's drainage systems to remove floodwaters. Past flood damage mitigation has focused on early warning to alert people of eminent flooding. The 2011 Bangkok flood was the first flood in a major metropolitan area in Southern Asia where many people had smartphones and were connected to the internet. The flood was slow in developing, so people had time to communicate and alert one another to the danger.[46]

Facebook worldwide has about 2 billion users, and Twitter has about 300 million. People are hooked on communicating via such means, and these communications can help reduce flood losses. For example, social media during the 2011 Bangkok flood reduced losses by an average of 37 percent. This even though many poorer people did not have smartphones (this has changed rapidly following the flood, and many more people now have smartphones). Many people in Bangkok were informed in real time of the dynamic nature of the coming flood. They learned what the depth of flooding was going to be, and many moved property to a safer location (often upstairs). The data from social media was often more reliable than from other sources and often offered information not otherwise available. In the United States, the Federal Emergency Management Agency is testing the use of social media for distributing disaster information. In developing countries, expanded access to mobile networks and broadband is justified, based on people being better informed during unfolding disasters. Today, there is rapid expansion of the use of smartphones that will be used during disasters to better inform people in harms way about urban floods.[47] Social media was also important during the 2017 Houston flood. People called and sent text messages to those who responded with water rescues.

6.7 CHECK your understanding

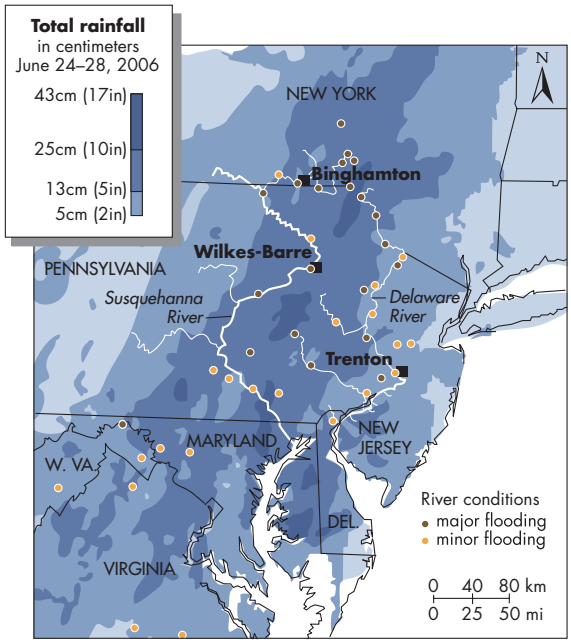
1. Why might levees, flood walls, and dams produce a false sense of security?
2. What is channelization and how has it been used in flood control?
3. Describe the main adjustments to the flood hazard that do not involve engineered structures.
4. Google FEMA Flood Map Service Center, enter your home address, and examine your personal flood hazard.
5. What is the potential role of social media in reducing the flood hazard?

6.8 Perception of the Flood Hazard

Whereas most governmental agencies, planners, and policy makers have an adequate perception and understanding of flooding, many individuals do not. The public knowledge of flooding, anticipation of future flooding, and willingness to accept adjustments caused by the hazard are highly variable.

Progress at the institutional level includes the preparation of thousands of maps of flood-prone areas. The maps show areas susceptible to flooding along streams, lakes, and coastlines; 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.[44] Still, the idea of restricting or prohibiting development on floodplains or of relocating present development to locations off the floodplain raises its own problems; it needs further community discussion before the general population will accept it.



(a)



(b)

▲ FIGURE 6.40 Mid-Atlantic Floods of June and July 2006
(a) Map of major and minor flooding. *(Based on the* New York Times *with data from National Weather Service)* (b) Collecting mail from flooded home in Wilkes-Barre, Pennsylvania. *(Matt Rourke/AP Images)*

This need was tragically evident in the 2006 floods in the mid-Atlantic states, when severe river flooding impacted the region from Virginia to New York (Figure 6.40). More than 200,000 floodplain residents were evacuated in Wilkes-Barre, Pennsylvania, alone, and damages of approximately a billion dollars were incurred. About 16 people lost their lives as cars were swept away by floodwaters and people drowned in flood-swollen creeks and rivers. At least 70 people were rescued from rooftops. In Conklin, New York, near Binghamton, nearly three-fourths of the town was flooded as the Susquehanna River crested about 4.2 m (~14 ft.) above flood level.

Increasing public awareness of the dangers of flash flooding could save many lives each year (see Case Study 6.5: Professional Profile). Public safety campaigns by the National Weather Service and local governments, including the city of Boulder, Colorado; Clark County Regional Flood Control District, Nevada; and the city of Austin, Texas, have been especially successful in increasing public awareness about flash floods. With at least half of all flood deaths in automobiles, the need to educate drivers is especially critical. The National Weather Service slogan "Turn Around, Don't Drown" summarizes a life-saving safety precaution for all motorists not to drive on flooded roads. For hilly or mountainous terrain, road and trail signs can warn people to climb to higher ground if floodwaters begin to rise. In a narrow stream valley, this can mean abandoning your vehicle for the safety of higher ground if floodwaters are rising rapidly ahead of you or if you hear a roaring sound coming from upstream.

PERSONAL ADJUSTMENT: WHAT TO DO AND WHAT NOT TO DO

Flooding is the most commonly experienced natural hazard. Although we can't prevent floods, individuals can be better prepared by learning what to do and what not to do before, during, and after a flood (Table 6.2).

6.8 CHECK your understanding

1. What is being done to raise public awareness of the flood hazard?
2. Summarize the personal adjustments you can make to reduce your flood hazard.

CASE study

6.5 Professional Profile

Nicholas Pinter, Southern Illinois University then U.C. Davis in California

Nicholas Pinter (Figure 6.5.A) was a doctoral student at the University of California, Santa Barbara, where he studied the high desert of the Owens Valley and in the adjacent Sierra Nevada and White Mountains of California. After doing postdoctoral research at Yale University, Nick went to Southern Illinois University at Carbondale. His research focuses on "quantifying human influences on the geology of the earth's surface." Recent research has shown that modern humans move more material each year than all the wind, running water, waves, and glacial ice on Earth. "It's both easy and dangerous," Nick says, "to underestimate how much people have influenced the planet, both locally and at the global scale."

Southern Illinois University at Carbondale is located near where the Mississippi, Ohio, Missouri, Illinois, and other rivers all come together. This central location kindled his interest in river processes and issues of flood hazard in particular. "Some research questions are purely theoretical, but as soon as you start looking at big rivers, the science becomes relevant to people's lives and government policy really fast," says Nick. He realized early on that some of the structures being built by the U.S. Army Corps of Engineers to facilitate shipping at low flows were behaving as large roughness elements and actually increasing the flood hazard during large floods. Over time, squeezing the river between levees and slowing down flows with structures built in the channel were leading to increasing flood stages. This means that, say 50 years ago, a flood of a certain discharge would inundate the banks at some depth. Today, the same discharge is associated with water many feet deeper and, hence, a greater flood hazard. Although a number of outside scientists have reached similar conclusions, the U.S. Army Corps of Engineers did not receive the news that its own construction projects were actually making the flooding much worse.

Nick Pinter and his students have worked diligently to counter the political resistance with rock-solid science: quantifying past increases in flood stages and risk and confirming what caused those increases with hydrologic, statistical, geospatial, and modeling analyses. Nick points out that it is difficult to achieve two goals at the same time. That is, if you want to increase a river's ability to transport goods through navigation at low flows, you may have one strategy. However, that strategy may not be the optimum solution for passage of a 100-year flood safely through the same stretch of river. "We live in the twenty-first century," says Nick, "in which robust science is vital to sustainable management of natural systems that are stretched to their limits in many places by the demands of modern society."

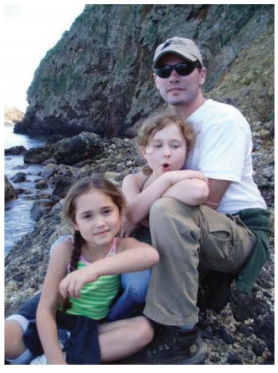


FIGURE 6.5.A Professor Nicholas Pinter
Professor Pinter is at the University of California, Davis. He is an expert on flooding of the Mississippi River and the role of human intervention through building flood defenses and structures to improve navigation. Nick holds an Endowed chair and I am very proud of him. He was one of my Ph.D. students at UCSB. *(Nicholas Pinter)*

TABLE 6.2 What to Do and What Not to Do Before and After a Flood

	Preparing for a Flood
What to Do	• Check with your local flood-control agency to see if your property is at risk from flooding. • If your property is at risk, purchase flood insurance if you can and be sure that you know how to file a claim. • Buy sandbags or flood boards to block doors. • Make up a flood kit, including a flashlight, blankets, rain gear, battery-powered radio, first-aid kit, rubber gloves, and key personal documents. Keep it upstairs if possible. • Find out where to turn off your gas and electricity. If you are not sure, ask the person who checks your meter when he or she next visits. • Talk about possible flooding with your family or housemates. Consider writing a flood plan, and store these notes with your flood kit.
What Not to Do	• Underestimate the damage a flood can do.
	When You Learn a Flood Warning Has Been Issued
What to Do	• Be prepared to evacuate. • Observe water levels and stay tuned to radio and television news and weather reports. • Move people, pets, and valuables upstairs or to higher ground. • Move your car to higher ground. It takes only 0.6 m (~2 ft.) of fast-flowing water to wash your car away. • Check on your neighbors. Do they need help? They may not be able to escape upstairs or may need help moving furniture. • Do as much as you can in daylight. If the electricity fails, it will be hard to do anything. • Keep warm and dry. A flood can last longer than you think, and it can get cold. Take warm clothes, blankets, a Thermos, and food supplies.
What Not to Do	• Walk in floodwater above knee level: It can easily knock you off your feet. Utility access holes, road works, and other hazards may be hidden beneath the water.
	After a Flood
What to Do	• Check home for damage; photograph any damage. • If insured, file a claim for damages. • Obtain professional help in removing or drying carpets and furniture as well as cleaning walls and floors. • Contact gas, electricity, and water companies. You will need to have your supplies checked before you turn them back on. • Open doors and windows to ventilate your home. • Wash water taps and run them for a few minutes before use. Your water supply may be contaminated; check with your water supplier if you are concerned.
What Not to Do	• Touch items that have been in contact with the water. Floodwater may be contaminated and could contain sewage. Disinfect and clean thoroughly everything that got wet.

Source: Based on Environment Agency, United Kingdom, Floodline: Prepare for Flooding, 2004.

APPLYING the 5 Fundamental Concepts

Houston Flood of 2017

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

The 2017 flood in Houston is the latest and most severe flood event in a region that has a serious flood hazard. As recently as 2016, a flood killed about eight people and flooded about 1,000 homes. A serious flood on Memorial Day in 2015 caused extensive damage, albeit less than in 2001 when floods inflicted about $9 billion in damages, destroying about 14,000 homes and claiming 23 lives. These floods occur when remnants of hurricanes stall over Houston, unfortunately a more common occurrence than previously thought. The 2017 flood was a 1,000-year event, by far the largest in Houston's history, but it occurred due to the same set of circumstances surrounding earlier floods. Since 1989, Houston has experienced 26 major floods; of these, six (25 percent) were associated with the remnants of hurricanes.

The 2007 flood map, showing major channels and the 100- and 500-year flood plains, are shown on Figure 6.41. The maps are considered too outdated and inadequate for the future. The maps are expensive to update, do not adequately consider climate change, and are subject to manipulation by local government. More development is allowed if flood maps shrink the flood zone. Nearly half of those flooded in 2017 were outside of mapped flood hazard areas. Of course, the flood greatly exceeded even the 500-year flood.

Houston is a huge metropolitan area with up to 40 percent of the area rendered impermeable to water from roofs, streets, freeways, and parking lots. The many trillions of gallons of rainfall that caused the 2017 flood was caused by the remnant of Hurricane Harvey moving very slowly and even doubling back for a second hit. More than the annual rainfall of the city fell in a couple of days. Water ran off quickly from urban areas and piled up in the normally sluggish stream channels and bayous.

Complicating factors make up a familiar list: Rapid population and development in recent decades; poor land-use planning that allowed development in flood hazard areas; inadequate flood maps that provided a false sense of security; loss of control of runoff from flood control dams; poor understanding of the total risk, given the recent flood history; and climate change. Houston is far from alone in terms of these complicating factors. Many U.S. cities from coast to coast, from New York to Los Angles, are vulnerable to catastrophic flooding.

As population continues to grow, we need to reduce the flood hazard in ways that do not require massive response but are proactive. We need plans for future flood hazard reduction that do not require massive evacuation from flood-prone areas but that avoid the hazard through better land-use practices, such as avoiding development in floodplains. That is a proactive solution for minimizing the hazard of future flooding in the United States. As we learned in Chapter 1, you can pay now in preparation or pay many times more if not prepared. Total flood losses are the sum of direct losses (Houston will flood from storms) and losses related to human actions that encourage poor land-use planning (development in flood risk areas); inadequate engineering structures, such as levees, flood walls, and flood control dams; and lack of flood insurance. Sometimes people and government are greedy, incompetent, or just lazy and not doing the right thing. Paying after a disaster is many times more expensive than

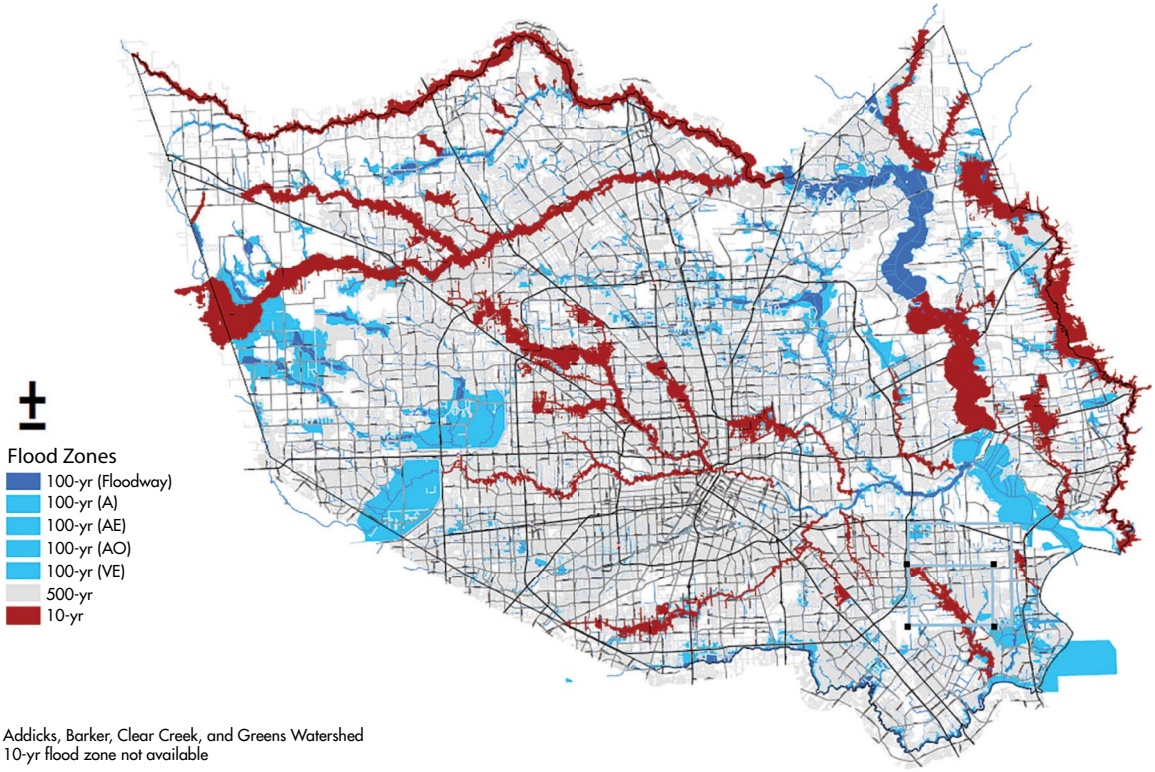


FIGURE 6.41 Flood Map for Houston Texas

Boundries for the 100-year flood (probability of 0.01) and 500-year flood (probability of 0.002) events. These FEMA maps are outdated (probably 2007 maps) and did not consider development on the past decade or impact of climate that has produced more intense storms. Many homes outside of the 500-year event boundary flooded. This suggests there existed a false sense of security that probably led many to not purchase flood insurance. (*Modified from FEMA flood hazard maps and Houston Flood Agency)*

prevention. Flood-proofing a building may cost a few thousand dollars; replacing the building after flood damages could cost thousands of times more. For example the 2001 flood in Houston greatly damaged the large Houston Medical Center. Following the flood the Center developed an ambitious flood-proof project that included 23 large flood doors and other barriers. Just prior to the 2017 flood the doors were closed and the Center was not damaged, saving massive flood damages and loss of medical care for people. Figure 6.42 shows the floodwaters surrounding but not entering the Medical Center.

Encouraging property owners to play an active part in limiting their potential losses to their property (e.g., flood-proofing) can save property owners from wading through polluted floodwater that enters their buildings. Government can and often does take on big projects to help reduce the flood hazard, and this is very important and often most important. In the end though, it is the property owner of a site who is damaged.

APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. Flooding is usually a predictable event in countries where accurate weather forecasts and stream monitoring are performed. Could the 2017 floods in Houston have been predicted? Why or why not?
2. Discuss the flood risk in Houston before and after the 2017 flood, based on what is known and unknown about the probability of flooding in the future.



< FIGURE 6.42 Flood Proofing of Texas Medical Center in Houston
Twenty-three large flood doors and flood barriers kept floodwaters out saving many millions of dollars in potential damages. *(floodbreak.com)*

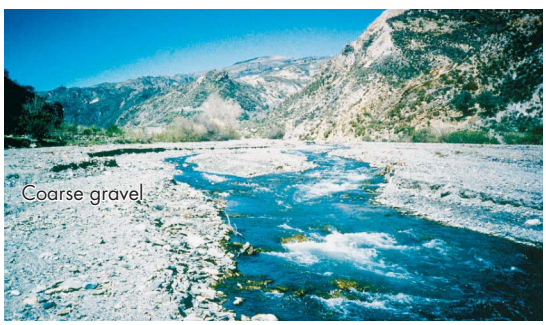
3. What other hazards were linked to the 2017 flood? Specifically, what flood processes were responsible and why?
4. What human decisions before and during the long 2017 flood made the consequences of the flood much worse?
5. What specific recommendation can you make to help minimize future consequences of flooding in Houston?

CONCEPTS in review

6.1 An Introduction to Rivers

LO:1 Explain basic river processes.

- Streams and rivers form a basic transport system of the rock cycle and are a primary erosion agent in shaping the landscape. The region drained by a stream system is called a drainage basin or watershed. Rivers carry chemicals in their dissolved load and sediment in their suspended and bed loads. Discharge refers to the volume of water moving past a particular location in a river per unit of time.
- Sediment deposited by lateral migration of meanders in a stream and by the periodic overflow of the stream banks during a flood forms a floodplain. The configuration of the stream channel as seen in an aerial view is called the channel pattern. A pattern can be braided or meandering or both characteristics may appear in the same river.



KEY WORDS
channel patterns (p. 213), **discharge** (p. 212), **drainage basin** (p. 211), **floodplain** (p. 213), **river** (p. 211), **river system** (p. 216)

6.2 Flooding

LO:2 Compare and contrast flash floods, downstream floods, and megafloods and know why the differences are important.

- The natural process of overbank flow is termed *flooding*. Flash floods in small drainage basins can be 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, increasing runoff from thousands of tributary basins.
- Flooding magnitude and frequency are difficult to predict on many streams because of changes in land use and limited historical records. This difficulty is especially pronounced for extreme events, such as 100-year floods. The probability that a 100-year flood or greater will take place each year is the same regardless of when the last 100-year flood occurred.



KEY WORDS

downstream floods (p. 220), **flash floods** (p. 220), **flooding** (p. 217), **levee** (p. 223), **megafloods** (p. 228), **recurrence interval** (p. 218)

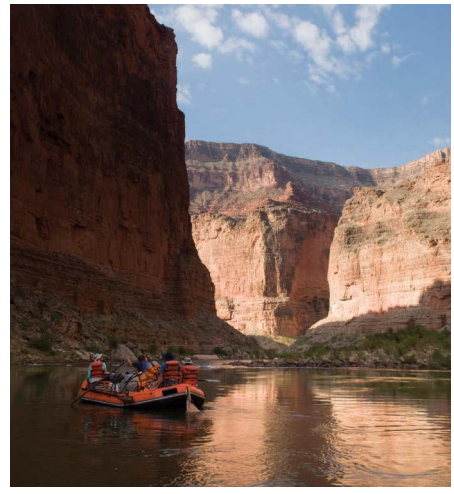
6.3, 6.4, and 6.5 Geographic Regions at Risk for Flooding Effects of Flooding, Linkages between Floods and Other Hazards Natural Service Functions of Floods

LO:3 Summarize regions at risk from flooding and the global impact.

LO:4 Differentiate between the effects of flooding and the linkages with other natural hazards.

LO:5 Describe the benefits of periodic flooding.

- River flooding is the most universally experienced natural hazard. Floods can occur just about anywhere there is water, and much of the United States faces the possibility of flooding.
- Annual losses from flooding worldwide are about 6,000 lives lost and economic losses of $23 billion. The number of floods and the number of people killed or affected, along with economic loss, is highly variable from region to region, reflecting the population of people living along rivers and exposed to flooding.
- Floods produce primary effects such as loss of life and damage to structures by floodwaters. Secondary effects include water pollution, disease, displacement of people, and fire.
- Although flooding causes many deaths and much damage, it does provide natural service functions such as the production of fertile lands, benefits to aquatic ecosystems, and maintenance of ample sediment supplies to naturally subsiding deltas such as the Mississippi.
- Water supply is intimately related to the concept of the **Water–Energy–Food Nexus** that consists of the complex linkages between water, energy, and agriculture. Water supply from runoff to rivers is stored in reservoirs where it provides a number of services, such as helping provide the water supply for human consumption, energy for power, and water to irrigate crops.



6.6 Human Interaction with Flooding

LO:6 Discuss how human activity can significantly affect river processes and flooding.

- Land-use changes, especially urbanization, have increased flooding in small drainage basins by covering much of the ground with impervious surfaces, such as buildings, parking lots, and roads, thereby increasing the runoff of storm water. Construction of a dam can significantly change the hydrology and flood frequency and magnitude downstream.



6.7 Minimizing the Flood Hazard: Structural Control to Floodplain Management

LO:7 Summarize why being proactive with flood hazards is, in the long term, more significant in reducing the flood hazard than being reactive after a flood.

LO:8 Evaluate the adjustments we can make to minimize flood deaths and damage.

- Engineering structures will still be needed to protect existing development in highly urbanized areas. These structures include physical barriers, such as levees and flood walls, and structures that regulate the release of water, such as dams and reservoirs.
- Channelization is the straightening, deepening, widening, cleaning, or lining of existing streams, usually with the goal of controlling floods or improving drainage. Channelization has often caused environmental degradation, so new projects must be closely evaluated.
- Preferred environmental adjustments to the flood hazard include flood insurance, flood-proofing, and floodplain regulation. 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 flood hazard mapping, which can be difficult and expensive. Planners use flood hazard maps to zone flood-prone areas for appropriate uses. In some cases, homes in flood-prone areas have been purchased and demolished by the government and their owners relocated to safe ground.
- Social media is becoming a tool in minimizing flood damages by providing real time data to people during a flood.



KEY WORDS

channelization (p. 241), **flood-proofing** (p. 243), **flood insurance** (p. 242), **floodplain regulation** (p. 243)

6.8 Perception of the Flood Hazard

LO:9 Summarize how people perceive flooding.

- 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 clearly perceive the hazard of living in flood-prone areas.



CRITICAL thinking questions

1. You are a planner working for a community that is expanding into the headwater portions of drainage basins. You are aware of the effects of urbanization on flooding and want to make recommendations to avoid some of these effects. Outline a plan of action.
2. You are working for a regional flood-control agency that has been channelizing streams for many years. Although bulldozers are usually used to straighten and widen the channel, the agency has been criticized for causing extensive environmental damage. You have been asked to develop new plans to minimize the damage to streams from channelization. What would you recommend?
3. Does the community you live in have a flood hazard? If not, why not? If there is a hazard, what has been done or is being done to reduce the hazard? What more could be done?
4. Your parents have recently heard about atmospheric rivers and past megafloods on a documentary film shown on television. They ask you what you think, having taken a course on natural hazards. How do you answer their question?
5. How might we better integrate the use of social media into flood hazard rediction?

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