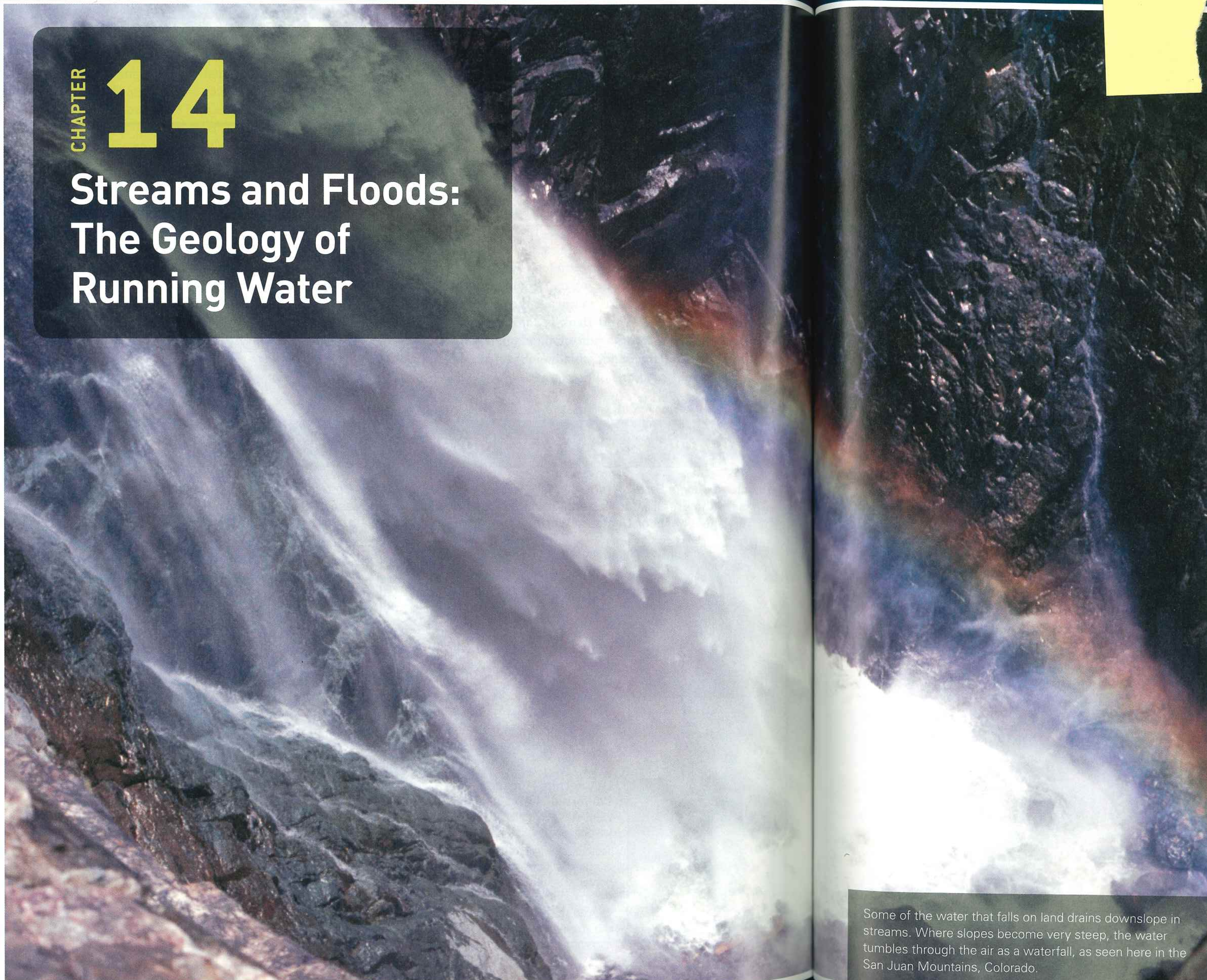
CHAPTER 14

Streams and Floods: The Geology of Running Water



Some of the water that falls on land drains downslope in streams. Where slopes become very steep, the water tumbles through the air as a waterfall, as seen here in the San Juan Mountains, Colorado.

Chapter Objectives

By the end of this chapter you should know . . .

- what streams and drainage networks are, and how they form and evolve.
- how to describe stream flow and erosion, and how streams transport and deposit sediment.
- how streams change from headwaters to mouth.
- how erosional and depositional landscapes formed by streams evolve over time.
- the nature and causes of flooding, and the steps that people take to protect against flooding.
- the environmental issues that pertain to streams.

As many fresh streams meet in one salt sea, as many lines close in the dial's center, so may a thousand actions, once afoot, end in one purpose.

—William Shakespeare (1564–1616)

14.1 Introduction

By the 1880s, Johnstown, built along the Conemaugh River in scenic western Pennsylvania, had become a significant industrial town. Recognizing the attraction of the surrounding hills as a summer retreat, speculators built a mud-and-gravel dam across the river, upstream of Johnstown, to trap a pleasant reservoir of cool water. A group of industrialists and bankers bought the reservoir and established the exclusive South Fork Hunting and Fishing Club. Unfortunately, the dam had been poorly designed, setting the stage for a monumental tragedy. On May 31, 1889, torrential rain drenched Pennsylvania, and the reservoir filled until water began to flow over the dam. Despite frantic attempts to strengthen the dam, the soggy structure abruptly collapsed, and the reservoir emptied into the Conemaugh River Valley. A 20-m-high wall of water roared downstream and slammed into Johnstown, transforming bridges and buildings into twisted wreckage (Fig. 14.1). When the water subsided, 2,300 people were dead, and Johnstown became the focus of national sympathy. It took years for the town to recover, and many residents simply picked up and left.

The unlucky inhabitants of Johnstown had experienced the immense power of **running water**, water that flows down the surface of sloping land in response to the pull of gravity. Geologists use

FIGURE 14.1 In 1889 raging waters destroyed Johnstown.

the term **stream** for any body of running water that flows along a **channel**, an elongate depression or trough. (In everyday English, we also refer to large streams as rivers and medium-sized ones as creeks or brooks.) Streams drain water from the landscape and carry it into lakes or to the sea, much as culverts drain water from a parking lot. In the process, streams erode the landscape and transport sediment and debris to sites of deposition. Generally, a stream stays within the confines of its channel, but when the supply of water entering a stream exceeds the channel's capacity, water spills out and covers the surrounding land, thereby causing a **flood**, such as the one that washed away Johnstown.

Earth is the only planet in the Solar System that currently hosts flowing streams. In this chapter, we examine how streams operate in the Earth System. First, we learn about the origin of running water and about the architecture of streams and stream networks. Then we look at the process of stream erosion and deposition and at the landscapes that form in response to these processes. Finally, we consider the nature and consequences of flooding.

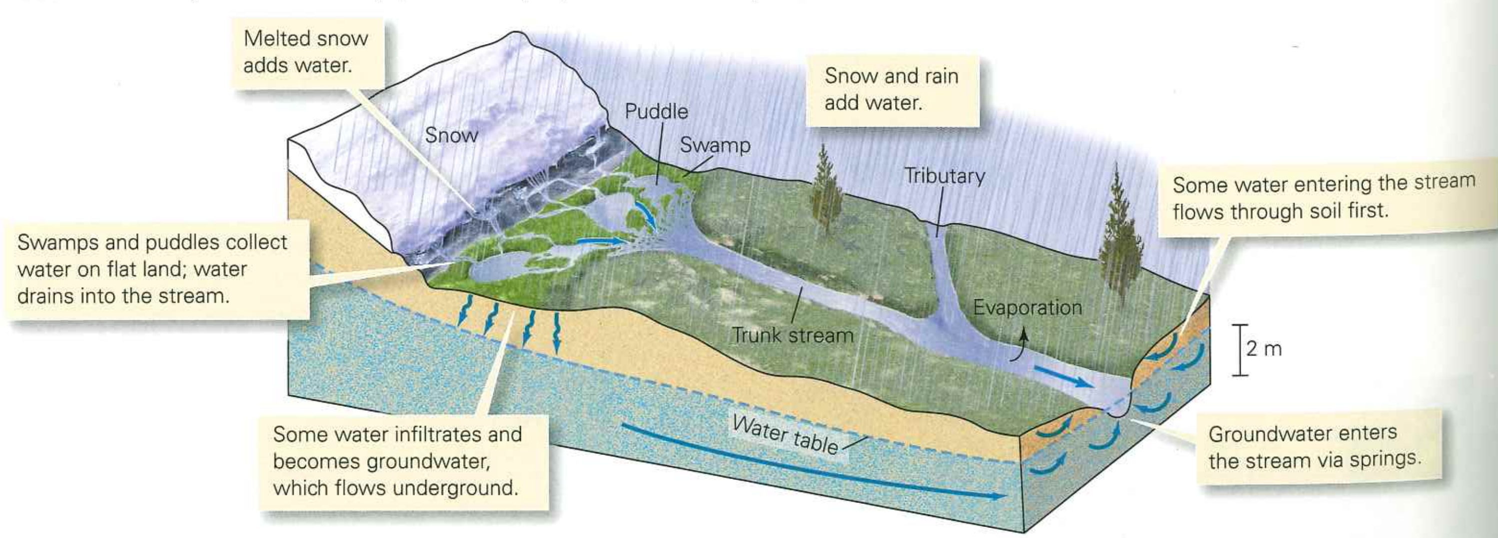
14.2 Draining the Land

Forming Streams and Drainage Networks

Where does the water in a stream come from? Recall that water enters the hydrologic cycle by evaporating from the Earth's surface and rising into the atmosphere (see Interlude F). After a relatively short residence time, atmospheric water condenses and falls back to the Earth's surface as rain or snow that accumulates in various reservoirs. Some rain or snow remains on the land as surface water (in puddles, swamps, lakes, snowfields, and glaciers), some flows downslope as a thin film called **sheetwash**, and some sinks into the ground, where it either becomes trapped in soil (as soil moisture) or descends below the water table to become groundwater. (As we discuss further in Chapter 16, the *water table* is the level below which groundwater fills all the pores and cracks in subsurface rock or sediment. Above the water table, air partially or entirely fills the pores and cracks.) Streams can receive input of water from all of these reservoirs (Fig. 14.2). Specifically, gravity pulls surface water (including meltwater) downhill into stream channels, the pressure exerted by the weight of new rainfall squeezes existing soil moisture back out of the ground, and groundwater seeps out of the channel walls into the channel, if the floor of the channel lies below the water table.

Running water collects in stream channels, because a channel is lower than the surrounding area and gravity

FIGURE 14.2 Excess surface water (runoff) comes from rain, melting ice or snow, and groundwater springs. On flat ground, water accumulates in puddles or swamps, but on slopes, it flows downslope in streams.



always moves material from higher to lower elevation. How does a stream channel form in the first place? The process of channel formation begins when sheetwash starts flowing downslope. Like any flowing fluid, sheetwash erodes its substrate (the material it flows over). The efficiency of such erosion depends on the velocity of the flow—faster flows erode more rapidly. In nature, the ground is not perfectly planar, not all substrate has the same resistance to erosion, and the amount of vegetation that covers and protects the ground varies with location. Thus, the velocity of sheetwash also varies with location. Where the flow happens to be a bit faster, or the substrate is a little weaker, erosion scours (digs) a channel. Since the channel is lower than the surrounding ground, sheetwash in adjacent areas starts to head toward it. With time, the extra flow deepens the channel relative to its surroundings, a process called **downcutting**, and a stream forms.

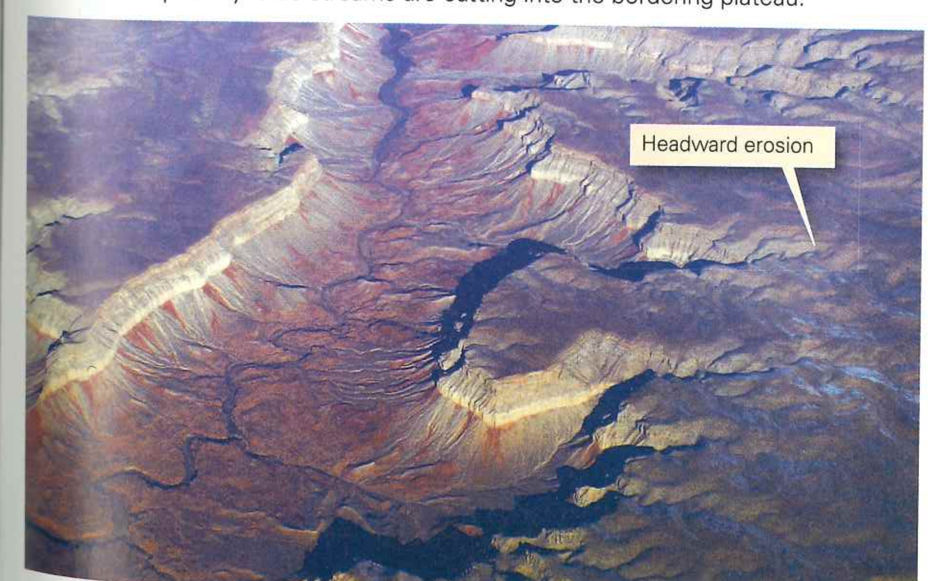
As its flow increases, a stream channel begins to lengthen at its origin, a process called **headward erosion** (Fig. 14.3). Headward erosion occurs for two reasons. First, it happens when the surface flow converging at the entrance to a channel has sufficient erosive power to downcut. Second, it happens at locations where groundwater seeps out of the ground and enters the entrance to the stream channel. Such seepage, called "groundwater sapping," gradually weakens and undermines the soil or rock just upstream of the channel's endpoint until the material collapses into the channel; the collapsed debris eventually washes away during a flood. Each increment of collapse makes the channel longer.

As downcutting deepens the main channel, the surrounding land surfaces start to slope toward the channel. Thus, new side channels, or **tributaries**, begin to form, and these flow into the main channel. Eventually, an array of linked streams evolves, with the smaller tributaries flowing into a *trunk stream*. The array of interconnecting streams together constitute the **drainage network**. Like transportation networks of roads, drainage networks of streams reach into all corners of a region, providing conduits for the removal of runoff.

The configuration of tributaries and trunk streams defines the map pattern of a drainage network. This pattern depends on the shape of the landscape and the composition of the substrate. Geologists recognize several types of networks on the basis of the network's map pattern (Fig. 14.4).

- *Dendritic*: When rivers flow over a fairly uniform substrate with a fairly uniform initial slope, they develop a dendritic network, which looks like the pattern of branches connecting to the trunk of a deciduous tree.
- *Radial*: Drainage networks forming on the surface of a cone-shaped mountain flow outward from the mountain peak, like spokes on a wheel. Such a pattern defines a radial network.
- *Rectangular*: In places where a rectangular grid of fractures (vertical joints) breaks up the ground, channels form along the preexisting fractures, and streams join each other at right angles, creating a rectangular network.
- *Trellis*: In places where a drainage network develops across a landscape of parallel valleys and ridges, major tributaries flow down a valley and join a trunk stream that cuts across the ridges. The resulting map pattern resembles a garden trellis, so the arrangement of streams constitutes a trellis network.
- *Parallel*: On a uniform slope, several streams with parallel courses develop simultaneously. The group comprises a parallel network.

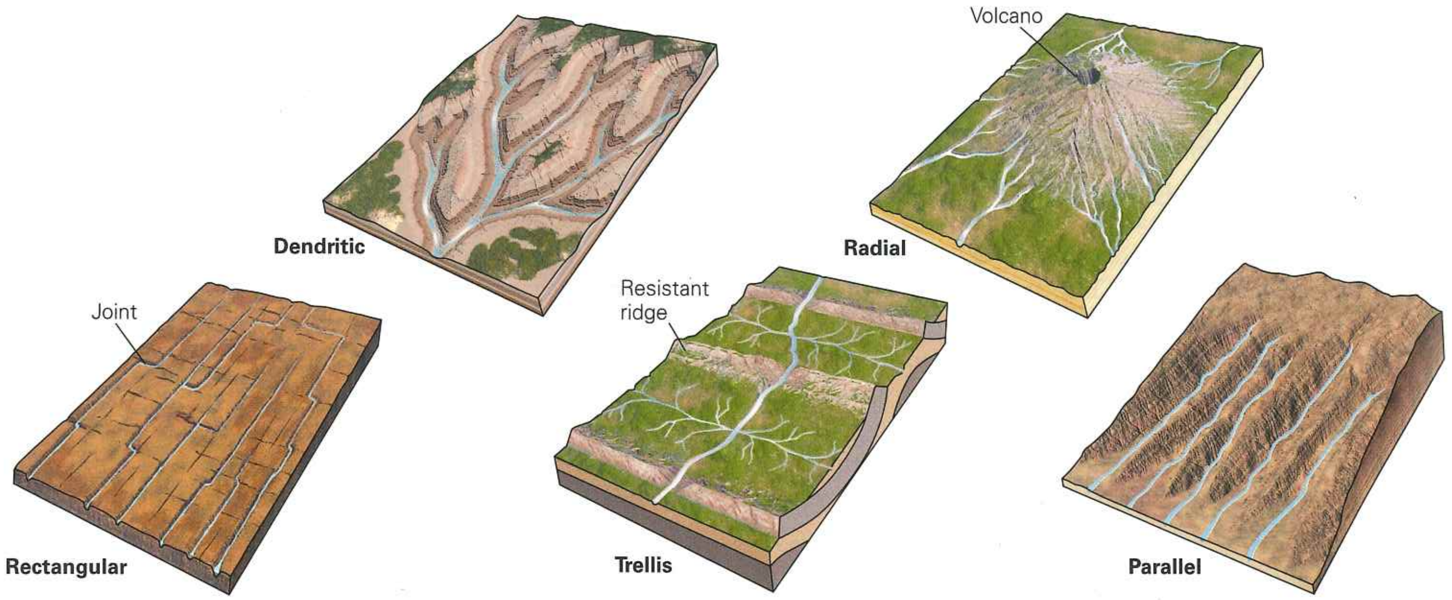
FIGURE 14.3 An example of headward erosion. The main stream flows in a deep valley. Side streams are cutting into the bordering plateau.



Drainage Basins and Divides

A drainage network collects water from a broad region, variously called a drainage basin, catchment, or **watershed**, and feeds it into the trunk stream, which carries the water away. The highland, or ridge, that separates one watershed from another is a **drainage divide** (Fig. 14.5a, b). A continental divide separates drainage that flows into one ocean from drainage that flows into another. For example, if you straddle the continental divide where it runs along the crest of the Rocky Mountains in the western United States, and pour a cup of water out of each hand, the water in one hand flows to the Atlantic, and the water in the other flows to the Pacific. Three

FIGURE 14.4 Block diagrams illustrating five types of drainage networks.

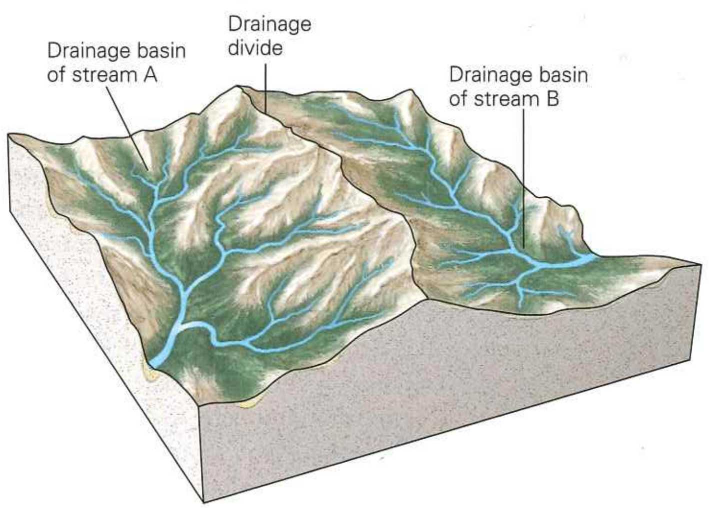


divides bound part of the Mississippi drainage basin, which drains the interior of the United States.

Streams That Last, Streams That Don't

Permanent streams flow all year long, whereas **ephemeral streams** flow only for part of the year. Some ephemeral streams flow only for tens of minutes to a few hours, following a heavy rain. Most permanent streams exist where the floor (or bed) of the stream channel lies *below* the water table (**Fig. 14.6a**; see Chapter 16). In these streams, which occur in humid or temperate climates, water comes not only from upstream or from surface runoff, but also from springs through which groundwater seeps. If the bed of a stream lies *above* the water table, then the stream can be permanent only when the rate at which water arrives from upstream exceeds the rate at which water infiltrates into the ground below. For example, the downstream portion of the Colorado River in the dry Sonoran Desert of Arizona flows all year, because enough water enters it from the river's wet headwaters upstream in Colorado; hardly any water enters the stream from the desert itself.

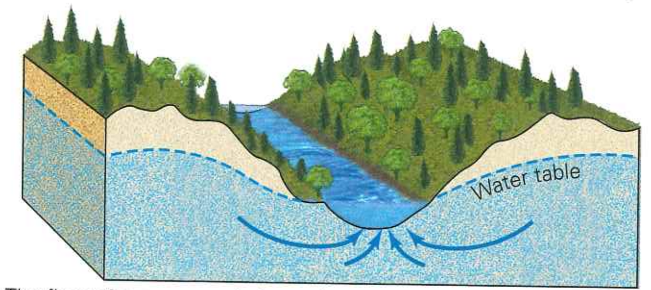
FIGURE 14.5 Drainage divides and basins.



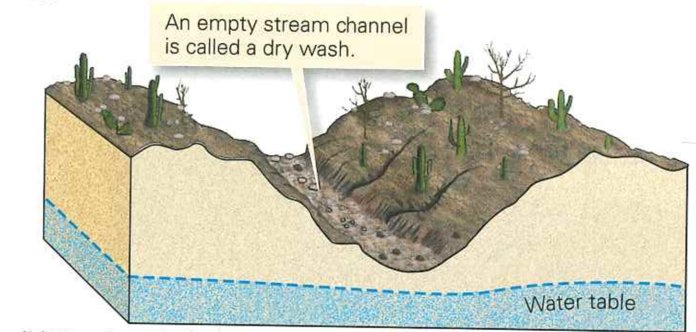
(a) A drainage divide is a relatively high ridge that separates two drainage basins.

(b) The major drainage basins of North America.

FIGURE 14.6 The contrast between permanent and ephemeral streams.



(a) The floor of a permanent stream in a temperate climate lies below the water table. Springs add water from below, so the stream contains water even between rains.



(b) The channel of an ephemeral stream lies above the water table, so the stream flows only when water enters the stream faster than it can infiltrate into the ground.

Streams that do not have a sufficient upstream source, and whose beds lie above the water table, are ephemeral, because the water that fills a channel due to a heavy rain or a spring thaw eventually sinks into the ground and/or evaporates, and the stream dries up (**Fig. 14.6b**). Streams whose watersheds lie entirely within an arid region tend to be ephemeral. The dry bed of an ephemeral stream is variously called a dry wash, an arroyo, or a wadi.

> ### Take-Home Message
> **Stream channels form by downcutting and lengthen by headward erosion. They carry water from sheetwash, lakes, springs, and melting snow or ice. Drainage networks carry water from a watershed to the sea. They have a variety of different geometries.**

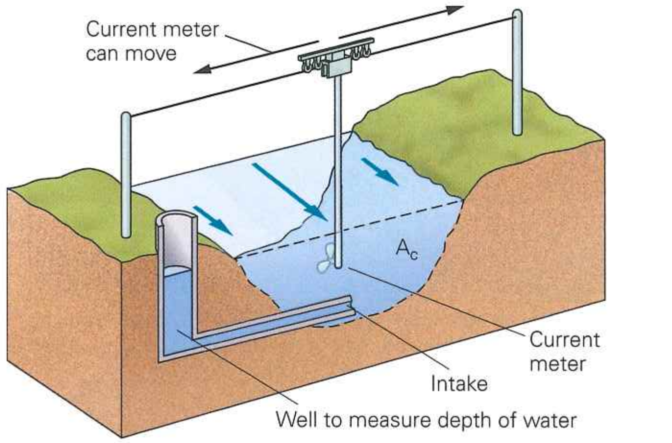
14.3 Describing Flow in Streams: Discharge and Turbulence

Imagine two streams—a larger one in which water flows slowly, and a smaller one in which water flows rapidly. Which stream carries more water? The answer is not obvious. To answer this question completely, geologists must calculate the streams' discharge. Technically speaking, we define **discharge** as the volume of water passing through a cross section of the stream in a given time. We can calculate stream discharge by using a simple formula: $D = A_c \times v_a$. In this formula, A_c is the area of the stream, as measured in an imaginary plane perpendicular to the stream flow, and v_a is the *average* velocity at which water moves in the downstream direction. For example, if a stream has a cross-sectional area of $100\ m^2$, and the water in the stream flows at an average velocity of 0.2 m/s, then discharge $= 100\ m^2 \times 0.2\ m/s = 20\ m^3/s$. Note that the discharge ends up being specified in units of volume per second. Stream discharge can be determined at a *stream-gauging station*, where instruments measure the velocity and depth of the water at several points across the stream (**Fig. 14.7a**).

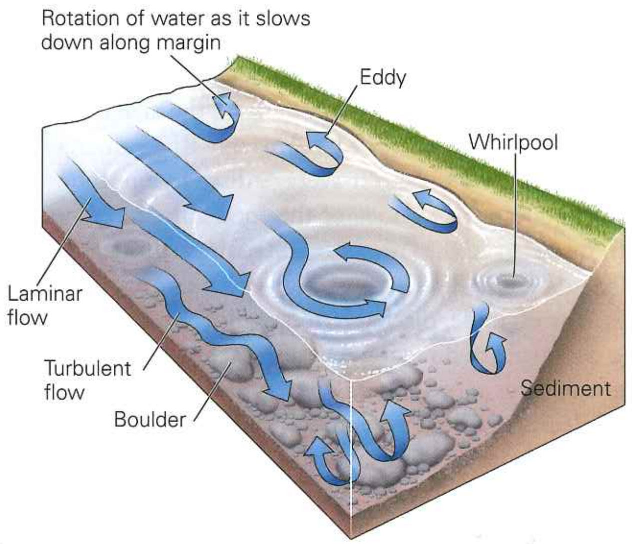
A stream's average discharge reflects the size of its drainage basin and the climate. The Amazon River drains a huge rainforest and has the largest average discharge in the world—about 200,000 m^3/s, or 15% of the total amount of runoff on Earth. In contrast, the "mighty" Mississippi's discharge is only 17,000 m^3/s. The discharge of a given stream varies along its length. For example, discharge in a temperate region increases in the downstream direction, because each tributary that enters the stream adds more water, whereas the discharge in an arid region decreases downstream, as progressively more water seeps into the ground or evaporates. Human activity can affect discharge—for example, if people divert the river's water for irrigation, the river's discharge decreases downstream. Finally, the discharge at a given location can vary with time: in a temperate climate, a stream's discharge during the spring may be double or triple the amount during a dry summer, and a flood may increase the discharge to more than a hundred times normal.

The average velocity of stream water (v_a) can be difficult to calculate because the water doesn't all travel at the same velocity, for two reasons. First, friction along the sides and floor of the stream slows the flow. Thus, water near the channel walls or the streambed (the floor of the stream) moves more slowly than water in the middle of the flow (Fig. 14.7a). In fact, the fastest-moving part of the stream lies near the surface in the center of the channel. Second, *turbulence*—the twisting, swirling motion of a fluid—can create eddies in which water curves and flows upstream or circles in place (**Fig. 14.7b**). Turbulence develops because the shearing motion of one water volume against its neighbor causes the neighbor to spin, and because obstacles, such as boulders, deflect water flow.

FIGURE 14.7 Flow velocity and turbulence in streams.



(a) At a stream-gauging station, geologists measure the cross-sectional area (A_c), the depth, and the average velocity of the stream. Velocity is slower near the banks.



(b) In detail, flow is turbulent. Turbulence can make measuring velocity difficult.

> **Take-Home Message**
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> **Stream discharge, the amount of water passing through a cross section of the stream in a given time, depends on such factors as watershed area and climate. Water velocity varies across a stream, and tends to be turbulent, so calculating average velocity is complicated.**

14.4 The Work of Running Water

How Do Streams Erode?

The energy that makes running water move comes from gravity. As water flows downslope from a higher to a lower elevation, the gravitational potential energy stored in water transforms into kinetic energy. About 3% of this energy goes into the work of eroding the walls and beds of stream channels. Running water causes erosion in four ways:

- *Scouring*: Running water can remove loose fragments of sediment, a process called scouring.
- *Breaking and lifting*: In some cases, the push of flowing water can break chunks of solid rock off the channel floor or walls. In addition, the flow of a current over a clast can cause the clast to rise, or lift off the substrate.
- *Abrasion*: Clean water has little erosive effect, but sediment-laden water acts like sandpaper and grinds or rasps away at the channel floor and walls, a process called abrasion. In places where turbulence produces long-lived whirlpools, abrasion by sand or gravel carves a bowl-shaped depression, called a *pothole*, into the floor of the stream (**Fig. 14.8a, b**).
- *Dissolution*: Running water dissolves soluble minerals as it passes, and carries the minerals away in solution.

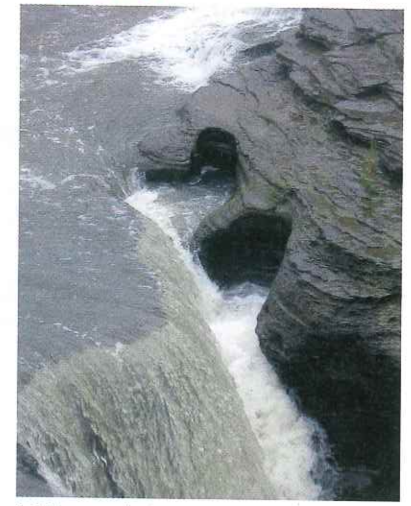
The efficiency of erosion depends on the velocity and volume of water and on its sediment content. A large volume of fast-moving, turbulent, sandy water causes more erosion than does a trickle of quiet, clear water. Thus, most erosion takes place during floods, when a stream carries a large volume of fast-moving, sediment-laden water.

How Do Streams Transport Sediment?

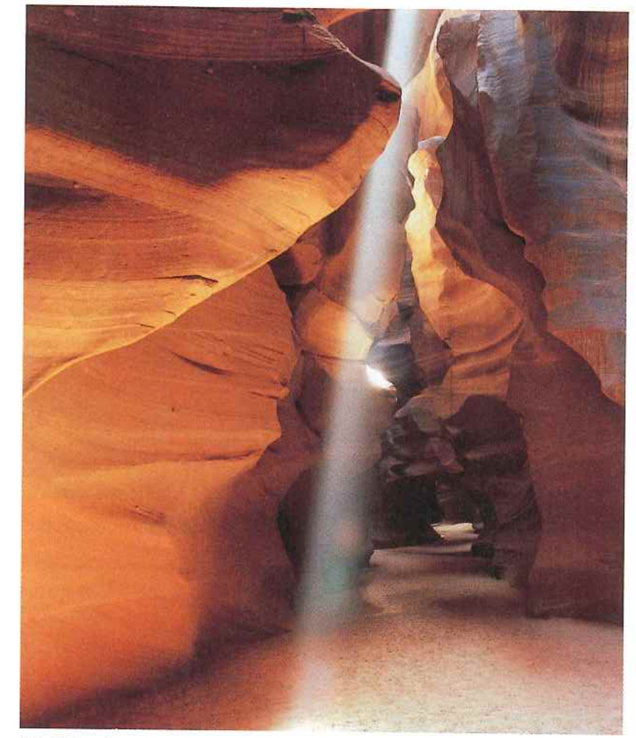
The Mississippi River received the nickname "Big Muddy" for a reason—its water can become chocolate brown because of all the clay and silt it carries. Geologists refer to the total volume of sediment carried by a stream as its sediment load. The sediment load consists of three components (**Fig. 14.8c**):

- *Dissolved load*: Running water dissolves soluble minerals in the sediment or rock that it flows over, and groundwater seeping into a stream brings dissolved minerals with it. The ions of these dissolved minerals constitute a stream's dissolved load.
- *Suspended load*: The suspended load of a stream usually consists of tiny solid grains (silt or clay size) that swirl along with the water without settling to the floor of the channel.
- *Bed load*: The **bed load** of a stream consists of large particles (such as sand, pebbles, or cobbles) that bounce or roll along the stream floor. Bed-load movement commonly involves **saltation**. During saltation, a multitude of grains bounce along in the direction of flow, within a zone that extends up from the surface of the streambed for a distance of several centimeters to several tens of centimeters. Each saltating grain in this zone follows a curved trajectory up through the water and then back down to the bed. When it strikes the bed, it knocks other grains upward, and thus supplies grains to the saltation zone.

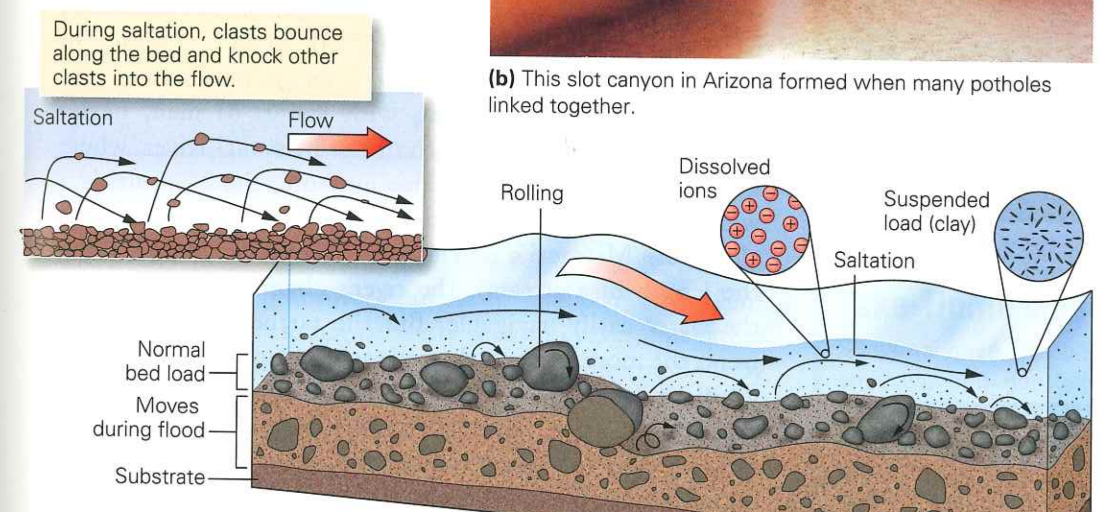
FIGURE 14.8 Erosion and transportation in streams.



(a) Two potholes in the bed of a stream near Ithaca, New York.



(b) This slot canyon in Arizona formed when many potholes linked together.



(c) Streams transport sediment in many forms: dissolved ions are in solution, tiny suspended grains are distributed through the water, and the bed load slides, rolls, and/or undergoes saltation.

When describing a stream's ability to carry sediment, geologists specify its competence and capacity. The **competence** of a stream refers to the maximum particle size it carries; a stream with high competence can carry large particles, whereas one with low competence can carry only small particles. Competence depends on water velocity. Thus, a fast-moving, turbulent stream has greater competence (it can carry bigger particles) than a slow-moving stream, and a stream in flood has greater competence than a stream with normal flow. In fact, the huge boulders that litter the bed of a mountain creek move only during floods. The **capacity** of a stream refers to the total quantity of sediment it can carry. A stream's capacity depends on its competence and discharge. So a large river has more capacity than a small creek.

Depositional Processes

A raging torrent of water can carry coarse and fine sediment—the finer clasts rush along with the water as suspended load, whereas the coarser clasts may bounce and tumble as bed load. If the flow velocity decreases, either because the slope of the streambed becomes shallower or because the channel broadens out and friction between the bed and the water increases, then the competence of the stream decreases and sediment settles out. The size of the clasts that settle at a particular locality depends on the decrease in flow velocity at the locality. For example, if the stream slows by a small amount, only large clasts settle; if the stream slows by a greater amount, medium-sized clasts settle; and if the stream slows almost to a standstill, the fine grains settle. Because of this process of *sediment sorting*, stream deposits tend to be segregated by size—gravel accumulates in one location and mud in another.

Geologists refer to sediments transported by a stream as **fluvial deposits** (from the Latin *fluvius*, meaning river) or **alluvium**. Fluvial deposits may accumulate along the stream bed in elongate mounds, called **bars** (**Fig. 14.9a, b**). In cases where the stream channel makes a broad curve, water slows along the inner edge of a curve, so a crescent-shaped **point bar** bordering the shoreline of the inner curve develops. During floods, a stream may overtop the banks of its channel and spread out over its **floodplain**, a broad flat area bordering the stream. Friction slows the water on the floodplain, so a sheet of silt and mud settles out to comprise floodplain deposits. Where a stream empties at its mouth into a standing body of water, the water slows and a wedge of sediment, called a **delta**, accumulates (**Fig. 14.9c**). We will discuss floodplains and deltas in more detail later in this chapter.

FIGURE 14.9 Sediment, carried and deposited by streams. The clast size depends on stream velocity.

(a) Gravel in a streambed of a mountain stream in Denali National Park, Alaska. The large clasts were carried during floods.

(b) Point bars of mud deposited along a gentle, slowly moving stream in Brazil.

(c) An air photo shows a muddy river emptying into the Black Sea. Currents along the shore are carrying the sediment away.

> **Take-Home Message**
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> **Streams erode by scouring, breaking and lifting, abrasion, and dissolution. They carry sediment as dissolved, suspended, or bed loads. Competence, the ability to carry sediment, depends on flow velocity. Where the velocity decreases, sediment settles out.**

14.5 How Do Streams Change Along Their Length?

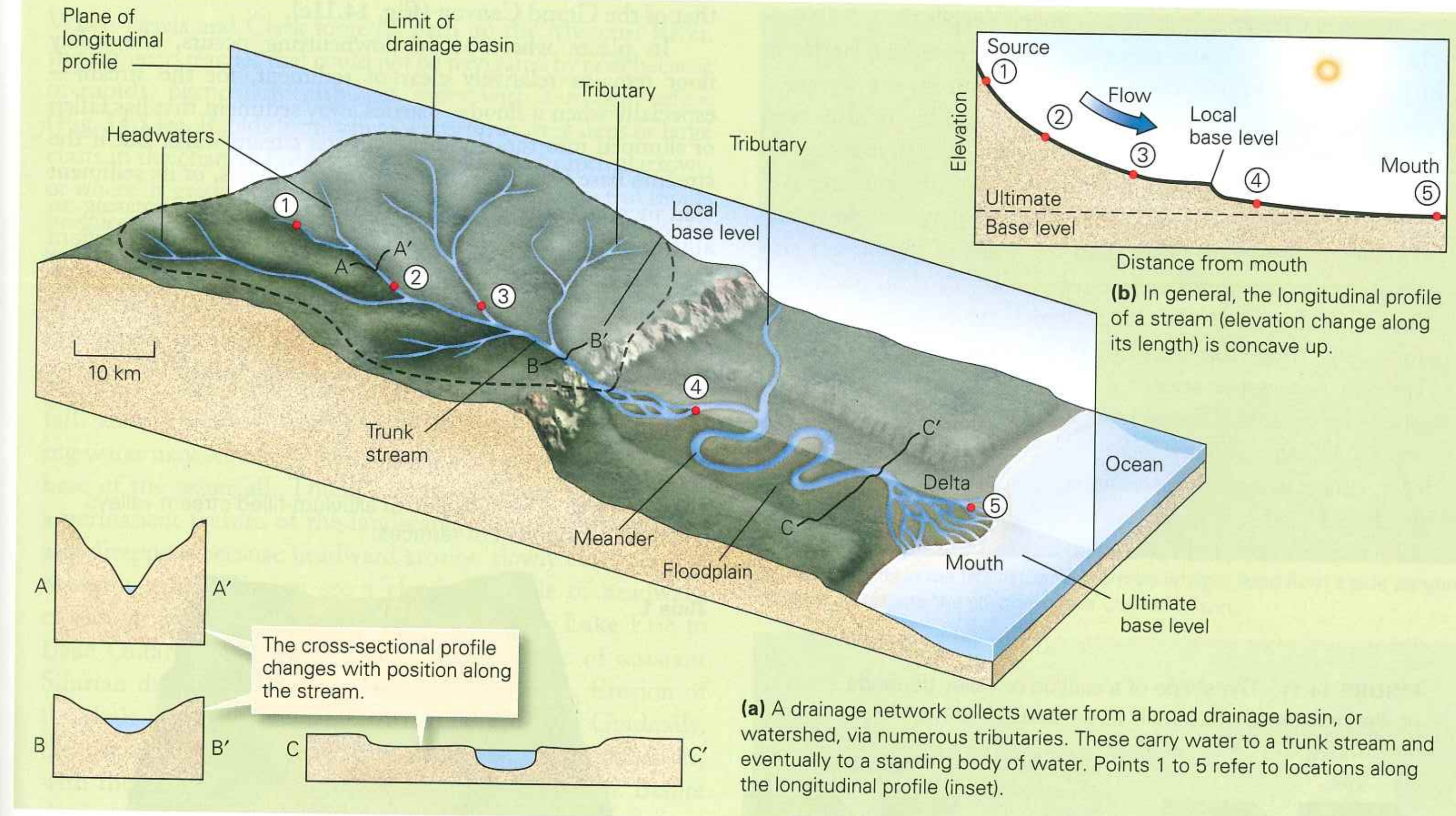
Longitudinal Profiles

In 1803, under President Thomas Jefferson's leadership, the United States bought the Louisiana Territory, a vast tract of land encompassing the western half of the Mississippi drainage basin. At the time, the geography of the territory was a mystery. To fill the blank on the map, Jefferson asked Meriwether Lewis and William Clark to lead a voyage of exploration across the Louisiana Territory to the Pacific.

Lewis and Clark, along with about 40 men, began their expedition at the mouth of the Missouri River, where it joins the Mississippi. At this juncture, the Missouri is a wide, languid stream of muddy water. The group found that along the Missouri's downstream *reach* (an interval along the length of a stream), the river's channel was deep and the water easily navigable. But the farther upstream they went, the more difficult their voyage became, for the **stream gradient** (the slope of the stream channel) became progressively steeper, and the stream's discharge diminished. When Lewis and Clark reached the site of what is now Bismarck, North Dakota, they had to abandon their original boats and haul smaller vessels up reaches where turbulent water plunges over a steep, bouldery bed, and occasionally they had to carry their boats around waterfalls, where water free-falls through the air. When they reached what is now southwestern Montana, they abandoned these boats as well and trudged along the stream valley on foot or on horseback, struggling up steep gradients until they reached the continental divide.

If Lewis and Clark had been able to plot a graph showing their elevation above sea level relative to their distance from the river's mouth, they would have found that the **longitudinal profile** of the Missouri, a cross-sectional image showing the variation in the river's elevation along its length, is roughly a concave-up curve (Fig. 14.10a, b). This curve illustrates that, typically, a stream's gradient is steeper near its headwaters (source) than near its mouth. Near its headwaters, an

FIGURE 14.10 Drainage basins, and the change in character of a stream along its longitudinal profile.



(a) A drainage network collects water from a broad drainage basin, or watershed, via numerous tributaries. These carry water to a trunk stream and eventually to a standing body of water. Points 1 to 5 refer to locations along the longitudinal profile (inset).

(b) In general, the longitudinal profile of a stream (elevation change along its length) is concave up.

idealized stream flows down deep valleys or canyons, whereas near its mouth, it flows over nearly horizontal plains. Real longitudinal profiles are not perfectly smooth curves, but rather display little plateaus and steps, representing interruptions by lakes or waterfalls.

The Concept of a Base Level

The lowest elevation a stream channel's surface can reach at a locality is the **base level** of the stream. A *local* base level is one that occurs at a location upstream of a drainage network's mouth, and the *ultimate* base level (that is, the lowest possible elevation along the stream's longitudinal profile) is sea level. The surface of a trunk stream cannot be lower than sea level, for if it were, the stream would have to flow upslope to enter the sea. The base level limits the depth to which a stream can downcut its channel.

Lakes or reservoirs can act as local base levels along a stream. A ledge of resistant rock can also act as a local base level, for the stream level cannot drop below the ledge until the ledge erodes away. Finally, where a tributary joins a larger stream, the surface of the larger stream acts as the base level for the tributary. Local base levels do not last forever, because running water eventually removes the obstructions that create them.

> **Take-Home Message**
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> **Streams have steeper regional gradients toward their sources, and gentler gradients near their mouths, so longitudinal profiles tend to be concave up. A stream's mouth cannot be lower than its base level. Sea level is the ultimate base level for drainage networks.**

14.6 Streams and Their Deposits in the Landscape

Valleys and Canyons

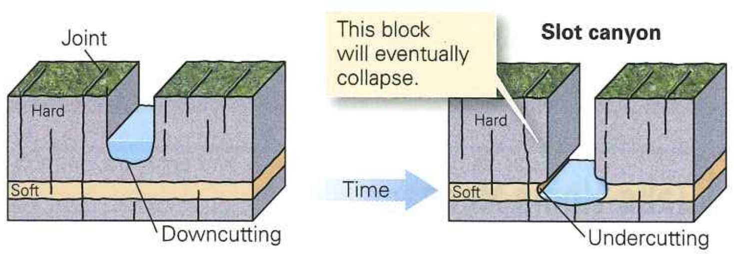
About 17 million years ago, a large block of crust, the region now known as the Colorado Plateau (located in Arizona, Utah, Colorado, and New Mexico), began to rise. Before the rise, the Colorado River had been flowing over a plain not far above sea level, causing little erosion. But as the land uplifted, the river began to downcut. Eventually, its channel lay as much as 1.6 km below the surface of the plateau at the base of a steep-walled gash now known as the Grand Canyon. The formation of the Grand Canyon illustrates a general phenomenon.

In regions where the land surface lies well above the base level, a stream can carve a deep trough, much deeper than the channel itself. If the walls of the trough slope gently, the landform is a *valley*, but if they slope steeply, the landform is a *canyon*.

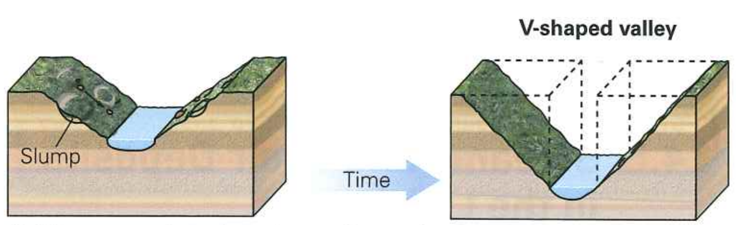
Whether stream erosion produces a valley or a canyon depends on the rate at which downcutting occurs relative to the rate at which mass wasting causes the walls on either side of the stream to collapse. In places where a stream downcuts through its substrate faster than the walls of the stream collapse, erosion creates a slot (steep-walled) canyon. Such canyons typically form in hard rock, which can hold up steep cliffs for a long time (**Fig. 14.11a**). In places where the walls collapse as fast as the stream downcuts, landslides and slumps gradually cause the slope of the walls to approach the angle of repose. When this happens, the stream channel lies at the floor of a valley whose cross-sectional shape resembles the letter V (**Fig. 14.11b**); this landform is called a **V-shaped valley**. Where the walls of the stream consist of alternating layers of hard and soft rock, the walls develop a stair-step shape such as that of the Grand Canyon (**Fig. 14.11c**).

In places where active downcutting occurs, the valley floor remains relatively clear of sediment, for the stream—especially when it floods—carries away sediment that has fallen or slumped into the channel from the stream walls. But if the stream's base level rises, its discharge decreases, or its sediment load increases, the valley floor fills with sediment, creating an alluvium-filled valley (**Fig. 14.12a**). The surface of the alluvium becomes a broad floodplain. If the stream's base level later drops again and/or the discharge increases, the stream will start to cut down into its own alluvium, a process that generates **stream terraces** bordering the present floodplain (**Fig. 14.12b**).

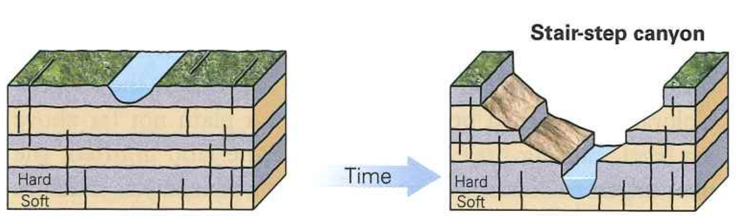
FIGURE 14.11 The shape of a canyon or valley depends on the resistance of its walls to erosion slumping.



(a) If downcutting by the stream happens faster than mass wasting on the walls, a slot canyon forms. The canyon widens as the stream undercuts the walls.



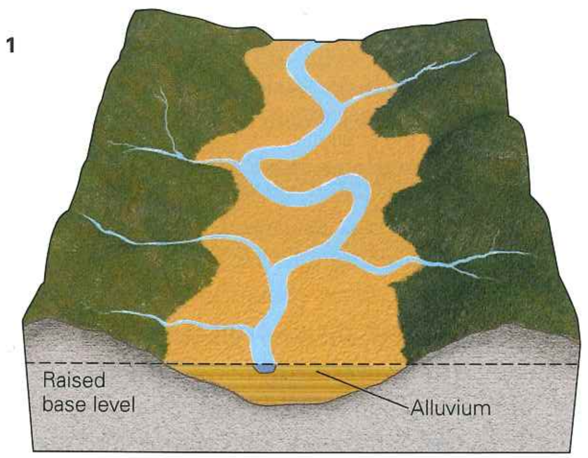
(b) If mass wasting takes place as fast as downcutting occurs, a V-shaped valley develops.



(c) Downcutting through alternating hard and soft layers produces a stair-step canyon.

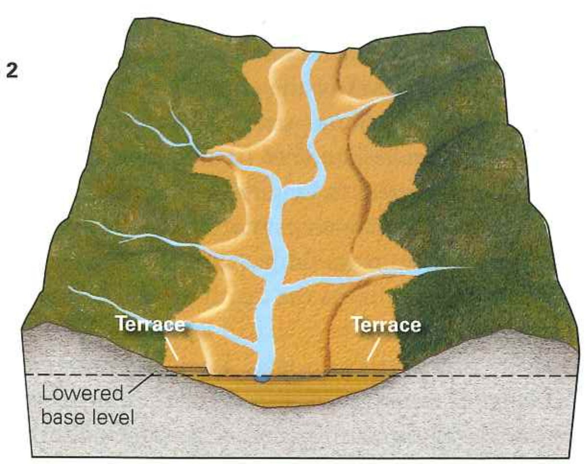
FIGURE 14.12 The evolution of alluvium-filled stream valleys and the development of terraces.

Time 1



(a) A rise in the base level or a decrease in discharge causes the valley to fill with alluvium.

Time 2



(b) Later, if the base level falls or the discharge increases, the stream downcuts through the alluvium and a new, lower floodplain develops. The remnants of the original alluvial plain remain as a pair of terraces.

Rapids and Waterfalls

When Lewis and Clark forged a path up the Missouri River, they came to reaches that could not be navigated by boat because of **rapids**, particularly turbulent water with a rough surface (**Fig. 14.13a**). Rapids form where water flows over steps or large clasts in the channel floor, where the channel abruptly narrows, or where its gradient abruptly changes. The turbulence in rapids produces eddies, waves, and whirlpools that roil and churn the water surface, in the process creating whitewater, a mixture of bubbles and water. Modern-day whitewater rafters thrill to the unpredictable movement of rapids.

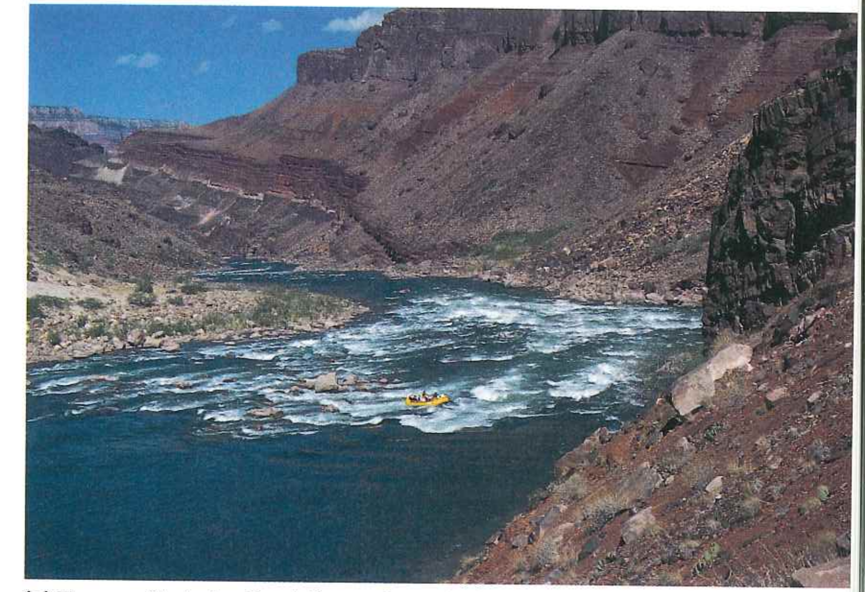
A **waterfall** forms where the gradient of a stream becomes so steep that some or all of the water literally free-falls above the streambed (**Fig. 14.13b**). The energy of falling water may scour a depression, called a plunge pool, at the base of the waterfall. Though a waterfall may appear to be a permanent feature of the landscape, all waterfalls eventually disappear because headward erosion slowly eats back the resistant ledge. We can see a classic example of headward erosion at Niagara Falls. As water flows from Lake Erie to Lake Ontario, it drops over a 55-m-high ledge of resistant Silurian dolostone, which overlies a weak shale. Erosion of the shale leads to undercutting of the dolostone. Gradually, the overhang of dolostone becomes unstable and collapses, with the result that the waterfall migrates upstream. Before the industrial age, the edge of Niagara Falls cut upstream at an average rate of 1 m per year; but since then, the diversion of water from the Niagara River into a hydroelectric power station has decreased the rate of headward erosion to half that (**Fig. 14.14a, b**).

Alluvial Fans and Braided Streams

Where a fast-moving stream abruptly emerges from a mountain canyon into an open plain at the range front, the water that was once confined to a narrow channel spreads out over a broad surface. As a consequence, the water slows and drops its sedimentary load, forming a sloping apron of sediment (sand, gravel, and cobbles) called an **alluvial fan** (**Fig. 14.15a**). The stream then divides into a series of small channels that spread out over the fan. During particularly strong floods, the water contains so much sediment that it becomes a debris flow that spreads over and smooths out the fan's surface.

In some localities, streams carry abundant coarse sediment during floods but cannot carry this sediment during normal flow. Thus, during normal flow, the sediment settles out and chokes the channel. As a consequence, the stream divides into numerous strands weaving back and forth between elongate bars of gravel and sand. The result is a **braided stream**—the name emphasizes that the streams entwine like strands of hair in a braid (**Fig. 14.15b**).

FIGURE 14.13 Examples of rapids and waterfalls.



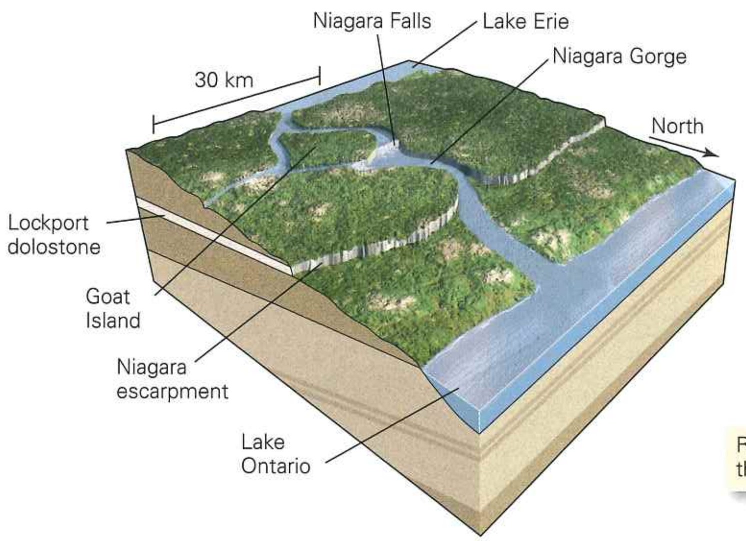
(a) These rapids in the Grand Canyon formed when a flood from a side canyon dumped debris into the channel of the Colorado River.

(b) Iguaçu Falls, at the Brazil-Argentina border, spills across layers of basalt. The basalt acts as a resistant ledge.

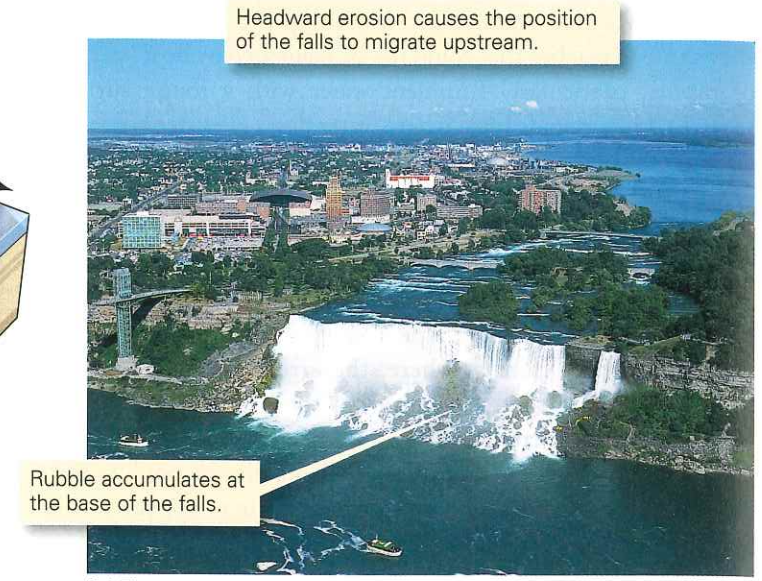
Meandering Streams and Their Floodplains

A riverboat cruising along the lower reaches of the Mississippi River cannot sail in a straight line, for the river channel winds back and forth in a series of snake-like curves called **meanders** (**Fig. 14.16a**). In fact, the boat has to go 500 km along the river channel to travel 100 km as the crow flies.

FIGURE 14.14 The formation of Niagara Falls, at the border between Ontario, Canada, and New York State. The falls tumble over the Lockport Dolomite, a relatively strong rock layer.



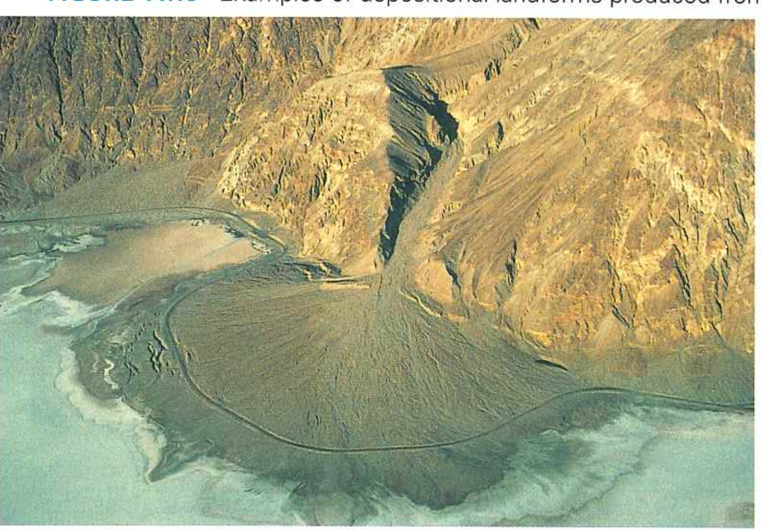
(a) Niagara Falls lies where water spills over the Niagara escarpment.



(b) The American Falls, a part of Niagara Falls.

How do meanders evolve? Even if a stream starts out with a straight channel, natural variations in the water depth and associated friction cause the fastest-moving current to swing back and forth. The water erodes the side of the stream more effectively where it flows faster, so it begins to cut away faster on the outer arc of the curve. Thus, each curve begins to migrate sideways and grow more pronounced until it becomes a meander (**Fig. 14.16b**). On the outside edge of a meander, erosion continues to eat away at the channel wall, forming a cut bank. On the inside edge, water slows down so that its competence decreases and sediment accumulates, forming a wedge-shaped deposit called a point bar, as noted earlier. With continued erosion, a meander may curve through more than 180°, so that the cut bank at the meander's entrance approaches the cut bank at its end, leaving a *meander neck*, a narrow isthmus of land separating the portions of the meander. When erosion eats through a meander neck, a straight reach called a *cutoff* develops. The meander that has been cut off is called an **oxbow lake** if it remains filled with water, or an *abandoned meander* if it dries out (**Fig. 14.16c**). Streams that develop many meanders are known, not surprisingly, as meandering streams. The course of a meandering stream naturally

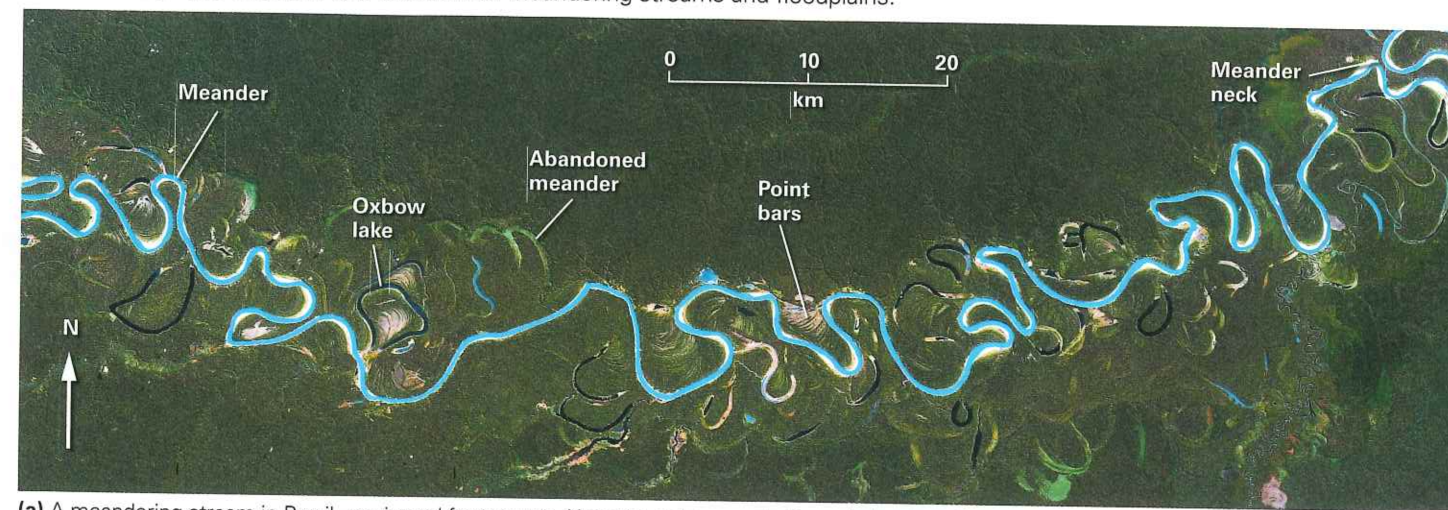
FIGURE 14.15 Examples of depositional landforms produced from stream sediment.



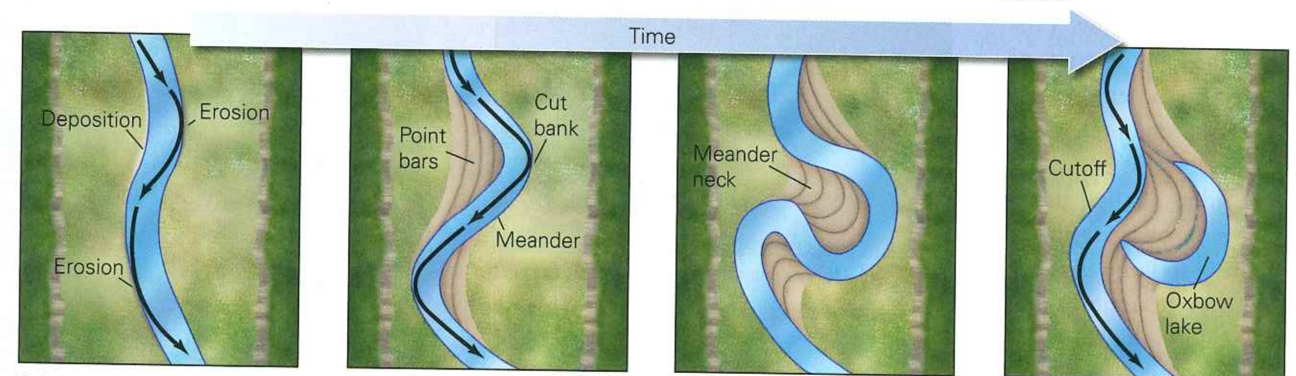
(a) An alluvial fan in Death Valley, California, consists of sand, gravel, and debris flows. The curving black line is a road.

(b) A braided stream, carrying meltwater from a glacier near Denali, Alaska, deposits elongate bars of gravel.

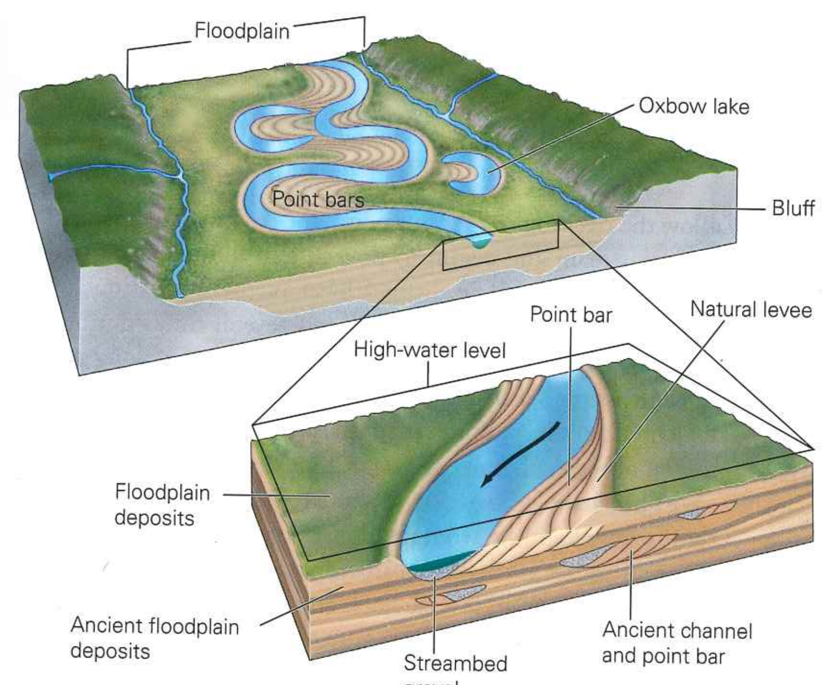
FIGURE 14.16 The character and evolution of meandering streams and floodplains.



(a) A meandering stream in Brazil, as viewed from space. Note the oxbows, cutoffs, and abandoned meanders.



(b) Meanders evolve because erosion occurs faster on the outer bank of a curve, and deposition takes place on the inner curve. Eventually, a cutoff isolates an oxbow lake.



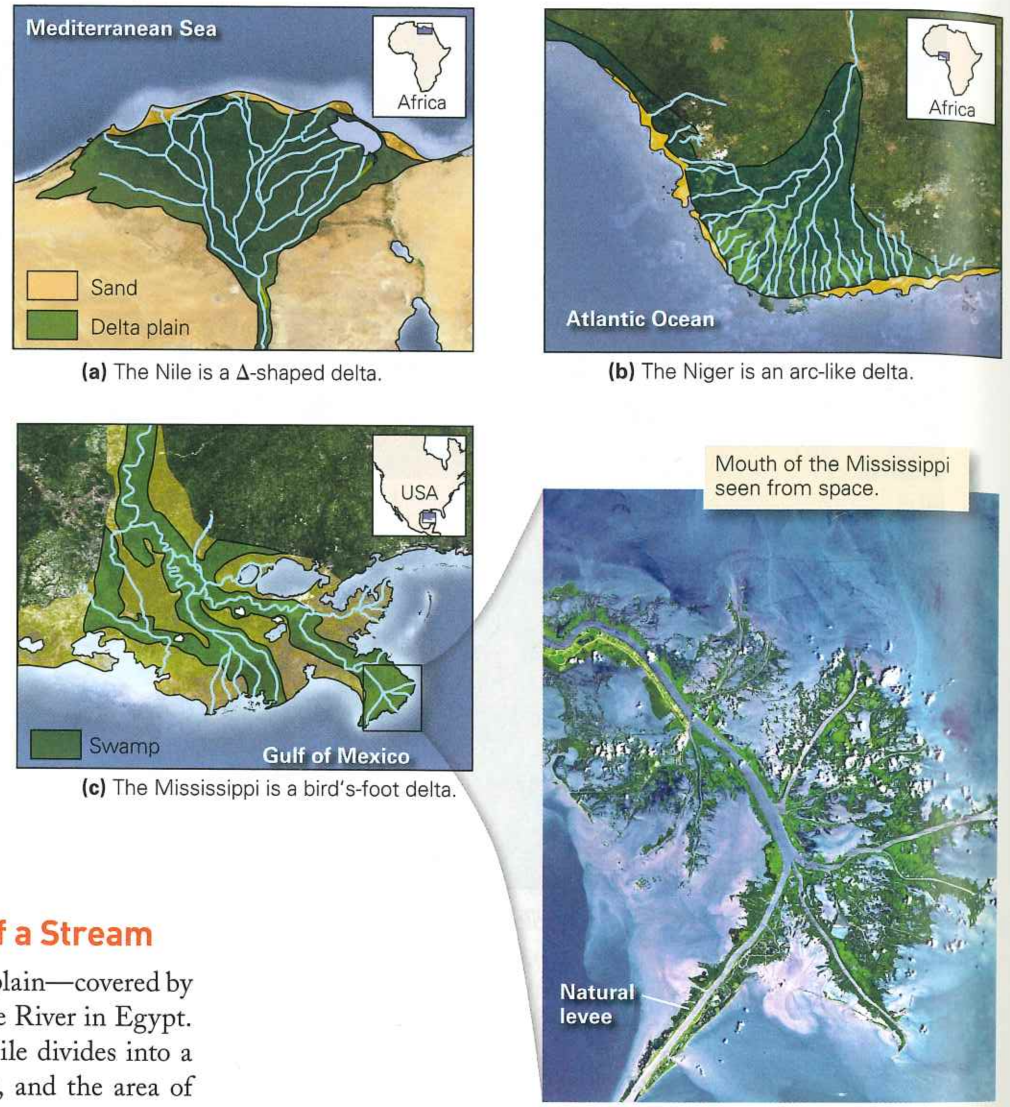
(c) Landforms along meandering streams include natural levees, point bars, and floodplains. Older deposits record the position of ancient channels and floodplains.

(d) The flat land of this flood plain hosts farm fields. Trees delineate the channel.

changes over time, on a time scale of years to centuries, as new meanders grow and old ones are cut off and abandoned.

Most meandering stream channels cover only a relatively small portion of a broad, gently sloping **floodplain** (**Fig. 14.16d**). Floodplains, as we noted earlier, are so named because during a flood, water overtops the edge of the stream channel and spreads out over the floodplain. In many cases, a floodplain terminates at its sides along a bluff, or escarpment; large floods may cover the entire floodplain from bluff to bluff. As the water rises above the channel walls and starts to spread out, over the floodplain, friction slows down the flow. This slowdown decreases the competence of the running water, so sediment settles out along the edge of the channel. Over time, the accumulation of this sediment creates a pair of low ridges, called **natural levees**, on either side of the stream. Natural levees may grow so large that the floor of the channel may become higher than the surface of the floodplain.

FIGURE 14.17 Delta shape varies depending on current activity, waves, and vegetation.



(a) The Nile is a Δ-shaped delta.

(b) The Niger is an arc-like delta.

(c) The Mississippi is a bird's-foot delta.

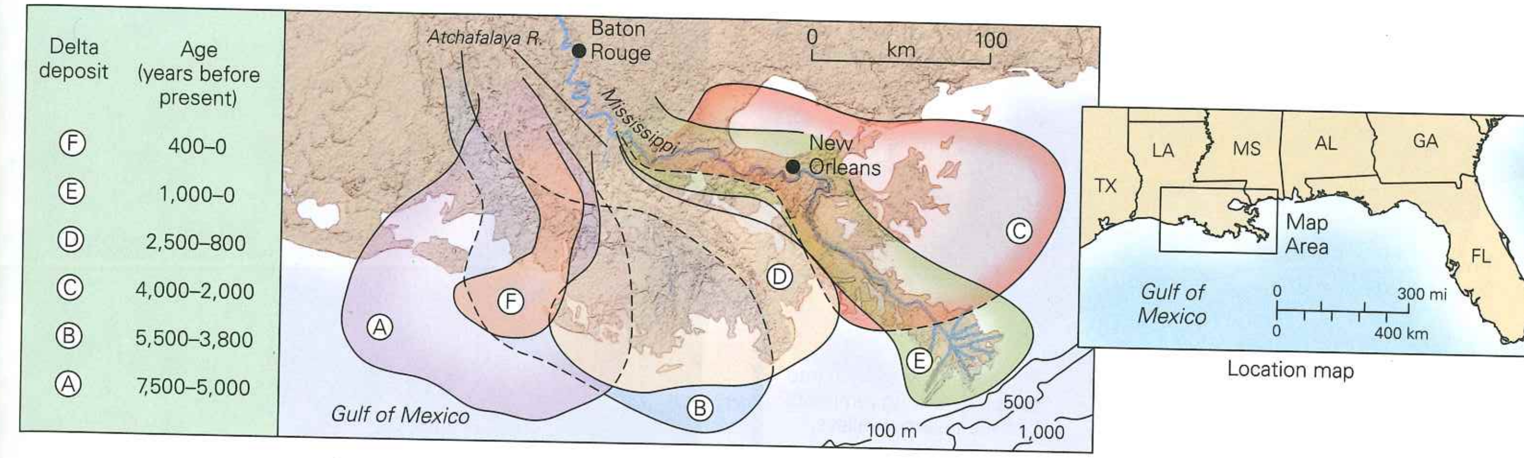
Deltas: Deposition at the Mouth of a Stream

Along most of its length, only a narrow floodplain—covered by green, irrigated farm fields—borders the Nile River in Egypt. But at its mouth, the trunk stream of the Nile divides into a fan of smaller streams, called **distributaries**, and the area of green agricultural lands broadens into a triangular patch. The Greek historian Herodotus noted that this triangular patch resembles the shape of the Greek letter delta (Δ), and so the region became known as the Nile Delta. Deltas develop where the running water of a stream enters standing water, the current slows, the stream loses competence, and sediment settles out. This can happen in either a lake or the sea (see Chapter 6).

Geologists refer to any wedge of sediment formed at a river mouth as a delta, even though relatively few have the triangular shape of the Nile Delta (**Fig. 14.17a–c**). Some deltas curve smoothly outward, whereas others consist of many elongate lobes formed at different times. Bird's-foot deltas, so-named because they resemble the scrawny toes of a bird, develop where several distributaries extend far out into relatively calm water; the end of the Mississippi's active channel ends in a bird's-foot delta (Fig. 14.17a–c). The existence of several overlapping deltas indicates that the main course of the river in the delta has shifted on several occasions. These shifts occur when a toe builds so far out into the sea that the slope of the stream becomes too gentle to allow the river to flow. At this point, the river overflows a natural levee upstream and begins to flow in a new direction, an event called an *avulsion*. The distinct lobes of the Mississippi Delta suggest that avulsions have happened several times during the past 9,000 years (**Fig. 14.18**). New Orleans, built along one of the Mississippi's distributaries, may eventually lose its riverfront, for a break in a levee upstream of the city could divert the Mississippi into the Atchafalaya River channel.

The shape of a delta depends on many factors. Deltas that form where the strength of the river current exceeds that of ocean currents have a bird's-foot shape, since the sediment can be carried far offshore. In contrast, deltas that form where the ocean currents are strong have a Δ shape, for the ocean currents redistribute sediment in bars running parallel to the shore. And in places where waves and currents are strong enough to remove sediment as fast as it arrives, a river has no delta at all.

FIGURE 14.18 A map showing ancient lobes of the Mississippi Delta. A major flood could divert water from the Mississippi into the channel of the Atchafalaya.



With time, the sediment of a larger delta compacts, and the weight of the delta pushes down the crust below. As a consequence, the surface of a delta slowly sinks. Distributaries can provide sediment that fills the resulting space so that the delta's surface remains at or just above sea level, forming a broad, flat area called a *delta plain*. But if people build up artificial levees to constrain the river to its channel, sediment gets carried directly to the seaward edge of the delta and the delta's interior "starves" (does not receive sediment). When this happens, the delta's surface drops below sea level. Because of this process, much of New Orleans lies below sea level (see Chapter 15).

> **Take-Home Message**
>
> **Erosion carves valleys and canyons, with shapes that depend on the balance between slope-collapse and downcutting rates. Streams choked with sediment become braided; those following snake-like paths are meandering. Deltas build into standing water.**

14.7 The Evolution of Drainage

Beveling Topography

Imagine a place where continental collision uplifts a region; the landscape will evolve (**Fig. 14.19a**). At first, rivers have steep gradients, flow over many rapids and waterfalls, and cut deep valleys. But with time, rugged mountains become low, rounded hills; once-deep, narrow valleys broaden into wide floodplains with more gradual gradients. As more time passes, even the low hills are beveled down, becoming small mounds or even disappearing altogether. (Some geologists have referred to the resulting landscape as a peneplain, from the Latin *paene*, which means almost; it lies at an elevation close to that of a stream's base level.)

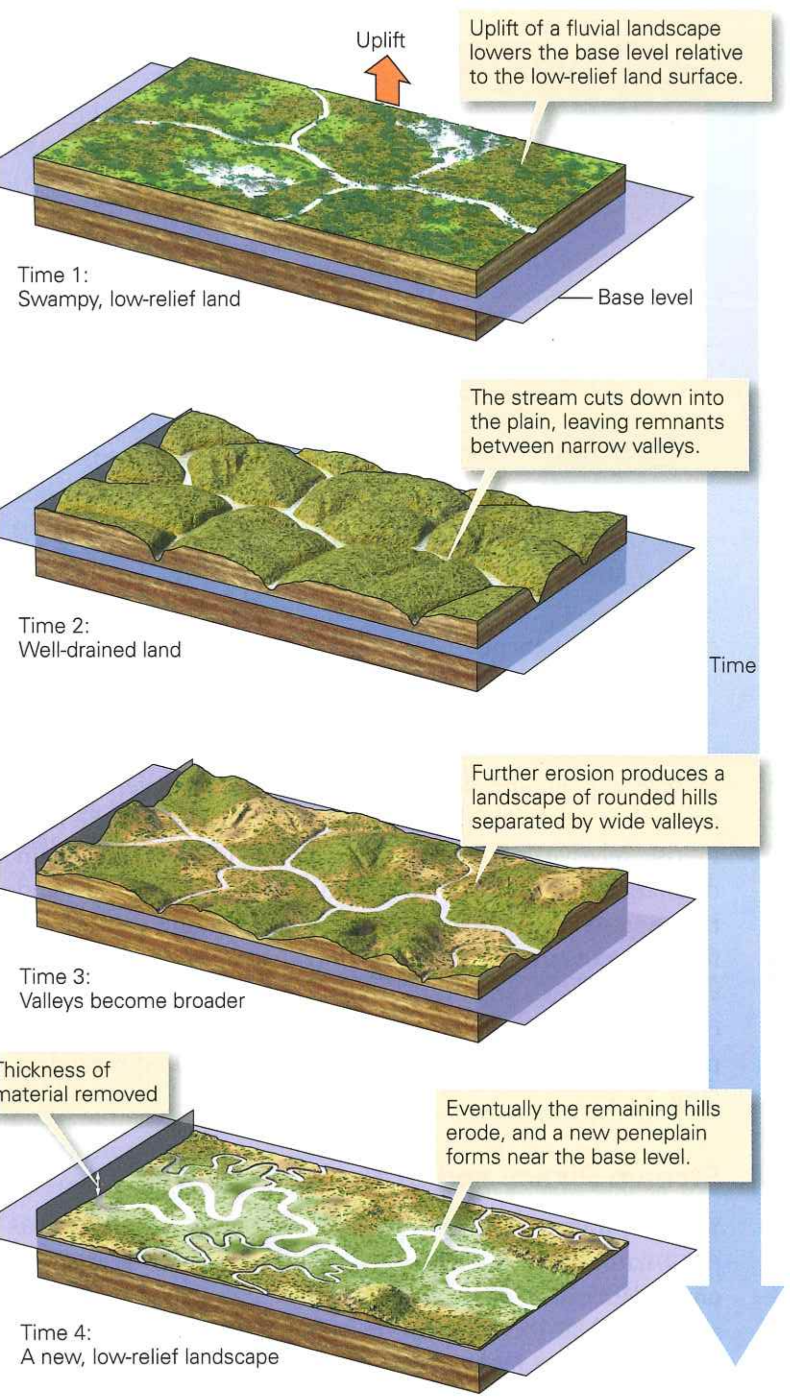
Though the above model makes intuitive sense, it is an oversimplification. Plate tectonics can uplift the land again, and/or global sea-level rise or fall can change the base level, so in reality peneplains rarely develop before downcutting begins again. **Stream rejuvenation** occurs when a stream starts to downcut into a land surface whose elevation lies near the stream's base level. Rejuvenation can be triggered by several phenomena, such as: a drop in base level, as happens when sea level falls; an uplift event that causes the land to rise relative to the base level; or an increase in stream discharge that makes the stream more able to erode and transport sediment. As we've seen, rejuvenation can lead to formation of stream terraces in alluvium. In cases where rejuvenation causes a stream to erode deeply into the land, a new canyon or valley will develop. If the rejuvenated stream had a meandering course, downcutting produces incised meanders (**Fig. 14.19b**).

Stream Piracy and Drainage Reversal

Stream piracy sounds like pretty violent stuff. In reality, it's just a natural process that happens when headward erosion by one stream causes the stream to intersect the course of another stream. When this happens, the pirate stream "captures" the water of the stream that it has intersected, so that the water of the captured stream starts to flow down the pirate stream. Because of piracy, the channel of the captured stream, downstream of the point of capture, dries up (**Fig. 14.20a, b**). In some cases, stream capture changes a "water gap" (a stream-carved notch through a ridge) into a dry "wind gap." In 1775, Daniel Boone, the legendary pioneer, led settlers through the Cumberland Gap, a wind gap in the Appalachians, to new homesteads in western Kentucky.

The pattern of stream flow in an area can also be altered, over time, on a continental scale. For example, when South America and Africa were adjacent to each other in Pangaea,

FIGURE 14.19 Fluvial landscapes evolve over time.



(a) When the base level drops, streams downcut and a hilly landscape develops. The relief, however, eventually erodes away.

(b) The "goosenecks" of the San Juan River, Utah, are incised meanders.

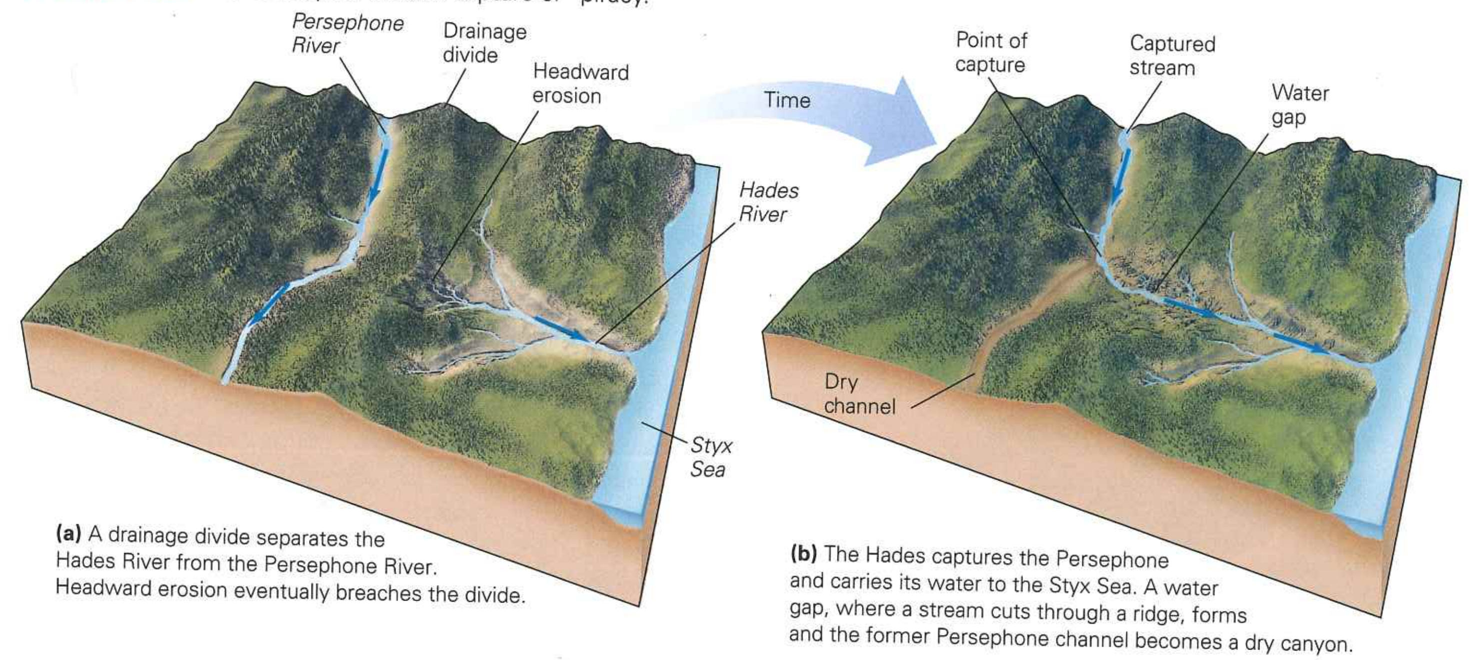
a highland existed along the boundary between the two continents, and the main drainage network of northern South America flowed westward. Later, when South America rifted away from Africa, a convergent plate boundary developed along the western margin of South America, causing the Andes Mountains to rise. The uplift of the Andes caused a **drainage reversal**, in that the overall slope direction of the drainage network became the opposite of what it once had been. As a consequence, westward flow became impossible, and the eastward-flowing Amazon drainage network developed.

Superposed and Antecedent Streams

The structure and topography of the landscape do not always appear to control the path, or course, of a stream. For example, imagine a stream that carves a deep canyon straight across a strong mountain ridge—why didn't the stream find a way around the ridge? We distinguish two types of streams that cut across resistant topographic highs:

- *Superposed streams*: Imagine a region in which streams start to flow over horizontal beds of strata that unconformably overlie folded strata. When the streams eventually erode down through the unconformity and start to downcut into the folded strata, they maintain their earlier course, ignoring the structure of the folded strata. Geologists call such streams **superposed streams**, because their preexisting geometry has been laid down on underlying rock structure (**Fig. 14.21a, b**).
- *Antecedent streams*: In some cases, tectonic activity (such as subduction or collision) causes a mountain range to rise up beneath an already established stream. If the stream downcuts as fast as the range rises, it can maintain its course and will cut right across the range. Geologists call such streams **antecedent streams** (from the Greek *ante*, meaning before) to emphasize that they existed before the range uplifted. Note that if the range rises faster than the stream downcuts, the new highlands divert (change) the stream's course so that it flows parallel to the range face (**Fig. 14.22a–c**).

FIGURE 14.20 The concept of stream capture or "piracy."



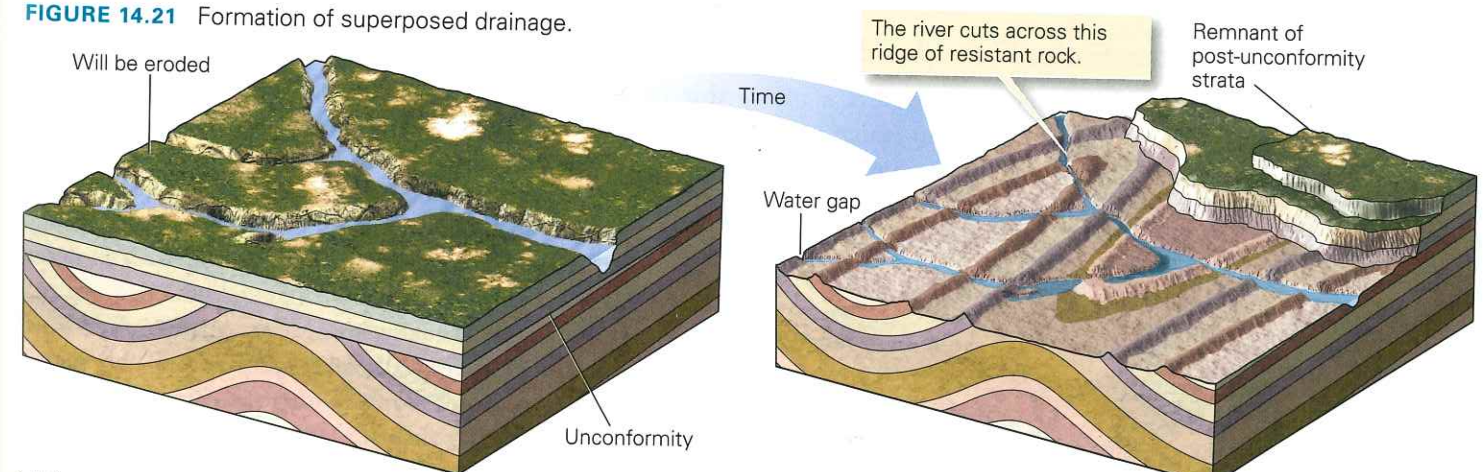
(a) A drainage divide separates the Hades River from the Persephone River. Headward erosion eventually breaches the divide.

(b) The Hades captures the Persephone and carries its water to the Styx Sea. A water gap, where a stream cuts through a ridge, forms and the former Persephone channel becomes a dry canyon.

Take-Home Message

Stream-carved landscapes evolve over time as gradients diminish and ridges between valleys erode away. Superposed streams attain their shape before cutting down into rock structure, whereas antecedent streams cut while the land beneath them uplifts.

FIGURE 14.21 Formation of superposed drainage.



(a) A superposed stream establishes its geometry while flowing over a uniform substrate above an unconformity.

(b) When erosion exposes underlying rock with a different structure, the river is superposed on the structure. As a result, it cuts across resistant ridges instead of flowing around them.

14.8 Raging Waters

The Inevitable Catastrophe

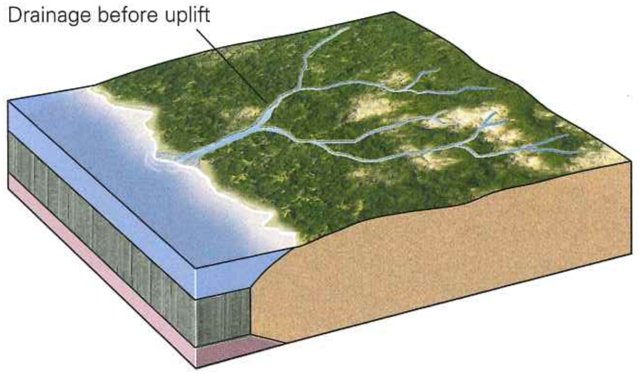
Up to now, this chapter has focused on the process of drainage formation and evolution and on the variety of landscape features formed by streams (see **Geology at a Glance**, pp. 438–439). Now we turn our attention to the havoc that a stream can cause when flooding takes place. Floods can be catastrophic—they can strip land of forests and buildings, they can bury land in clay and silt, and they can submerge cities. A **flood** occurs when the volume of water flowing down a stream exceeds the volume of the stream channel, so water rises out of the normal channel and spreads out over a floodplain or delta plain, or fills a canyon to a greater depth than normal.

Floods happen (1) during abrupt, heavy rains, when water falls on the ground faster than it can infiltrate and thus becomes surface runoff; (2) after a long period of continuous rain, when the ground has become saturated with water and can hold no more; (3) when heavy snows from the previous winter melt rapidly in response to a sudden hot spell; or (4) when a dam holding back a lake or reservoir, or a levee or retaining wall holding back a river or canal, suddenly collapses and releases the water that it held back.

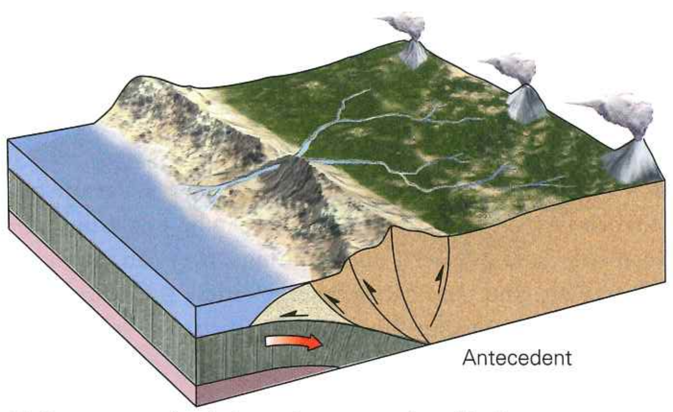
Geologists find it convenient to divide floods into two general categories. Floods that occur during a "wet season," when rainfall is heavy or when winter snows start to melt, are called **seasonal floods**. Floods of this type typically take place in tropical regions during monsoons, and in temperate regions during the spring when storms drench the land frequently and/or a heavy winter snowpack melts. When seasonal floods submerge floodplains, they produce *floodplain floods*, and when they submerge delta plains they produce *delta-plain floods* (**Fig. 14.23a–c**).

Events during which the floodwaters rise so fast that it may be impossible to escape from the path of the water are called **flash floods** (**Fig. 14.24a, b**). These happen during unusually intense rainfall or as a result of a dam collapse (as in the 1889 Johnstown flood) or levee failure. During a flash flood, a canyon or valley may fill to a level many meters above normal. In some cases, a wall of water may slam downstream with great force, leaving devastation in its wake, but the floodwaters subside after a short time. Flash floods can be particularly unexpected in arid or semiarid climates, where isolated thundershowers may suddenly fill the channel of an otherwise dry wash, whose unvegetated ground allows runoff to reach the channel faster. Such a flood may even affect areas downstream that had not received a drop of rain.

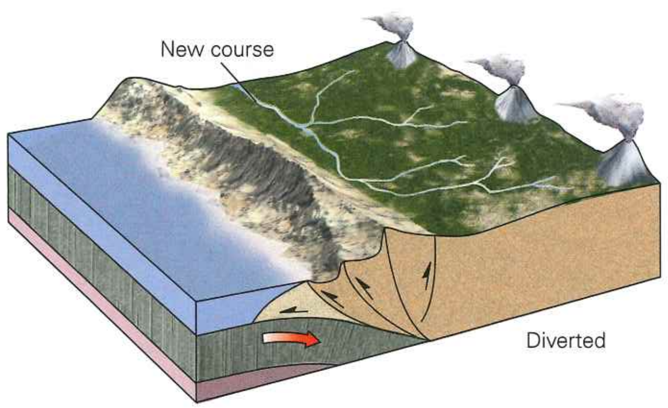
FIGURE 14.22 Development of antecedent and diverted streams.



(a) Prior to mountain building, a stream flows across a flat landscape to the sea.



(b) If stream erosion is faster than mountain uplift, the stream cuts across the range and is antecedent.



(c) If uplift happens faster than erosion, the stream is diverted and flows along the edge of the range.

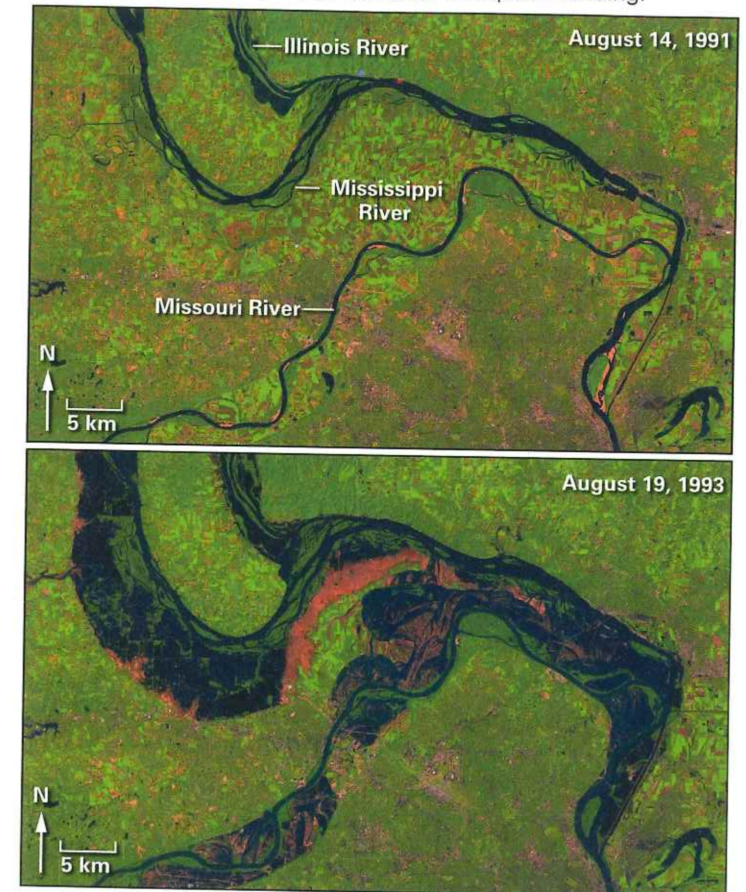
Case Study: A Seasonal Flood

In the spring of 1993, the jet stream, the high-altitude (10–15 km high) wind current that strongly affects weather systems, drifted southward. For weeks, the jet stream's cool, dry air formed an invisible wall that trapped warm, moist air from the Gulf of Mexico over the central United States. When this air rose to higher elevations, it cooled, and the water it held condensed and fell as rain, rain, and more rain. In fact, almost a whole year's supply of rain fell in just that spring—some regions received 400% more than usual. Because the rain fell over such a short period, the ground became saturated and could no longer absorb additional water, so the excess entered the region's streams, which carried it into the Missouri and Mississippi rivers. Eventually, the water in these rivers rose above the height of levees or broke through levees, and spread out over the floodplain. By July, parts of nine states were underwater (see Fig. 14.23a).

The roiling, muddy flood uprooted trees, cars, and even coffins (which floated up from inundated graveyards). All barge traffic along the Mississippi came to a halt, bridges and roads were undermined and washed away, and towns along the river were submerged. For example, in Davenport, Iowa, the riverfront district and baseball stadium were covered with 4 m (14 ft) of water. In Des Moines, Iowa, 250,000 residents lost their supply of drinking water when floodwaters contaminated the municipal water supply with raw sewage and chemical fertilizers. Rowboats replaced cars as the favored mode of transportation in towns where only the rooftops remained visible. In St. Louis, Missouri, the river crested 14 m (47 ft) above flood stage.

For 79 days, the flooding continued. When the water finally subsided, it left behind a thick layer of sediment, filling living rooms and kitchens in floodplain towns and burying crops in floodplain fields. In the end, more than 40,000 square km of the floodplain had been submerged, 50 people died, at least 55,000 homes were destroyed, and countless acres of crops were buried. Officials estimated that the flood caused over $12 billion in damage. Comparable flooding happened again in the spring of 2011, in the Mississippi and Missouri drainage basins.

FIGURE 14.23 Examples of seasonal floodplain flooding.



(a) Satellite photos (before and during) show the extent of flooding during the 1993 Mississippi River flood.

(b) Great Falls, Montana, was submerged by floodwaters in 1975.

(c) In 2007, contaminated floodwaters spread disease in Indonesia.

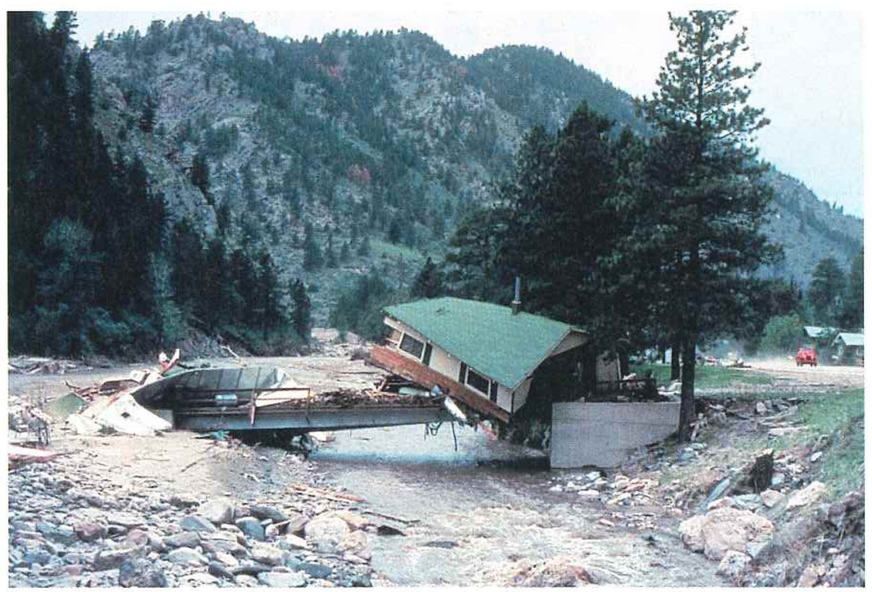
Case Study: A Flash Flood

On a typical sunny day in the Front Range of the Rocky Mountains, north of Denver, Colorado, the Big Thompson River seems quite harmless. Clear water, dripping from melting ice and snow higher in the mountains, flows down its course through a narrow canyon, frothing over and around boulders. In places, vacation cabins, campgrounds, and motels line the river. The landscape seems immutable, but as is the case with so many geologic features, permanence is an illusion.

On July 31, 1976, easterly winds blew warm, moist air from the Great Plains toward the Rocky Mountain front. As this air rose over the mountains, towering thunderheads built up, and at 7:00 P.M. rain began to fall. It poured, in quantities that even old-timers couldn't recall. In a little over an hour, 19 cm (7.5 inches) of rain drenched the watershed of the Big

FIGURE 14.24 Flash floods can occur after torrential rains.

(a) A flash flood in a desert region of Israel has washed over a highway forcing the evacuation of truckers.



(b) During the 1976 Big Thompson River flash flood, this house was carried off its foundation and dropped on a bridge.

Thompson River. The river's discharge grew to more than four times the maximum recorded at any time during the previous century. The river rose quickly, in places reaching depths several meters above normal. Turbulent water swirled down the canyon at up to 8 m per second and churned up so much sand and mud that it became a viscous slurry. Slides of rock and soil tumbled down the steep slopes bordering the river and fed the torrent with even more sediment. The water undercut house foundations and washed the houses away, along with their inhabitants (see Fig 14.24b). Roads and bridges disappeared, and boulders that had stood like landmarks for generations bounced along in the torrent like beach balls, striking and shattering other rocks along the way. Cars drifted downstream until they finally wrapped like foil around obstacles. When the flood subsided, the canyon had changed forever, and 144 people had lost their lives.

Living with Floods

Flood Control Mark Twain once wrote of the Mississippi that we "cannot tame that lawless stream, cannot curb it or confine it, cannot say to it, 'go here or go there,' and make it obey." Was Twain right? Since ancient times, people have attempted to control courses of rivers so as to prevent undesired flooding. In the 20th century, flood-control efforts intensified as the population living along rivers increased. For example, since the passage of the 1927 Mississippi River Flood Control Act (drafted after a disastrous flood took place that year), the U.S. Army Corps of Engineers has labored to control the Mississippi. First, engineers built about 300 dams along the river's tributaries so that excess runoff could be stored in the reservoirs and later be released slowly. Second, they built **artificial levees** of sand and mud, and built concrete flood walls to increase the channel's volume. Artificial levees and flood walls isolate a discrete area of the floodplain (**Fig. 14.25a–c**).

Although the Corps' strategy worked for floods up to a certain size, it was insufficient to handle the 1993 and 2011 floods when reservoirs filled to capacity, and additional runoff headed downstream. The river rose until it spilled over the tops of some levees and undermined others. "Undermining" occurs when rising water levels increase the water pressure on the river side of the levee, forcing water through sand under the levee. In susceptible areas, water begins to spurt out of the ground on the dry side of the levee, thereby washing away the levee's support. The levee finally becomes so weak that it collapses, and water fills in the area behind it. In some cases, the Corps of Engineers intentionally dynamites levees along a relatively unpopulated reach of the river upstream of a vulnerable town. This diverts water out onto a portion of the floodplain where the water will do less damage, and prevents the floodwaters from overtopping levees close to the town.

Another solution to flooding in some localities may involve restoration of wetland areas along rivers, for wetlands can absorb significant quantities of floodwater. Also, where appropriate, planners may prohibit construction within designated land areas adjacent to the channel, so that floodwater can fill these areas without causing expensive damage. The existence of such areas, which are known as **floodways**, effectively increases the volume of water that the river can carry and thus helps prevent the water level from rising too high.

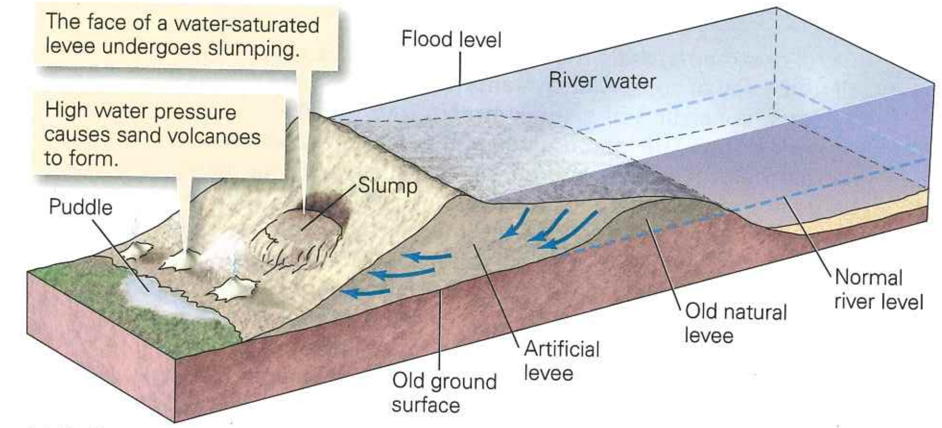
Evaluating Flooding Hazard When making decisions about investing in flood-control measures, mortgages, or insurance, planners need a basis for defining the hazard or risk posed by flooding. If floodwaters submerge a locality every year, a bank officer would be ill advised to approve a loan that would promote building there. But if floodwaters submerge the locality very rarely, then the loan may be worth the risk. Geologists characterize the risk of flooding in two ways. The **annual probability** of flooding indicates the likelihood that a flood of a given size or larger will happen at a specified locality during any given year. For example, if we say that a flood of a given size has an annual probability of 1%, then we mean there is a 1 in 100 chance that a flood of at least this size will happen in any given year. The **recurrence interval** of a flood of a given size is defined as the *average* number of years between successive floods of at least this size. For example, if a flood of a given size happens once in 100 years, *on average*, then it is assigned a recurrence interval of 100 years and is called a "100-year-flood." Note that annual probability and recurrence interval are related:

Did you ever wonder . . .
what do newscasters mean by a "100-year flood"?

$$\text{annual probability} = \frac{1}{\text{recurrence interval}}$$

For example, the annual probability of a 50-year-flood is 1/50, which can also be written as 0.02 or 2%.

FIGURE 14.25 Holding back rivers to prevent floods.



(a) Engineers build artificial levees to keep floodwater in the channel. Levees weaken and may fail when infiltrated by water.

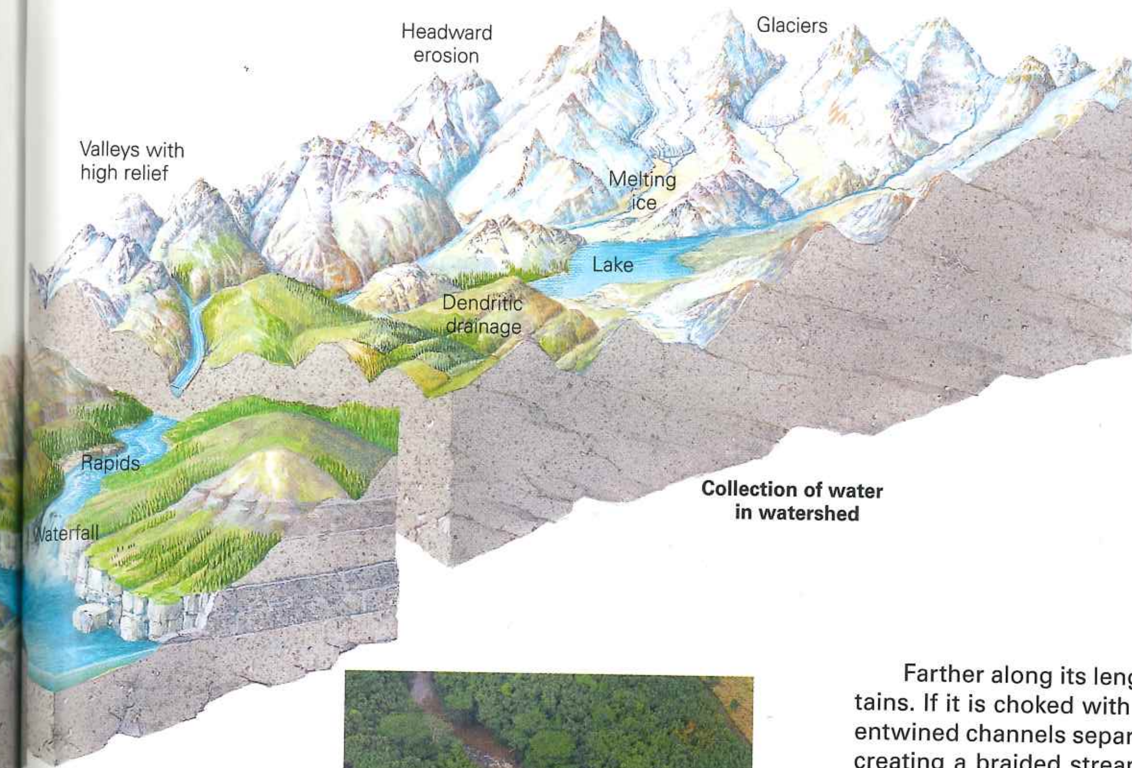
(b) At a levee breach, water flows from the river to the floodplain.

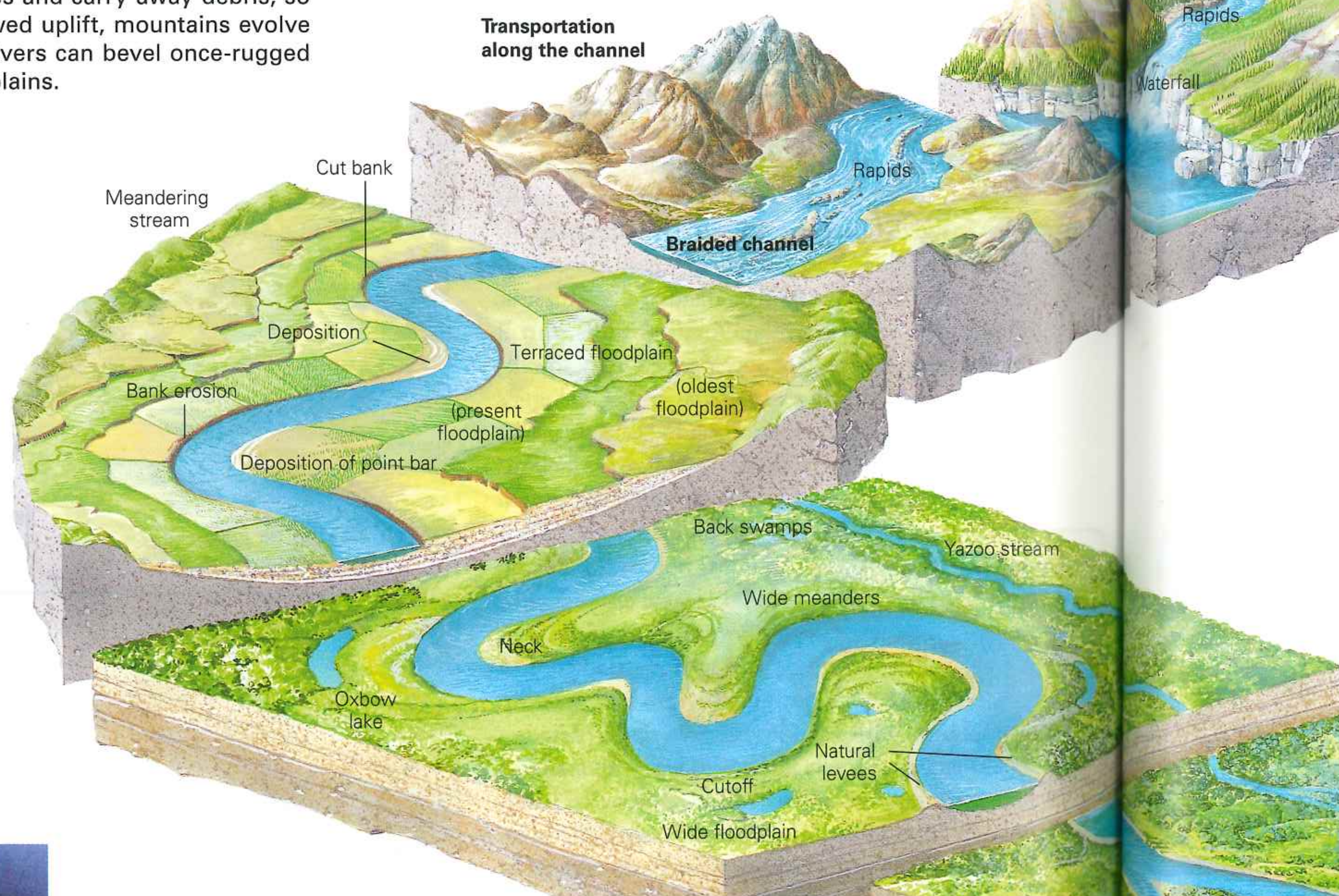
(c) A concrete floodwall at Cape Girardeau, Missouri. When floods threaten, a crane drops a gate into the slot to hold out the river.

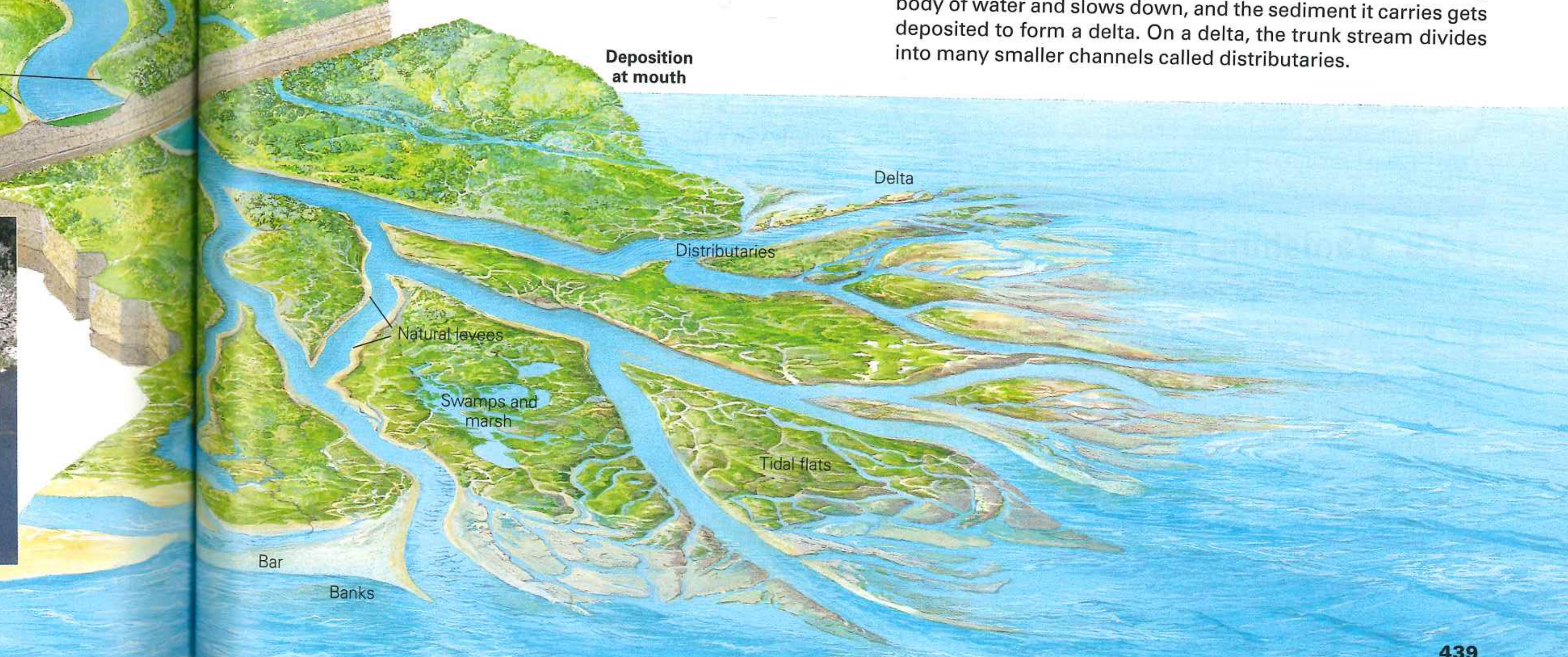
River Systems

Rivers, or streams, drain the landscape of surface runoff. Typically, an array of connected streams called a drainage network develops, consisting of a trunk stream into which numerous tributaries flow. The land drained is the network's watershed. A stream starts from a source, or headwaters. Some headwaters are in the mountains, collecting water from rainfall or from melting ice and snow. In the mountains, streams carve deep, V-shaped valleys and tend to have steep gradients. For part of its course, a river may flow over a bouldery bed, forming rapids, and it may drop off an escarpment, as a waterfall. Rivers gradually erode landscapes and carry away debris, so after a while, if there is no renewed uplift, mountains evolve into gentle hills. Through time, rivers can bevel once-rugged mountain ranges into nearly flat plains.

Developing drainage networks.







Streams contribute to carving mountains.

Waterfall in Hawaii spilling over a basalt ledge.

Farther along its length, the river emerges from the mountains. If it is choked with sediment, it may split into numerous entwined channels separated from one another by gravel bars, creating a braided stream. Where a stream that has not been choked by sediment flows over flat ground, it becomes a meandering stream, winding back and forth in snake-like curves called meanders. The current flows faster on the outer arc of a curve, so erosion takes place there, whereas the current flows more slowly on the inner arc, where it drops sediment. Because of erosion and deposition, a meandering stream changes shape over time. Occasionally, a meander may be cut off, leaving a curving lake called an oxbow lake. A broad floodplain, covered with water only during floods, may develop on either side of the stream. Natural levees build up between the channel and the floodplain from sediment dropped as a flooding river starts to spill out of its channel. Eventually, a river reaches a standing body of water and slows down, and the sediment it carries gets deposited to form a delta. On a delta, the trunk stream divides into many smaller channels called distributaries.

Point bars forming on inner curves.

Meanders, abandoned meanders, and cutoffs.

A small delta in a mountain lake.

Unfortunately, some people are misled by the meaning of recurrence interval, and think that they do not face future flooding hazard if they buy a home within an area just after a 100-year flood has occurred. Their confidence comes from making the incorrect assumption that because such flooding just happened, it can't happen again until "long after I'm gone." They may regret their decision because two 100-year floods can occur in consecutive years or even in the same year (alternatively, the interval between such floods could be, say, 210 years).

The recurrence interval for a flood along a particular river reflects the size of a flood. For example, the discharge of a 100-year flood is larger than that of a 2-year flood, because the 100-year event happens less frequently (**Fig. 14.26a**). To define this relationship, geologists construct graphs that plot flood discharge on the vertical axis against recurrence interval on the horizontal axis (**Fig. 14.26b**).

Knowing the discharge during a flood of a specified annual probability, and knowing the shape of the river channel and the elevation of the land bordering the river, hydrologists can predict the extent of land that will be submerged by such a flood. Such data, in turn, permit hydrologists to produce **flood-hazard maps**. In the United States, the Federal Emergency Management Agency (FEMA) produces maps that show the 1% annual probability (100-year) flood area and the 0.2% annual probability (500-year) flood risk zones (**Fig. 14.26c**).

Take-Home Message

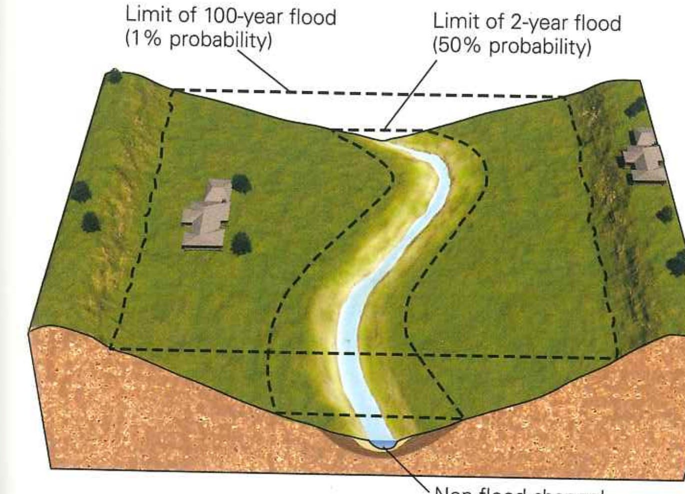
Seasonal floods submerge floodplains and delta plains at certain times of the year. Flash floods are sudden and short-lived. We can specify the probability that a certain size of flood will happen in a given year, but flood-control efforts meet with mixed success.

14.9 Vanishing Rivers

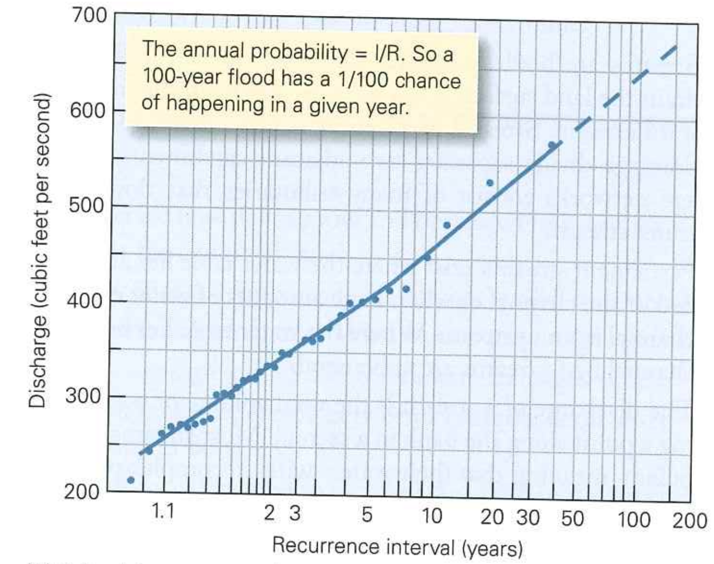
As *Homo sapiens* evolved from hunter-gatherers into farmers, areas along rivers became attractive places to settle. Rivers serve as avenues for transportation and are sources of food, irrigation water, drinking water, power, recreation, and (unfortunately) waste disposal. Further, their floodplains provide particularly fertile soil for fields, replenished annually by seasonal floods. Considering the multitudinous resources that rivers provide, it's no coincidence that ancient cultures developed in river valleys and on floodplains. Nevertheless, over time, humans have increasingly tended to abuse or overuse the Earth's rivers. Here we note four pressing environmental issues pertaining to rivers.

- *Pollution:* The capacity of some rivers to carry pollutants has long been exceeded, transforming them into deadly cesspools. Pollutants include raw sewage and storm drainage from urban areas, spilled oil, toxic chemicals from industrial sites, floating garbage, excess fertilizer, and animal waste. Some pollutants directly poison aquatic life, some feed algae blooms that strip water of its oxygen, and some settle out to be buried along with sediments.
- *Dam Construction:* In 1950, there were about 5,000 large (over 15 m high) dams worldwide, but today there are over 38,000. Damming rivers has both positive and negative results. Reservoirs provide irrigation water and hydroelectric power, and they trap some floodwaters and create popular recreation areas. But in some locations their construction destroys "wild rivers" (the whitewater streams of hilly and mountainous areas) and alters the ecosystem of a drainage network by forming barriers to migrating fish, by decreasing the nutrient supply to organisms downstream, by removing the source of sediment for the delta, and by eliminating seasonal floods that replenish nutrients in the landscape.
- *Overuse of Water:* Because of growing populations, our thirst for river water continues to increase, but the supply of water does not. The use of water has grown especially in response to the "green revolution" of the 1960s, during which huge new tracts of land came under irrigation. Today, 65% of the water taken out of rivers is used for agriculture, 25% for industry, and 9% for drinking. As a result, in some places human activity consumes the entire volume of a river's water, so that the channel contains little more than a saline trickle, if that, at its mouth. For example, except during unusually wet years, the Colorado River's channel contains almost no water where it crosses the Mexican border, for huge pipes and canals carry the water instead to Phoenix and Los Angeles (**Fig. 14.27**).
- *Effects of Urbanization and Agriculture on Streams:* When it rains in a naturally vegetated region, or in an agricultural region, much of the water that falls from the sky either soaks into the ground or gets absorbed by plants. Some of the soil moisture or groundwater eventually seeps into a nearby stream, but the remainder flows elsewhere underground. As a result, the amount of water that reaches nearby streams after a storm is less than the total amount of precipitation, and a significant lag occurs between the time when the water falls and when the stream's discharge increases. Urbanization changes both the volume of water reaching the stream and the length of the time lag, because when developers

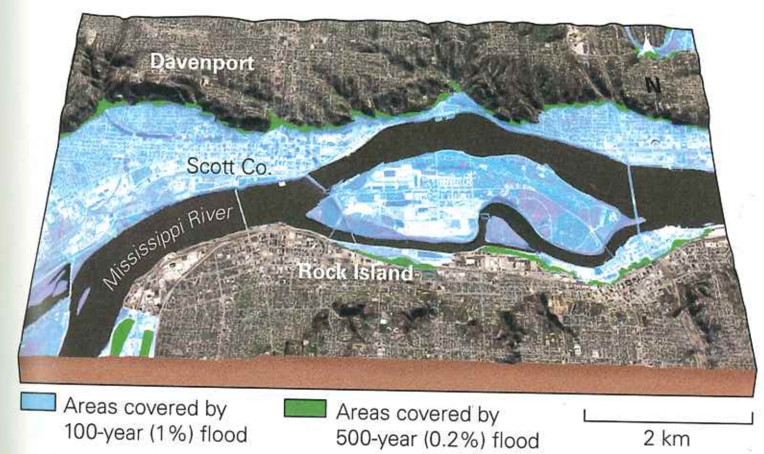
FIGURE 14.26 The conceptual relationship between flood size and probability.



(a) A 100-year flood covers a larger area than a 2-year flood and occurs less frequently.

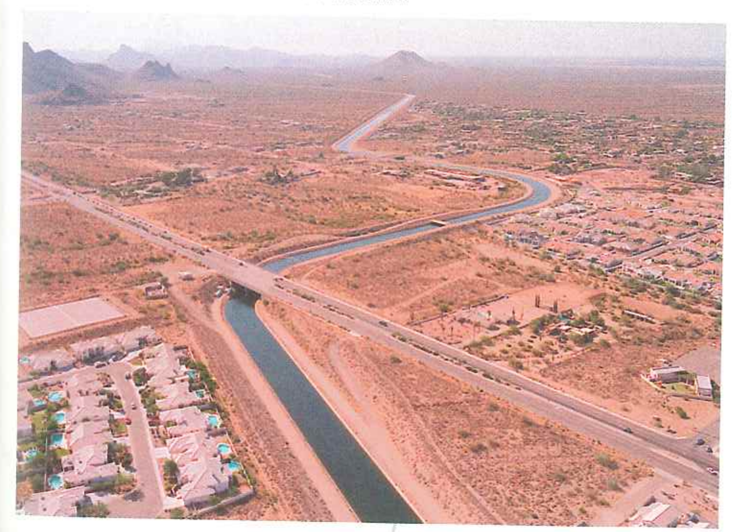


(b) A flood-frequency graph shows the relationship between the recurrence interval and the discharge for an idealized river.



(c) A flood-hazard map shows areas likely to be flooded. Here, near Rock Island, Illinois, even large floods are confined to the floodplain.

FIGURE 14.27 The Central Arizona Project canal shunts water from the Colorado River to Phoenix.



transform fields and forests into parking lots, roads, and buildings, a layer of impermeable concrete and asphalt prevents rainfall from infiltrating, and the amount of living biomass is smaller. Storm sewers and streets divert water directly to streams, so not only does the volume of water entering the streams increase, but also the rate at which the volume changes increases.

- Although we tend to think of farmland as "vegetated land," it actually has less plant cover than does natural grassland or forest. That's because the land surface between the crop rows remains bare during the growing season, and after harvest, entire fields become a broad expanse of exposed soil. Sheetwash flowing across the unprotected land surface erodes and carries with it significant volumes of sediment. Thus, a river's sediment load increases significantly when farms replace forests nearby.

Take-Home Message

People have greatly modified streams by constructing dams and levees, by discarding pollutants into the water, and by modifying discharge.

Chapter Summary

- Streams are bodies of water that flow down channels and drain the land surface. They grow by downcutting and headward erosion. Streams carry water out of a drainage basin; a drainage divide separates two adjacent catchments. Drainage networks consist of many tributaries that flow into a trunk stream.
- Permanent streams exist where the water table lies above the bed of the channel or when large amounts of water enter the channel from upstream. Where the water table lies below the channel bed, streams are ephemeral.
- The discharge of a stream is the total volume of water passing a point along the bank in a second. Most streams are turbulent, meaning that their water swirls in complex patterns.
- Streams erode the landscape by scouring, lifting, abrading, and dissolving. The resulting sediment provides dissolved loads, suspended loads, and bed loads. The total quantity of sediment carried by a stream is its capacity. Capacity differs from competence, the maximum particle size a stream can carry. When stream water slows, it deposits alluvium.
- The longitudinal profile of a stream is concave up. Typically, a stream has a steeper gradient at its headwaters than near its mouth.
- Streams cut valleys or canyons, depending on the rate of downcutting relative to the rate at which the slopes on either side of the stream undergo mass wasting. The amount of downcutting is limited by the base level. Where a stream flows down steep gradients and has a bed littered with large rocks, rapids develop, and where a stream plunges off a vertical face, a waterfall forms.
- A meandering stream wanders back and forth across a floodplain. It erodes its outer bank and deposits a point bar on the inner bank. Eventually, a meander may be cut off and turn into an oxbow lake. Natural levees form on either side of the river channel. Braided streams consist of many entwined channels.
- Where streams or rivers flow into standing water, they deposit deltas. Different deltas have different shapes.
- Fluvial erosion can bevel landscapes to a nearly flat plain. If the base level drops or the land surface rises, stream rejuvenation causes the stream to start downcutting. The headward erosion of one stream may capture the flow of another.
- If an increase in rainfall or spring melting causes more water to enter a stream than the channel can hold, a flood results. Some floods are seasonal and submerge floodplains or delta plains. Flash floods happen very rapidly. Officials try to prevent floods by building reservoirs and levees.
- Rivers are becoming a vanishing resource because of pollution, damming, and overuse of water.

Key Terms

alluvial fan (p. 427)
alluvium (p. 423)
annual probability (p. 437)
antecedent stream (p. 432)
artificial levee (p. 436)
bar (p. 423)
base level (p. 425)
bed load (p. 422)
braided stream (p. 427)
capacity (p. 423)
channel (p. 418)
competence (p. 423)
delta (p. 423)
discharge (p. 421)
distributary (p. 430)
downcutting (p. 419)
drainage divide (p. 419)
drainage network (p. 419)
drainage reversal (p. 432)
ephemeral stream (p. 420)
flash flood (p. 434)
flood (pp. 418, 433)
flood-hazard map (p. 440)
floodplain (pp. 423, 430)
floodway (p. 437)
fluvial deposit (p. 423)
headward erosion (p. 419)
longitudinal profile (p. 424)
meander (p. 427)
natural levee (p. 430)
oxbow lake (p. 428)
permanent stream (p. 420)
point bar (p. 423)
rapids (p. 427)
recurrence interval (p. 437)
running water (p. 417)
saltation (p. 422)
seasonal flood (p. 434)
sheetwash (p. 418)
stream (p. 418)
stream gradient (p. 424)
stream piracy (p. 431)
Stream rejuvenation (p. 431)
stream terrace (p. 426)
superposed stream (p. 432)
tributary (p. 419)
V-shaped valley (p. 426)
waterfall (p. 427)
watershed (p. 419)

Review Questions

1. What role do streams serve during the hydrologic cycle?
2. Describe the four different types of drainage networks.
3. Distinguish between permanent and ephemeral streams.
4. How does discharge vary according to the stream's length, and how does weather affect discharge?
5. Why is *average* downstream velocity always less than maximum downstream velocity?
6. Describe how streams erode the Earth's surface.
7. What are three components of sediment load in a stream?
8. Distinguish between a stream's competence and capacity.
9. Describe how the character of a drainage network changes, along its length, from headwaters to mouth.
10. What is the difference between a *local* base level and the ultimate base level of a stream?
11. How does a braided stream differ from a meandering stream? What is a floodplain?
12. Describe how meanders form, develop, are cut off, and then are abandoned.
13. Describe how deltas grow and develop. How do they differ from alluvial fans?
14. How does a stream-eroded landscape evolve over time?
15. What is stream piracy? What causes a drainage reversal?
16. How are superposed and antecedent drainages similar?
17. What is the difference between a seasonal flood and a floodplain flood?
18. What activities tend to increase flood risk and damage?
19. What is the recurrence interval of a flood, and how is it related to the annual probability?
20. How have humans abused and overused the resource of running water?

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Every chapter of SmartWork contains active learning exercises to assist you with reading comprehension and concept mastery. This chapter also features:

- What a Geologist Sees exercises on drainage networks, erosion, and river landscapes.
- Problems that help students learn how to calculate discharge.
- A video exercise that demonstrates sediment transport.

On Further Thought

21. Records indicate that flood crests for a given amount of discharge along the Mississippi River have been getting *higher* since 1927, when a system of levees began to block off portions of the floodplain. Why?

SEE FOR YOURSELF N. . . **Stream Landscapes**

Download *Google Earth*™ from the Web in order to visit the locations described below (instructions appear in the Preface of this book). You'll find further locations and associated active-learning exercises on Worksheet N of our **Geotours Workbook**.

River-cut gorge in the Himalayas
Latitude 28°9′41.82″N,
Longitude 85°23′1.04″E

This NE oblique view, from 6 km, looks upstream along a deep gorge, about 50 km north of Katmandu. The gorge was cut by rivers flowing out of the Himalaya Mountains. Note that, in the upper reaches of a river, it has a steep gradient and can downcut substantially. If you position your view to look straight upstream, you'll note that the valley has a V-shape in profile.

Headward erosion, Utah
Latitude 38°17′58.16″N,
Longitude 109°50′18.76″W

In the desert areas of Utah, from 8 km, you can see intermittent tributaries flow down tributary canyons into the Colorado River in Canyonlands National Park. The tributaries cut horizontal strata. You can see a steep escarpment at the head of each tributary canyon. Groundwater sapping at this locality causes collapse of debris into the canyon, resulting in the headward erosion of the tributaries.