CHAPTER

14

Streams and Lakes

About 1.3 billion cubic kilometers of water exist at the Earth's surface. If the surface were perfectly level, water would form a layer 2 kilometers thick surrounding the entire planet. Of this huge quantity, 97.5 percent is salty seawater, and another 1.8 percent is frozen into the great ice caps of Antarctica and Greenland. Only about 0.65 percent is fresh water in streams, underground reservoirs, lakes, and wetlands. Thus, although the hydrosphere contains a great amount of water, only a tiny fraction is fresh and liquid.

The clear water of the Big Sandy River flows from the Wind River Mountains of Wyoming.

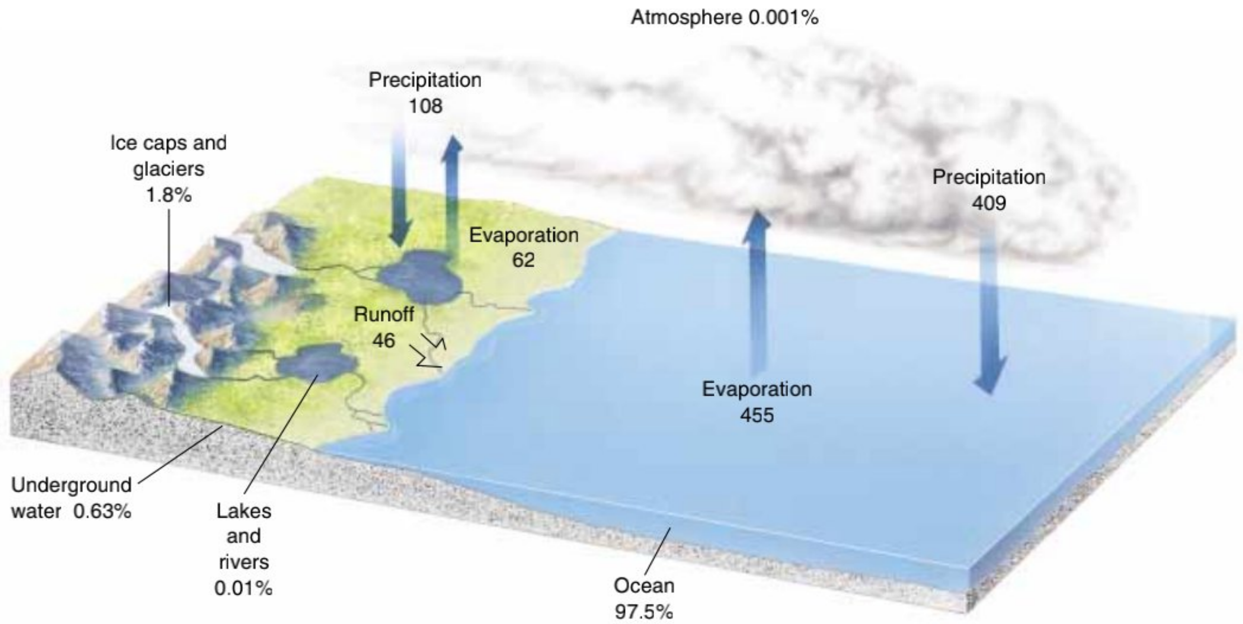

Figure 14–1 The hydrologic cycle shows that water circulates constantly among the sea, the atmosphere, and the land. Numbers indicate thousands of cubic kilometers of water transferred each year. Percentages show proportions of total global water in different portions of the Earth's surface.

14.1 THE WATER CYCLE

Water evaporates from the sea, falls as rain, and flows from land back to the sea. The circulation of water among sea, land, and the atmosphere is called the **hydrologic cycle**, or the water cycle (Fig. 14–1).

Water evaporates from sea and land to form clouds and invisible water vapor in the atmosphere. Water also evaporates directly from plants as they breathe, a process called **transpiration**. Atmospheric moisture then returns to the Earth's surface as **precipitation**: rain, snow, hail, and sleet.

Water that falls onto land can follow three different paths:

1. **Surface water** flowing to the sea in streams and rivers is called **runoff**. Surface water may stop temporarily in a lake or wetland, but eventually it flows to the oceans.
2. Some water seeps into the ground to become part of a vast subterranean reservoir known as **ground water**. Although surface water is more conspicuous, 60 times more water is stored as ground water than in all streams, lakes, and wetlands combined. Ground water also seeps through bedrock and soil toward the sea, although it flows much more slowly than surface water.
3. The remainder of water that falls onto land evaporates or transpires back into the atmosphere.

14.2 STREAMS

Geologists use the term **stream** for all water flowing in a channel, regardless of the stream's size. The term **river** is commonly used for any large stream fed by smaller ones called **tributaries**. Most streams run year round, even during times of drought, because they are fed by ground water that seeps into the stream bed.

Normally a stream flows in its **channel**. The floor of the channel is called the **bed**, and the sides of the channel are the **banks**. When rainfall is heavy or when snow melts rapidly, a **flood** may occur. During a flood, a stream overflows its banks and spreads over adjacent land called a **flood plain**.

STREAM FLOW

A slow stream flows at 0.25 to 0.5 meter per second (1 to 2 kilometers per hour), whereas a steep, flooding stream may race along at about 7 meters per second (25 kilometers per hour). Three factors control current velocity: (1) the gradient of the stream; (2) the discharge; and (3) the shape and roughness of the channel.

Gradient

Gradient is the steepness of a stream. The lower Mississippi River has a shallow gradient and drops only 10 centimeters per kilometer of stream length. In contrast, a tumbling mountain stream may drop 40 meters or more per kilometer. Obviously, if all other factors are equal, a stream flows more rapidly down a steep channel than a gradual one.

Discharge

Discharge is the amount of water flowing down a stream. It is expressed as the volume of water flowing past a point per unit time, usually in cubic meters per second (m^3/sec). The largest river in the world is the Amazon, with a discharge of 150,000 m^3/sec. In contrast, the Mississippi River, the largest in North America, has a discharge of about 17,500 m^3/sec, approximately one ninth that of the Amazon.

A stream's discharge can change dramatically from month to month or even during a single day. For example, the Selway River, a mountain stream in Idaho, has a discharge of 100 to 130 m^3/sec during early summer, when mountain snow is melting rapidly. During the dry season in late summer, the discharge drops to about 10 to 15 m^3/sec (Fig. 14–2). A desert stream may dry up completely during summer but become the site of a flash flood during a sudden thunderstorm.

Stream velocity increases when discharge increases. Thus, a stream flows faster during flood, even though its gradient is unchanged. The velocity of a stream also generally increases in a downstream direction because tributaries add to the discharge.

Channel Shape and Roughness

Friction between flowing water and the stream channel slows current velocity. Consequently, water flows more slowly near the banks than near the center of a stream. If you paddle a canoe down a straight stream channel, you move faster when you stay away from the banks.

The total friction depends on both the shape of a stream channel and its roughness. If streams of equal cross-sectional area are compared, a semicircular channel has the least surface in contact with the water and therefore imposes the least friction. If other factors are equal, a stream with this shape will flow more rapidly than one that is either wide and shallow or narrow and deep.

A rough channel creates more friction than a smooth one. Boulders in the stream bed increase turbulence and resistance, so a stream flows more slowly through a rough channel than a smooth one (Fig. 14–3).

14.3 STREAM EROSION

A stream may erode sediment and bedrock from its channel. When it does so, it carries the sediment and deposits it in its bed or flood plain farther downstream, or on a delta where it enters the sea or a lake.

STREAM ENERGY: THE ABILITY OF A STREAM TO ERODE AND CARRY SEDIMENT

The ability of a stream to erode and carry sediment depends on its energy. The energy of a stream is proportional to both velocity and discharge. A rapid, high-volume stream is a high-energy stream. It can move

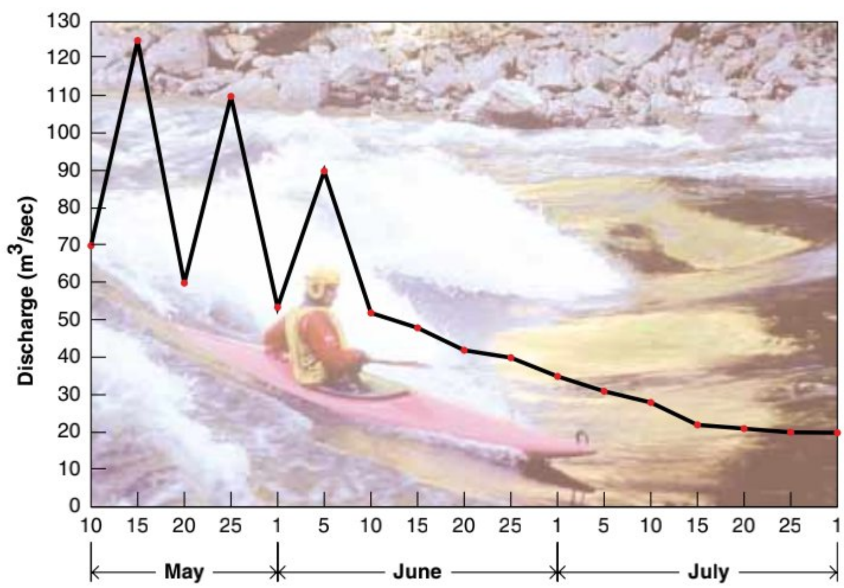

Figure 14–2 The hydrograph for the Selway River in the spring and summer of 1988 shows that the discharge varied from 125 to 15 m^3/sec.

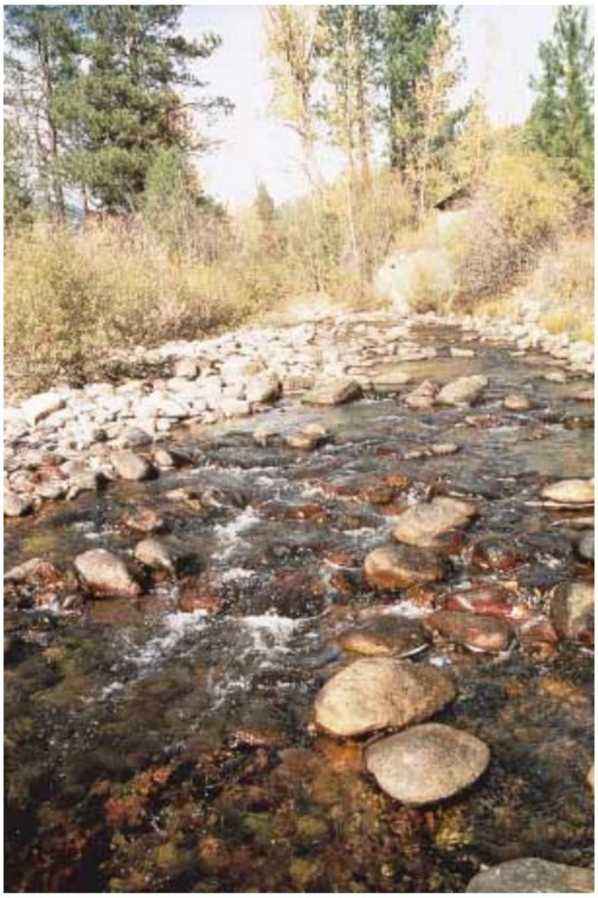

Figure 14–3 A boulder-choked stream bed in the North Fork of Trapper Creek, Bitterroot Mountains, Montana, creates turbulence and resistance to flow.

boulders as well as smaller particles and can carry a large load of sediment. In contrast, a slow, low-volume stream flows with much less energy; it moves only fine sediment and carries a much smaller sediment load.

The **competence** of a stream is a measure of the largest particle it can carry. It depends mostly on current velocity. Thus, a swiftly flowing stream can carry cobbles, boulders, and even automobiles during a big flood; but a slow stream with the same volume carries only silt and clay.

Velocity controls competence only when a stream is deep enough to cover the particles, but in a shallow stream, discharge becomes critical. To illustrate this point, think of a tiny but very steep stream tumbling over boulders. Although it may flow at great speed, it cannot move the boulders because it is not deep enough to cover them completely.

The **capacity** of a stream is the total amount of sediment it can carry past a point in a given amount of time. Capacity is proportional to both current velocity and discharge. Thus, a fast, large stream can carry more sediment than a slow, small one.

Because the ability of a stream to erode and carry sediment is proportional to its velocity and discharge, most erosion and sediment transport occur during the few days each year when the stream is flooding. Relatively little erosion and sediment transport occur during the remainder of the year. To see this effect for yourself, look at any stream during low water. It will most likely be clear, indicating little erosion or sediment transport. Look at the same stream when it is flooding. It will probably be muddy and dark, indicating that the stream is eroding its bed and banks and carrying a large load of sediment.

STREAM EROSION

A stream weathers and erodes its bed and banks by three processes: hydraulic action, abrasion, and solution (Fig. 14–4).

Hydraulic action is the process in which flowing water erodes sediment directly. To demonstrate hydraulic action, point a garden hose at bare dirt. In a short time the water will erode a small hole, displacing soil and small pebbles. Similarly, a stream can erode its bed and banks, especially when the current is moving swiftly.

Although it can erode loose soil, water by itself is not abrasive and is ineffective at wearing away solid rock. However, when a stream carries sand and other sediment, the grains grind against each other and against rocks in the channel in a process called **abrasion**. Thus, a sediment-laden stream is like flowing sandpaper.

Abrasion rounds sediment of all sizes, from sand to boulders (Fig. 14–5). It also erodes bedrock and forms **potholes** in a stream bed. A pothole forms where the current recirculates cobbles trapped in a small hollow in bedrock (Fig. 14–6). Over time, the cobbles can abrade a deep circular hole in the bedrock.

In cold climates, ice is an abrasive agent. In winter, ice on a frozen stream expands and gouges the stream banks. During spring breakup, the flooding stream drives great sheets of ice into the stream banks to erode rock and soil.

Flowing water dissolves ions from rocks and minerals in the stream bed. Most of a stream's dissolved load, however, comes from weathering of soils by ground water, which eventually seeps into the stream. This process is described in Chapter 6.

SEDIMENT TRANSPORT

After a stream erodes soil or bedrock, it carries the sediment downstream in three forms: dissolved load, suspended load, and bed load (Fig. 14–7).

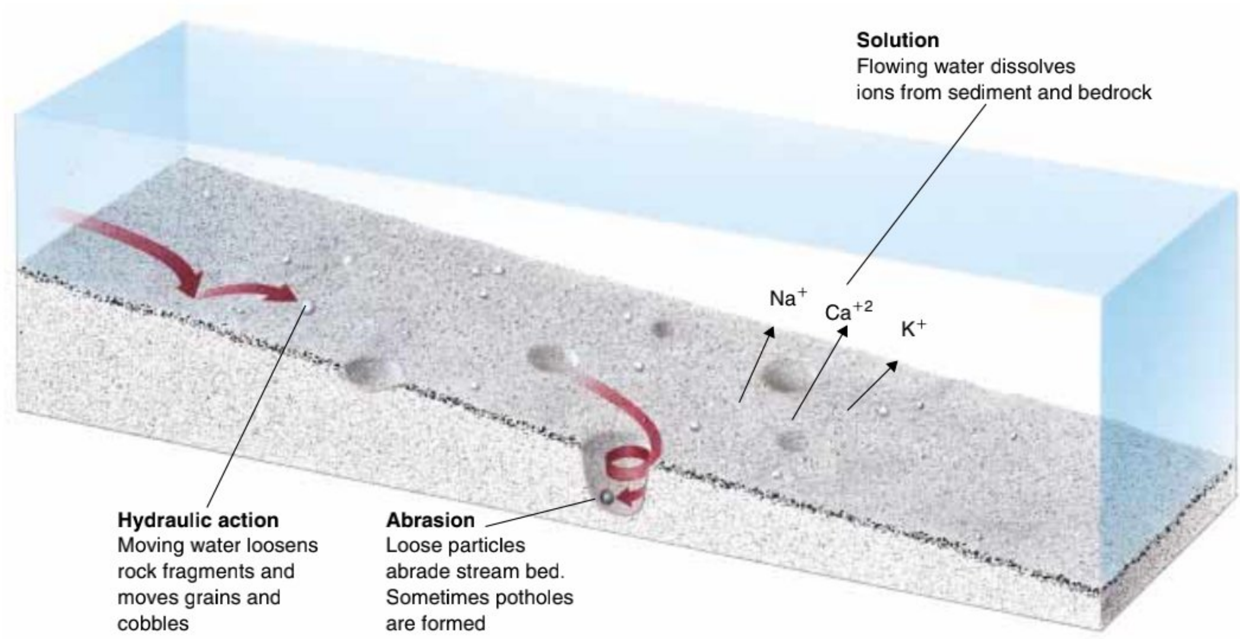

Figure 14–4 A stream weathers and erodes its channel by hydraulic action, abrasion, and solution.

Figure 14–5 Stream abrasion has rounded these rocks in the Bitterroot River, Montana.

Ions dissolved in water are called **dissolved load**. A stream's ability to carry dissolved ions depends mostly on its discharge and its chemistry, not its velocity. Thus, even the still waters of a lake or ocean contain dissolved substances; that is why the sea and some lakes are salty.

Figure 14–6 Potholes form in bedrock when a stream recirculates cobbles. (Courtesy of Scott Resources/Hubbard Scientific)

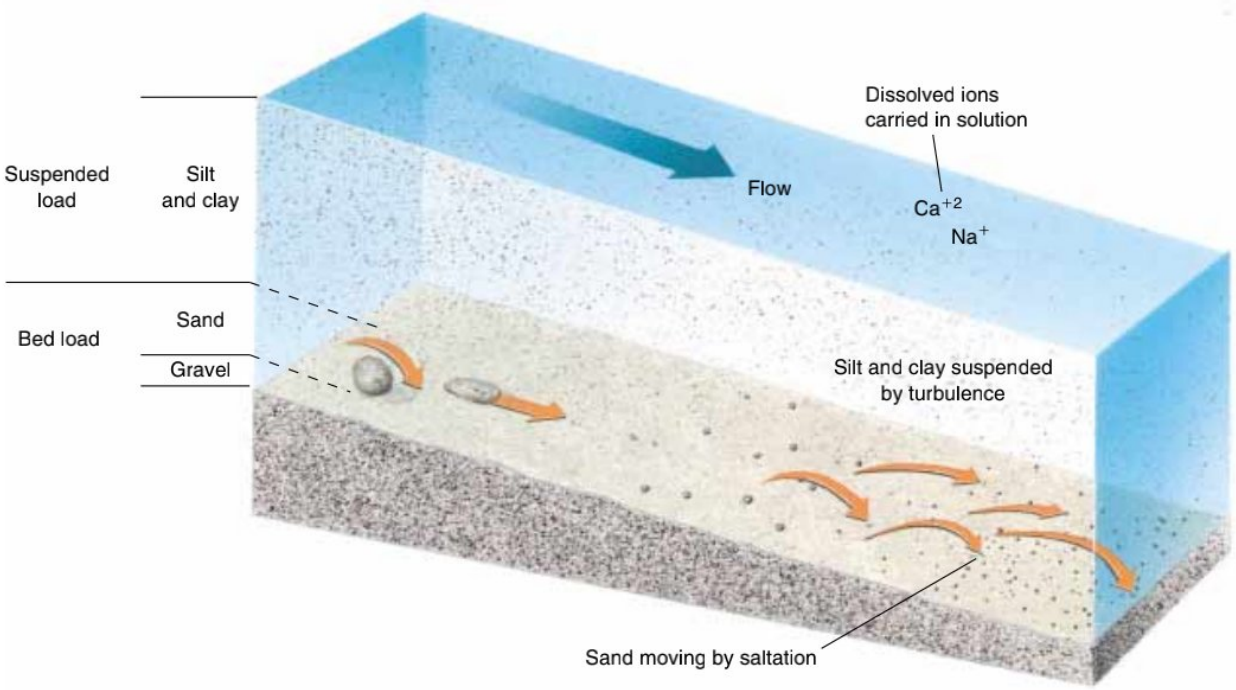

Figure 14–7 A stream carries dissolved ions in solution, silt and clay in suspension, and larger particles as bed load.

Even a slow stream can carry fine sediment. If you place loamy soil in a jar of water and shake it up, the sand grains settle quickly. But the smaller silt and clay particles remain suspended in the water as **suspended load**, giving it a cloudy appearance. Clay and silt are small enough that even the slight turbulence of a slow stream keeps them in suspension. A rapidly flowing stream can carry sand in suspension.

During a flood, when stream energy is highest, the rushing water can roll boulders and cobbles along the bottom as **bed load**. Sand also moves in this way, but if the stream velocity is sufficient, sand grains bounce over the stream bed in a process called **saltation**. Saltation occurs because a turbulent stream flows with many small chaotic currents. When one of these currents scours the stream bed, it lifts sand and carries it a short distance before dropping it back to the bed. The falling grains strike other grains and bounce them up into the current. The overall effect is one of millions of sand grains hopping and bouncing downstream over the stream bed.

The world's two muddiest rivers—the Yellow River in China and the Ganges River in India—each carry more than 1.5 *billion* tons of sediment to the ocean every year. The sediment load of the Mississippi River is about 450 million tons per year. Most streams carry the greatest proportion of sediment in suspension, less in solution, and the smallest proportion as bed load (Fig. 14–8).

14.4 STREAM DEPOSITS

A large, swift stream can carry all sizes of particles from clay to boulders. When the current slows down, its competence decreases and the stream deposits the largest particles in the stream bed. If current velocity continues to decrease—as a flood wanes, for example—finer particles settle out on top of the large ones. Thus, a stream **sorts** its sediment according to size. A waning flood might deposit a layer of gravel, overlain by sand and finally topped by silt and clay (Fig 14–9).

Streams also sort sediment in the downstream direction. Many mountain streams are choked with boulders and cobbles, but far downstream, their deltas are composed mainly of fine silt and clay. This downstream sorting is curious because stream velocity generally increases in the downstream direction. Competence increases with velocity, so a river should be able to transport larger particles than its tributaries. One explanation for downstream sorting is that abrasion wears away the boulders and cobbles to sand and silt as the sediment moves downstream over the years. Thus, only the fine sediment reaches the lower parts of most rivers.

A stream deposits its sediment in three environments: (1) **Channel deposits** form in the stream channel itself; (2) **alluvial fans** and **deltas** form where stream

Figure 14–8 The Mississippi River carries the greatest proportion of its sediment as suspended load. Numbers indicate sediment load per year.

gradient suddenly decreases as a stream enters a flat plain, a lake, or the sea; and (3) flood plain deposits accumulate on a flood plain adjacent to the stream channel.

Figure 14–9 The lower portion of this photograph shows coarse gravel overlain by finer sediment. The coarse gravel was deposited during a flood; the finer sediment accumulated as the flood waned. The upper gravel accumulated during a second flood. (G. R. Roberts, New Zealand)

CHANNEL DEPOSITS

A **bar** is an elongate mound of sediment. Bars are transient features that form in the stream channel and on the banks. They commonly form in one year and erode the next. Rivers used for commercial navigation must be recharted frequently because bars shift from year to year.

Imagine a winding stream such as that in Figure 14–10. The water on the outside of the curve A-A′ moves faster than the water on the inside. The stream erodes its outside bank because the current's inertia drives it into the outside bank. At the same time, the slower water on the inside point of the bend deposits sediment, forming a **point bar**. A **mid-channel bar** is a sandy and gravelly deposit that forms in the middle of a stream channel.

Most streams flow in a single channel. In contrast, a **braided stream** flows in many shallow, interconnecting channels (Fig. 14–11). A braided stream forms where more sediment is supplied to a stream than it can carry. The stream dumps the excess sediment, forming mid-channel bars. The bars gradually fill a channel, forcing the stream to overflow its banks and erode new channels. As a result, a braided stream flows simultaneously in several channels and shifts back and forth across its flood plain.

Braided streams are common in both deserts and glacial environments because both produce abundant sediment. A desert yields large amounts of sediment because it has little or no vegetation to prevent erosion. Glaciers grind bedrock into fine sediment, which is carried by streams flowing from the melting ice.

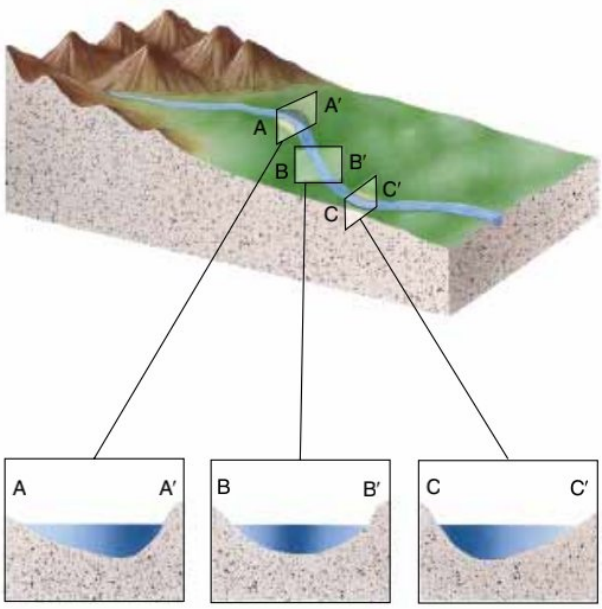

Figure 14–10 In a winding stream, the current flows most rapidly on the outside of a bend, and slowest on the inside bend. In a straight section, the current is fastest in the center of the channel. The dark-shaded zone in each cross section shows the area with fastest flow.

ALLUVIAL FANS AND DELTAS

If a steep mountain stream flows onto a flat plain, its gradient and velocity decrease abruptly. As a result, it deposits most of its sediment in a fan-shaped mound called an alluvial fan. Alluvial fans are common in many arid and semiarid mountainous regions (Fig. 14–12).

A stream also slows abruptly where it enters the still water of a lake or ocean. The sediment settles out to form a nearly flat landform called a delta. Part of the delta lies above water level, and the remainder lies slightly below water level. Deltas are commonly fan-shaped, resembling the Greek letter "delta" (Δ).

Both deltas and alluvial fans change rapidly. Sediment fills channels, which are then abandoned while new channels develop, as in a braided stream. As a result, a stream feeding a delta or fan splits into many channels called **distributaries**. A large delta may spread out in this manner until it covers thousands of square kilometers (Fig. 14–13). Most fans, however, are much smaller, covering a fraction of a square kilometer to a few square kilometers.

Figure 14–14 shows that the Mississippi River has flowed through seven different delta channels during the past 5000 to 6000 years. But, in recent years, engineers have built great systems of levees in attempts to stabilize the channels. If the Mississippi River were left alone, it would probably abandon the lower 500 kilometers of its present path and cut into the channel of the Atchafalaya River to the west. However, this part of the delta is heavily industrialized, and it is impractical to allow the river to change its course, to flood towns in some areas and leave shipping lanes and wharves high and dry in others.

14.5 DOWNCUTTING AND BASE LEVEL

A stream erodes downward into its bed and laterally against its banks. Downward erosion is called **downcutting** (Fig. 14–15). The **base level** of a stream is the deep-

Figure 14–11 The Chaba River in the Canadian Rockies is braided because glaciers pour more sediment into the stream than the water can carry.

Figure 14–12 This alluvial fan in the Canadian Rockies formed where a steep mountain stream deposits most of its sediment as it enters a flat valley.

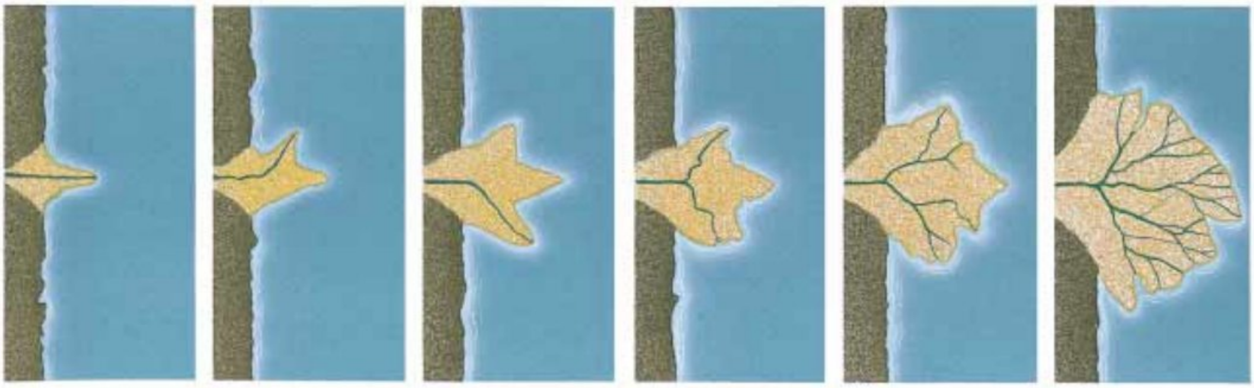

Figure 14–13 A delta forms and grows with time where a stream deposits its sediment as it flows into a lake or the sea.

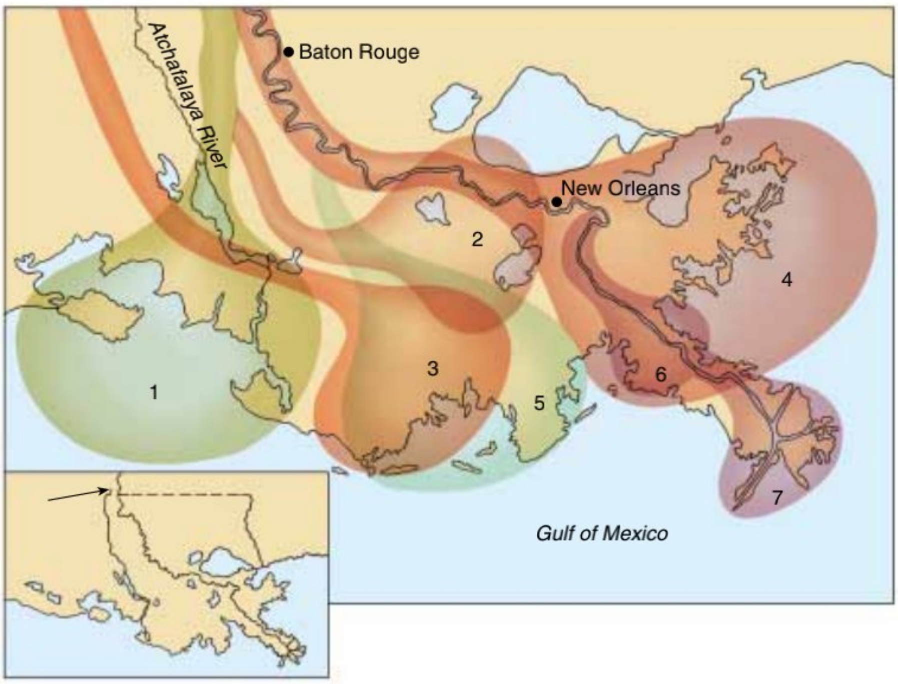

Figure 14–14 The Mississippi River has flowed into the sea by seven different channels during the past 6000 years. As a result, the modern delta is composed of seven smaller deltas formed at different times. The oldest delta is numbered 1, and the current delta is 7.

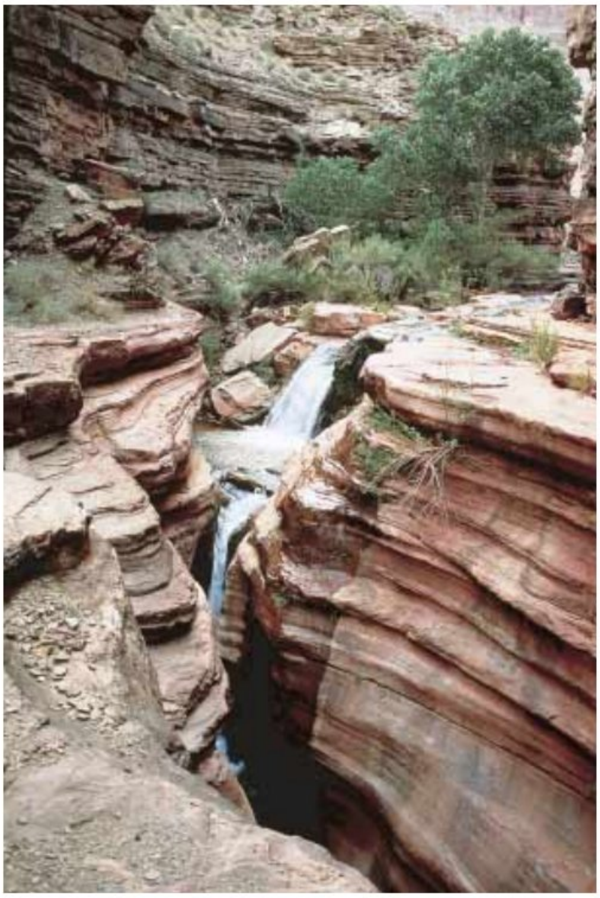

Figure 14–15 Deer Creek, a tributary of Grand Canyon, has downcut its channel into solid sandstone.

est level to which it can erode its bed. For most streams,[1] the lowest possible level of downcutting is sea level, which is called the **ultimate base level**. This concept is straightforward. Water can only flow downhill. If a stream were to cut its way down to sea level, it would stop flowing and hence would no longer erode its bed.

In addition to ultimate base level, a stream may have a number of **local**, or **temporary, base levels**. For example, a stream stops flowing where it enters a lake. It then stops eroding its channel because it has reached a temporary base level (Fig. 14–16a). A layer of rock that resists erosion may also establish a temporary base level because it flattens the stream gradient. Thus, the stream slows down and erosion decreases. The top of a waterfall is a temporary base level commonly established by resistant rock. Niagara Falls is held up by a resistant layer of dolomite over softer shale. As the falling water erodes the shale, it undermines the dolomite cap, which periodically collapses. As a result, Niagara Falls has retreated 11 kilometers upstream since its formation about 9000 years ago (Fig. 14–17).

If a stream has numerous temporary base levels, it erodes its bed in the steep places where it flows rapidly, and it deposits sediment in the low-gradient stretches where it flows more slowly (Fig. 14–16b). Over time, erosion and deposition smooth out the irregularities in the gradient. An idealized **graded stream** has a smooth, concave profile (Fig. 14–16c). Once a stream becomes graded, the rate of channel erosion becomes equal to the rate at which the stream deposits sediment in its channel.

[1] We say "for most streams" because a few empty into valleys that lie below sea level.

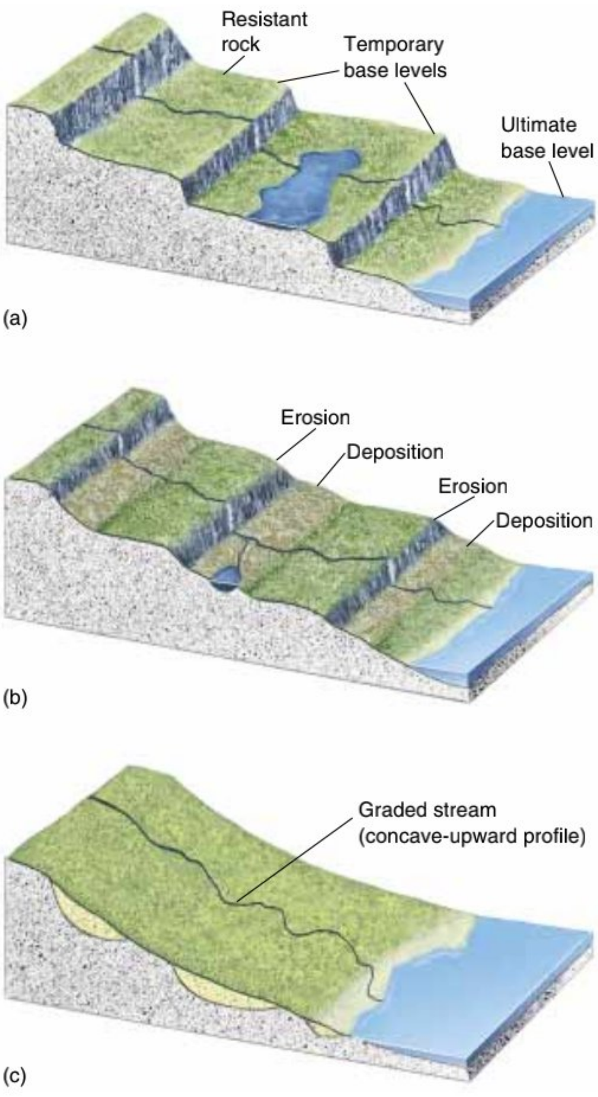

Figure 14–16 An ungraded stream (a) has many temporary base levels. With time, the stream smooths out the irregularities (b) to develop a graded profile (c).

Figure 14–17 Niagara Falls has eroded 11 kilometers upstream in the last 9000 years and continues to erode today. (Hubertus Kanus/Photo Researchers, Inc.)

Figure 14–18 A steep mountain stream eroded a V-shaped valley into soft shale in the Canadian Rockies.

Thus, there is no net erosion or deposition, and the stream profile no longer changes. An idealized graded stream such as this does not actually exist in nature, but many streams come close.

SINUOSITY OF A STREAM CHANNEL

A steep mountain stream usually downcuts rapidly into its bed. As a result, it cuts a relatively straight channel with a steep-sided, V-shaped valley (Fig. 14–18). The stream maintains its relatively straight path because it flows with enough energy to erode and carry off any material that slumps into its channel.

In contrast, a low-gradient stream is less able to erode downward into its bed. Much of the stream energy is directed against the banks, causing **lateral erosion**. Lateral erosion undercuts the valley sides and widens a stream valley.

Most low-gradient streams flow in a series of bends called **meanders** (Fig. 14–19). A random event may initiate the development of meanders. For example, if the right bank of a slow stream collapses into the channel, the current cannot quickly erode the material and carry it away. Instead, the obstruction deflects the current toward the left bank, where it undercuts the bank and causes another slump. The new slump then deflects the current back to the right bank. Thus, a single, random cave-in creates a sinuous current that erodes the stream's outside bends. Over time, the meanders propagate downstream.

A meandering stream wanders back and forth across its entire flood plain, forming a wide valley with a flat bottom. A meandering channel seems to be the natural pattern for a low-gradient stream, but geologists do not fully understand why. Most agree that meanders mini-

Figure 14–19 A low-gradient stream commonly flows in a series of looping bends called meanders. This one is in Baffin Island, Canada.

mize flow resistance of the channel and allow the stream to expend its energy uniformly throughout its channel.

In many valleys, meanders become so pronounced that the outside of one meander approaches that of another. Given enough time, the stream erodes the narrow neck of land separating the two meanders and creates a new channel, abandoning the old meander loop. Because the current no longer flows through the entrance and exit of the abandoned meander, sediment accumulates at those points, isolating the old meander from the stream to form an **oxbow lake** (Fig. 14–20).

Most streams do not maintain the same sinuosity throughout their entire length. For example, a meandering stream may develop a straight channel if it flows into an area of steeper gradient, or it may become braided if it encounters a supply of excess sediment.

LANDFORM EVOLUTION AND TECTONIC REJUVENATION

According to a model popular in the first half of this century, streams erode mountain ranges and create landforms in a particular sequence. At first, the streams cut steep, V-shaped valleys. Over time, erosion decreases the gradient, and the valleys widen into broad flood plains. Eventually, the entire landscape flattens, forming a large, low, featureless plain called a **peneplain**.

This model of continuous leveling of the Earth's surface tells only half the story because over geologic time, tectonic forces uplift the land and interrupt the simple, idealized sequence. A stream is **rejuvenated** when tectonic activity raises the land. As the land rises, the stream becomes steeper. As a result, its energy increases and it erodes downward into its bed.

If tectonic uplift steepens the gradient of a meandering stream, the stream may downcut rapidly, preserving the winding channel by cutting it deeply into bedrock, forming **incised meanders** (Fig. 14–21). If the stream occupied a broad flood plain before tectonic rejuvenation, floodwaters of the newly incised channel would no longer reach the old flood plain. The old, abandoned flood plain at a higher elevation is then called a **stream terrace** (Fig. 14–22).

Incised meanders and stream terraces can form without tectonic uplift. If the climate becomes wetter, the discharge increases and a graded stream then cuts downward into its bed, abandoning the old flood plain. The rate of downcutting also increases when temporary base level is lowered. For example, a stream may stop

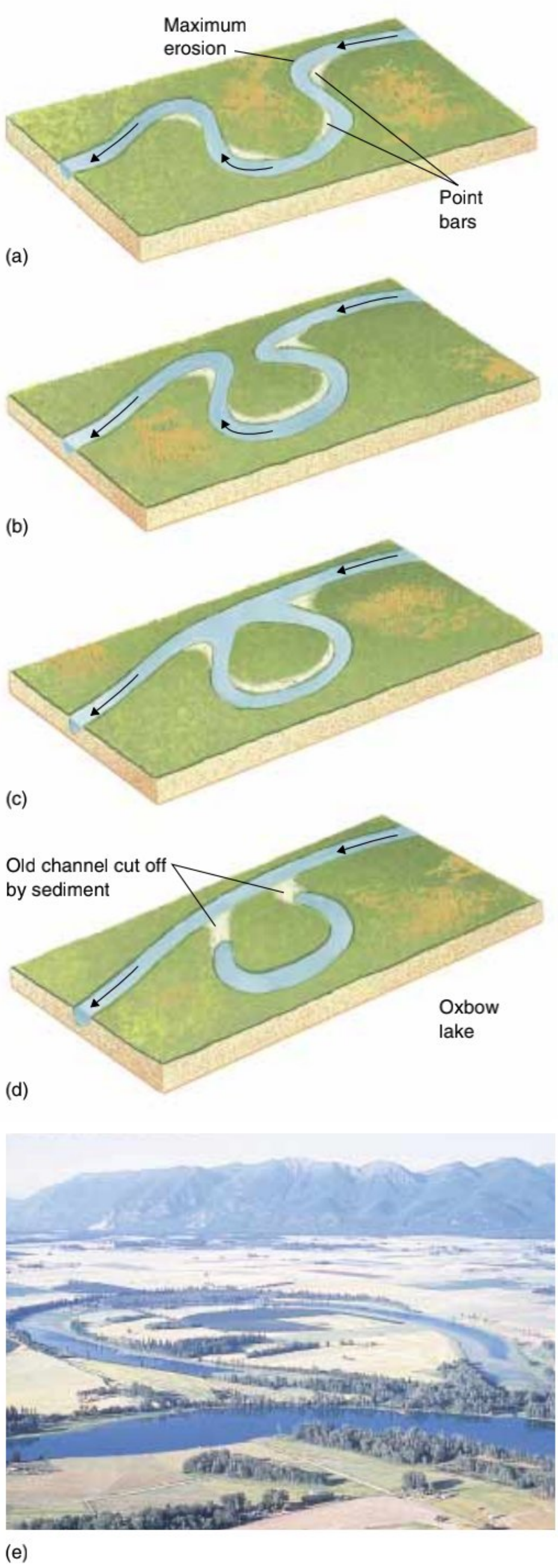

Figure 14–20 An oxbow lake forms where a stream erodes through a meander neck. This one is in the Flathead River, Montana.

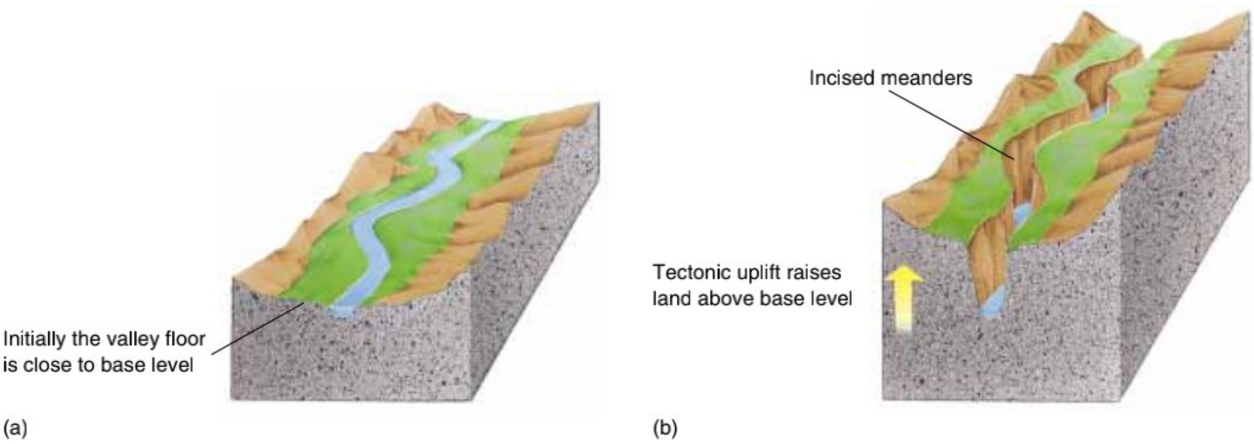

Figure 14–21 (a) If tectonic uplift steepens the gradient of a meandering stream, (b) the stream may downcut into bedrock to form incised meanders. (c) The Escalante River cut an incised meander into sandstone.

downcutting at a temporary base level that is supported by a layer of resistant rock. When the stream finally erodes through this layer, it may start downcutting through softer rock below, quickly deepening its channel and abandoning its flood plain.

STREAMS THAT FLOW THROUGH MOUNTAIN RANGES

Some streams flow through a mountain range, plateau, or ridge of resistant rock. Why don't they flow around the mountains rather than cutting directly through them?

Rejuvenation often causes such odd behavior. Imagine a stream flowing across a plain. If tectonic forces uplift the center of the plain, and if the uplift occurs slowly, the stream may cut through the rising bedrock to keep its original course (Fig. 14–23). A stream of this type is said to be **antecedent** because it existed before the uplift rose. The Grand Canyon is an antecedent stream channel; it formed as the Colorado River cut downward through more than 1600 meters of sedimentary rock, as the Colorado Plateau rose.

A stream may also cut through mountains by the process of **superposition**. If an old mountain range is covered with younger sedimentary rocks, a stream cutting its channel into the sedimentary rocks is unaffected by the buried mountains. Eventually, the stream may downcut until it reaches the buried mountains. At this point the channel may be too deep to shift laterally, and the stream may cut through the range rather than flow around it (Fig. 14–24).

Stream Piracy

Consider two streams flowing in opposite directions from a mountain range. One of the streams may cut downward

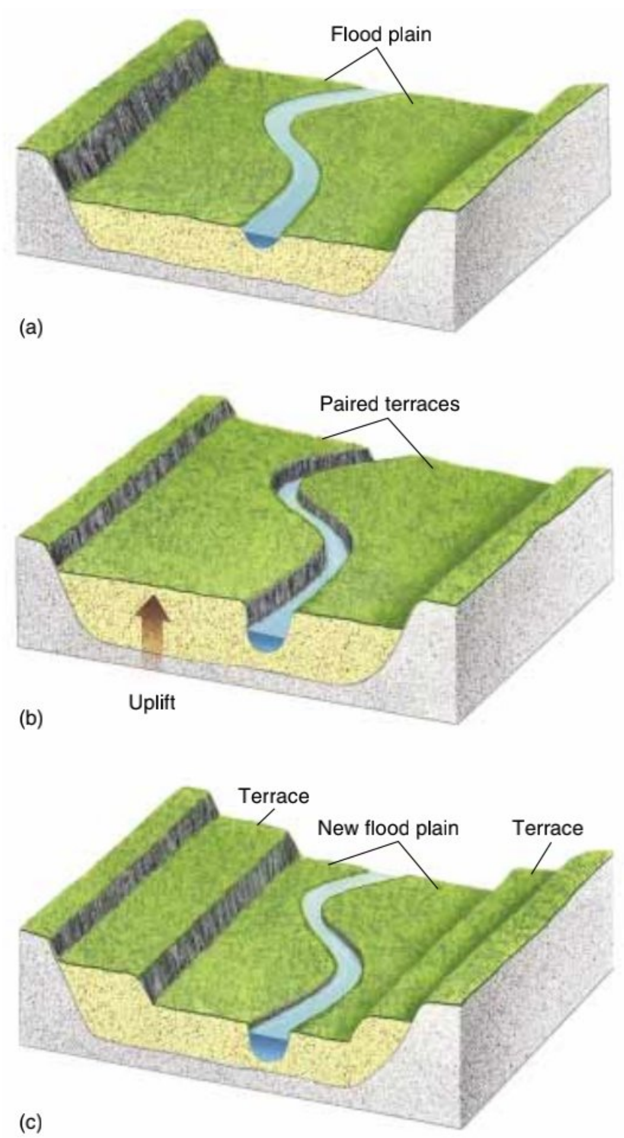

Figure 14–22 Formation of terraces. (a) A stream has formed a broad flood plain. (b) Tectonic uplift or climatic change causes the stream to downcut into its bed. As the stream cuts downward, the old flood plain becomes a terrace above the new stream level. (c) A new flood plain forms at the lower level.

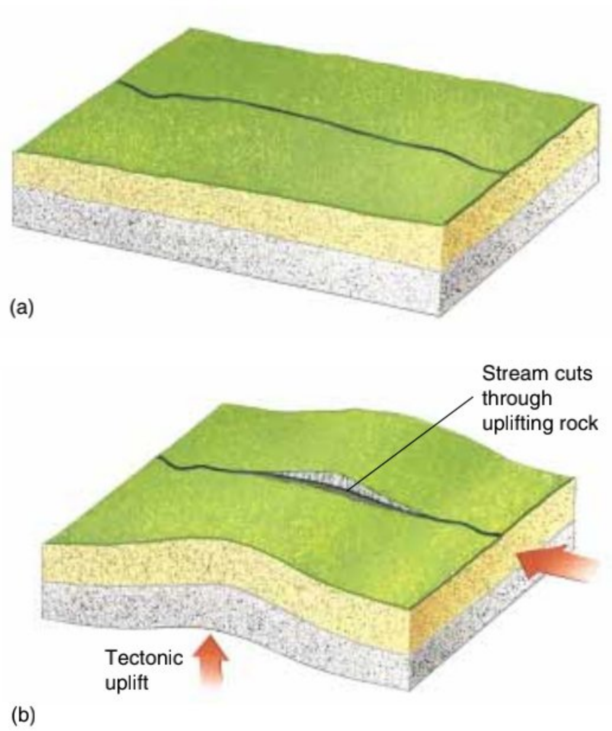

Figure 14–23 An antecedent stream forms where tectonic forces form a ridge, but a stream erodes its bed as rapidly as the land rises. Thus, the stream is able to maintain its original path by cutting through the rising ridge.

faster than the other because one side of the range is steeper than the other, because it receives more rainfall, or because the rock on one side is softer than rock on the other (Fig. 14–25). The stream that is downcutting more rapidly will also cut its way backward into the mountains. This process is called **headward erosion**. If headward erosion continues, the more deeply eroded stream may intercept the higher stream on the opposite side of the range. The stream at higher elevation then reverses direction and flows into the lower one. This sequence of events is called **stream piracy**.

► 14.6 DRAINAGE BASINS

The region drained by a stream and its tributaries is called a **drainage basin**. Mountain ranges or other raised areas called **drainage divides** separate adjacent drainage basins. For example, streams on the western slope of the Rocky Mountains are parts of the Colorado and Columbia River drainage basins, which ultimately empty into the Pacific Ocean. Tributaries on the eastern slope of the Rockies are parts of the Mississippi and Rio Grande basins, which flow into the Gulf of Mexico. A drainage basin can be large, like the Mississippi basin, or as small as a single mountain valley.

In most drainage basins, the pattern of tributaries resembles the veins in a leaf. Each tributary forms a V pointing downstream where it joins the main stream. This type of system is called a **dendritic drainage pattern** (Fig. 14–26a). Dendritic drainages develop where streams flow over uniform bedrock. Because they are not

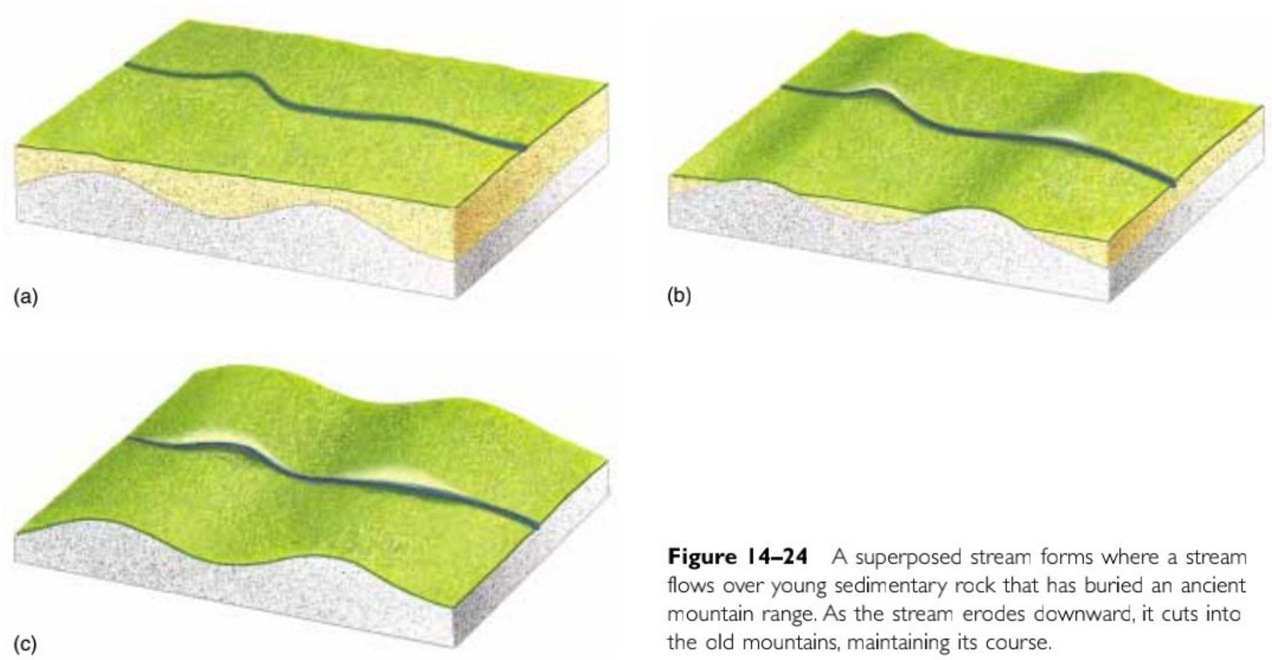

Figure 14–24 A superposed stream forms where a stream flows over young sedimentary rock that has buried an ancient mountain range. As the stream erodes downward, it cuts into the old mountains, maintaining its course.

deflected by resistant layers of bedrock, the streams take the shortest route downslope.

In some regions, bedrock is not uniform. For example, Figure 14–26b shows a layer of sandstone lying over granite. The rocks were faulted and tilted after the sandstone formed. As a result, parallel outcrops of easily eroded sandstone alternate with bands of hard granite. Streams followed the softer sandstone, forming a series of long, straight, parallel channels intersected at right angles by short tributaries. This type of drainage pattern, called a **trellis pattern**, is common in the tilted rocks of the Appalachian Mountains. A **rectangular pattern** can

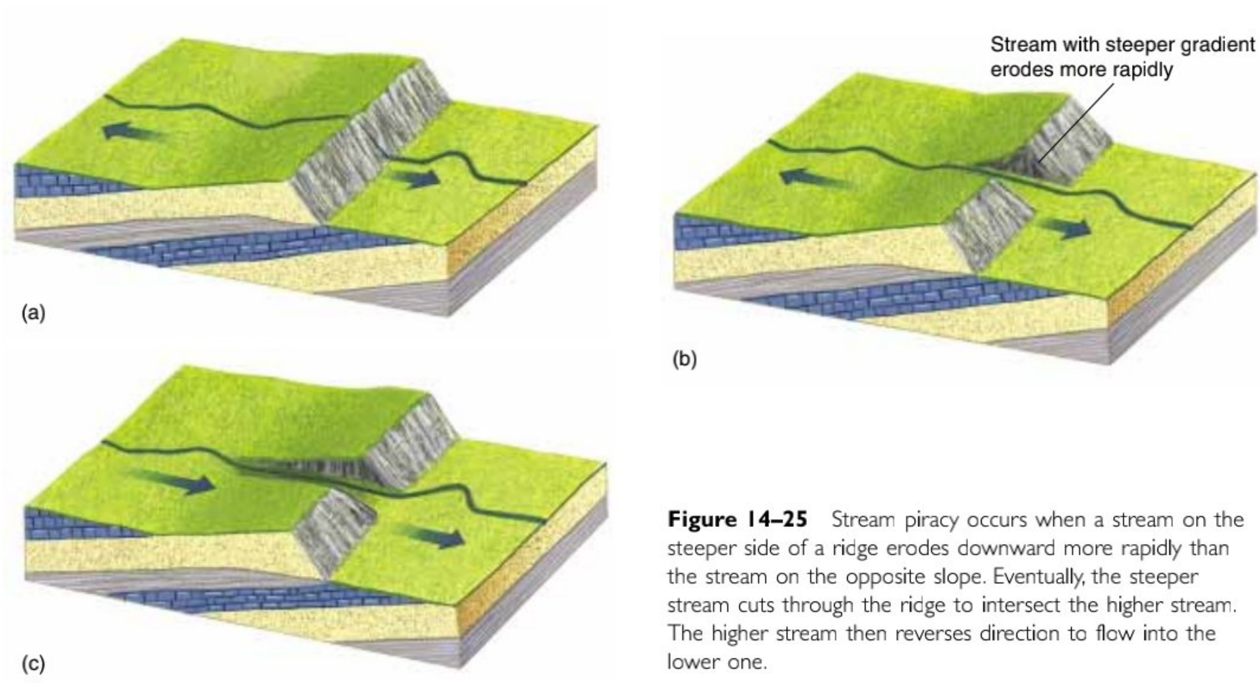

Figure 14–25 Stream piracy occurs when a stream on the steeper side of a ridge erodes downward more rapidly than the stream on the opposite slope. Eventually, the steeper stream cuts through the ridge to intersect the higher stream. The higher stream then reverses direction to flow into the lower one.

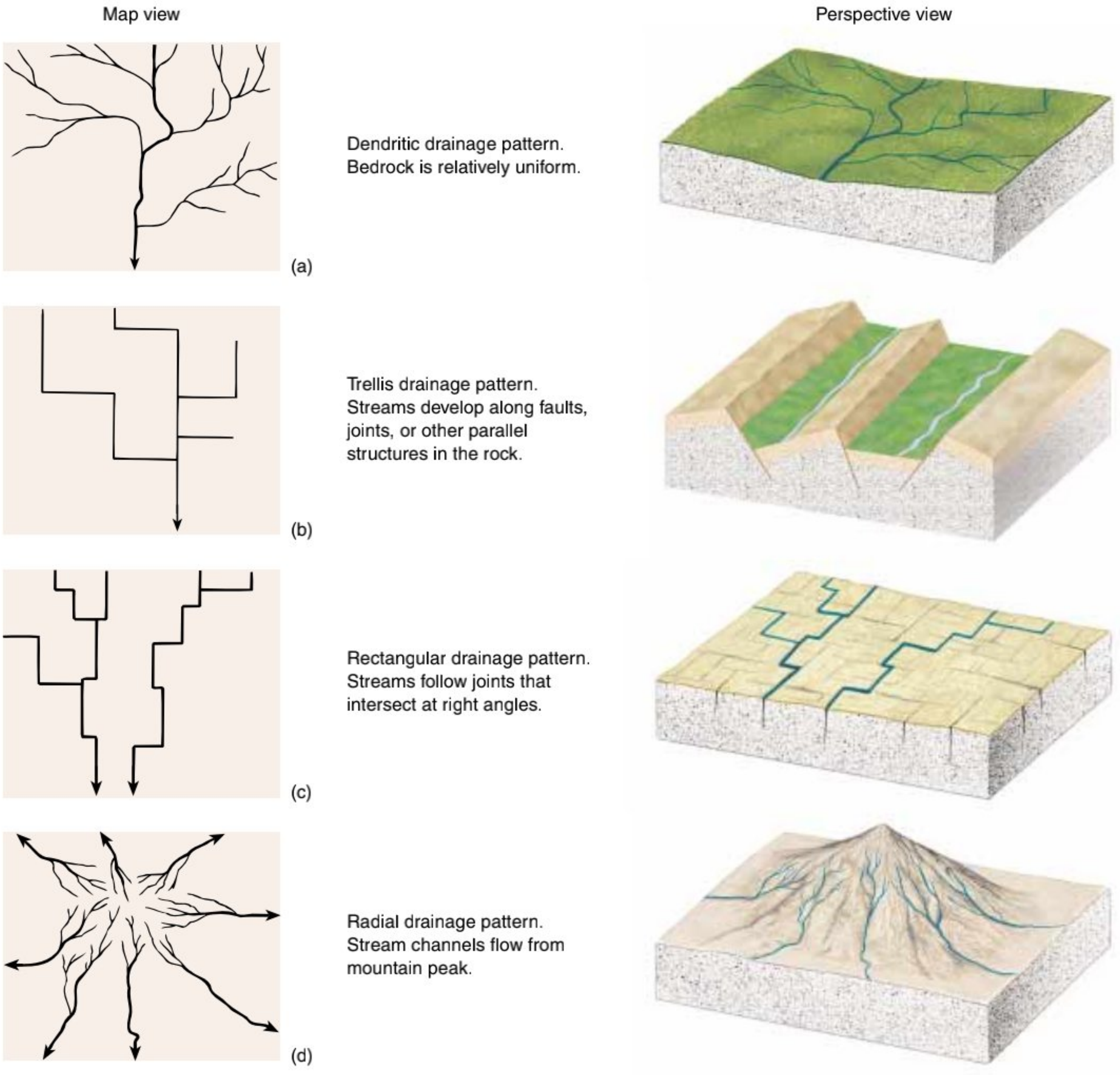

Figure 14–26 Bedrock structures and topography control drainage patterns. (a) A dendritic pattern reflects homogeneous bedrock. (b) Parallel faults and contrasting rock types may form a trellis drainage pattern. (c) A rectangular pattern reflects bedrock fractures that intersect at right angles. (d) A radial pattern forms on a peak.

develop if streams follow faults or joints that intersect at right angles. In this case, the main stream and its tributaries are of approximately the same length (Fig. 14–26c). A **radial drainage pattern** develops where a number of streams originate on a mountain and radiate outward from the peak (Fig. 14–26d).

The next time you fly in an airplane, look out the window and try to determine the type of drainage pattern below and what it tells you about the geology of the area.

14.7 FLOODS

When stream discharge exceeds the volume of a stream channel, water overflows onto the flood plain, creating a flood. Floods in the United States cause an annual average of 85 human deaths and more than $1 billion in property damage. The 1993 Mississippi River floods cost about $12 billion. Two weeks of torrential rains flooded portions of California in January of 1995, killing at least 9 people and causing $1.3 billion in damage. In the summer of 1993, raging rivers killed more than 150 people in southern China, flash floods and related landslides killed 1800 people in Nepal, and 1350 people died in monsoon floods in northern India and Bangladesh.

Although flooding is a natural event, human activities can increase flood frequency and severity. Stream discharge increases where forests are logged, prairies plowed, or cities paved. Without trees, shrubs, or grass to absorb rain, water runs over the land and seeps through the ground to increase stream flow. In cities, nearly all rainwater runs off pavement directly into nearby streams.

Floods are costly in part because people choose to live in flood plains. Many riverbank cities originally grew as ports, to take advantage of the easy transportation afforded by rivers. Rivers are no longer the important transportation arteries that they were 100 years ago, but the flood plain cities continue to thrive and grow.

Although we normally think of floods as destructive events, river and flood plain ecosystems depend on floods. For example, cottonwood tree seeds germinate only after a flood. Many species of fish gradually lose out to stronger competitors during normal flows, but have adapted better to floods so that their populations increase as a result of flooding.

In some cases, flooding even benefits humans. Frequent small floods dredge bigger channels, which reduce the severity of large floods. Flooding streams carry large sediment loads and deposit them on flood plains to form fertile soil. So, paradoxically, the same floods that cause death and disaster create the rich soils that make flood plains so attractive for farming.

FLOODS AND STREAM SIZE

Rapid snowmelt or a single intense thunderstorm can flood a small stream. In 1976, a series of summer storms saturated soil and bedrock near Rocky Mountain National Park, northwest of Denver. Then a large thunderhead dropped 19 centimeters of rain in 1 hour in the headwaters of Big Thompson Canyon. The Big Thompson River flooded, filling its narrow valley with a deadly, turbulent wall of water. Some people in the valley tried to escape by driving toward the mouth of the canyon, but traffic clogged the two-lane road and trapped motorists in their cars, where they drowned. A few residents tried to escape by scaling the steep canyon walls, but the rising waters caught some of them. Within a few hours, 139 people had died and five were missing. By the next day, the flood was over (Fig. 14–27).

Big Thompson Canyon is a relatively small drainage basin that flooded rapidly during a locally heavy rain. In contrast, the Mississippi River basin covers 3.2 million square kilometers, and the river itself has a discharge of 17,500 m^3/sec. A sudden downpour in any of its small tributaries would have no effect on the Mississippi. A flood on the Mississippi results from large amounts of rainfall over a broad area. The Mississippi River flood of 1993 plagued parts of the Mississippi flood plain for two months.

Figure 14–27 The 1976 Big Thompson Canyon flood in Colorado lifted this house from its foundation and carried it downstream. (USGS)

FLOOD FREQUENCY

Many streams flood regularly, some every year. In any stream, small floods are more common than large ones, and the size of floods can vary greatly from year to year. A ten-year flood is the largest flood that occurs in a given stream on an average of once every ten years. A 100-year flood is the largest that occurs on an average of once every 100 years. For example, a stream may rise 2 meters above its banks during a ten-year flood, but 7 meters during a 100-year flood. Thus, a 100-year flood is higher and larger, but less frequent, than a ten-year flood.

NATURAL LEVEES

As a stream rises to flood stage, both its discharge and velocity increase. It expends much of this increased energy eroding its bed and banks, thus increasing its sediment load.

The current of a flooding stream slows abruptly where water leaves the channel to flow onto the flood plain. The sudden decrease in current velocity causes the stream to deposit sand on the stream banks. The sand forms ridges called **natural levees** at the margins of the channel (Fig. 14–28). Farther out on the flood plain, the flood water carries finer particles, mostly clay and silt. As a flood wanes, this fine sediment settles onto the flood plain, renewing and enriching the soil.

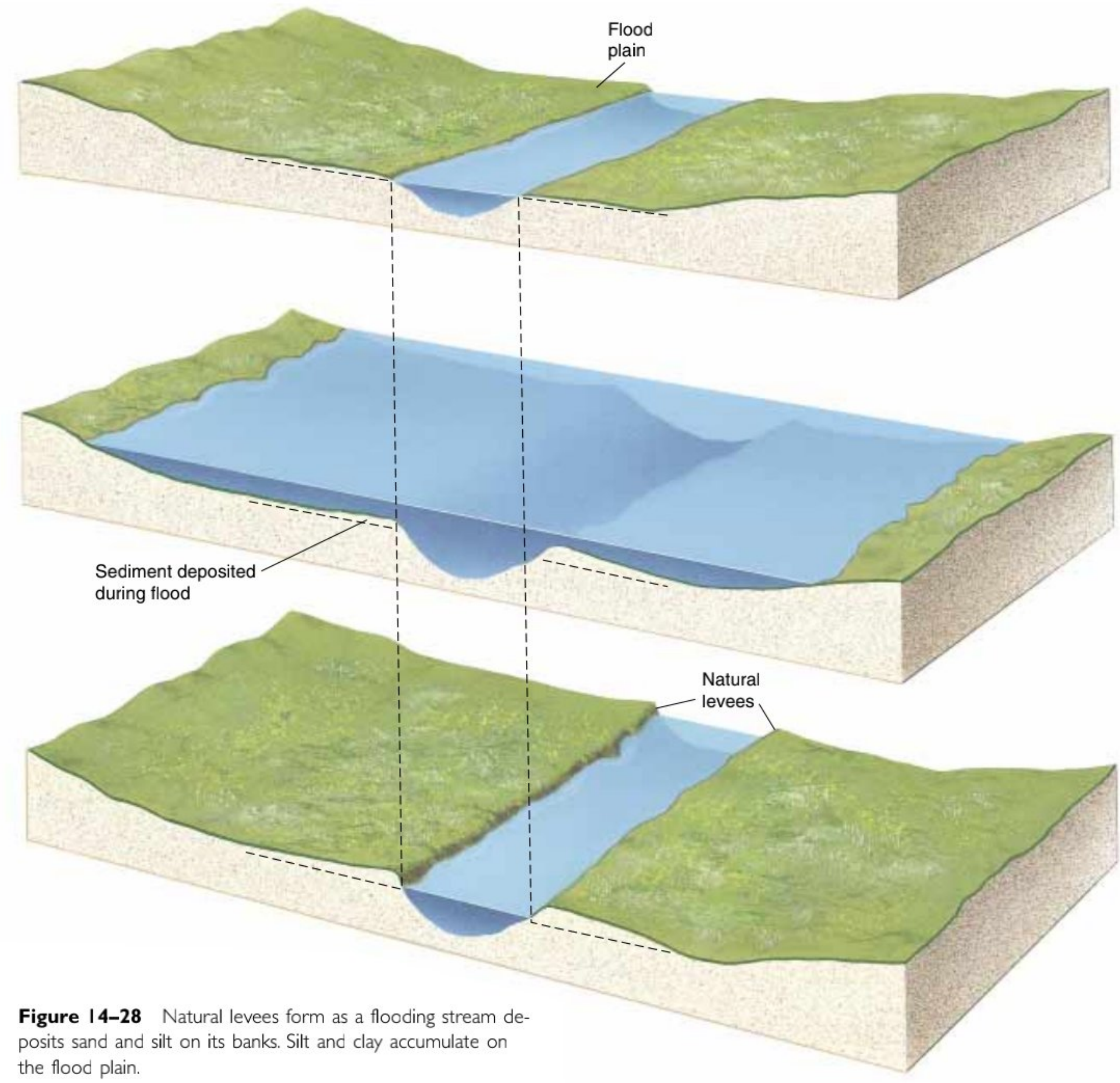

Figure 14–28 Natural levees form as a flooding stream deposits sand and silt on its banks. Silt and clay accumulate on the flood plain.

CASE STUDY Flood Control and the 1993 Mississippi River Floods

During the late spring and summer of 1993, heavy rain soaked the upper Midwest. Thirteen centimeters fell in already saturated central Iowa in a single day. In mid-July, 2.5 centimeters of rain fell in 6 minutes in Papillion, Nebraska. As a result of the intense rainfall over such a large area, the Mississippi River and its tributaries flooded. In Fargo, North Dakota, the Red River, fed by a day-long downpour, rose 1.2 meters in 6 hours, flooding the town and backing up sewage into homes and the Dakota Hospital. In St. Louis, Missouri, the Mississippi crested 14 meters above normal and 1 meter above the highest previously recorded flood level. At its peak, the flood inundated nearly 44,000 square kilometers in a dozen states. Damage to homes and businesses on the flood plain reached $12 billion. Forty-five people died.

During the 1993 Mississippi River flood, control projects saved entire towns and prevented millions of dollars in damage. However, in some cases, described in the following section, control measures increased damage. Geologists, engineers, and city planners are studying these conflicting results to plan for the next flood, which may be years or decades away.

ARTIFICIAL LEVEES AND CHANNELS

An artificial levee is a wall built of earth, rocks, or concrete along the banks of a stream to prevent rising water from spilling out of the stream channel onto the flood plain. In the past 70 years, the U.S. Army Corps of Engineers has spent billions of dollars building flood control structures, including 11,000 kilometers of levees along the banks of the Mississippi and its tributaries (Fig. 14–29).

As the Mississippi River crested in July 1993, flood waters surged through low areas of Davenport, Iowa, built on the flood plain. However, the business district of nearby Rock Island, Illinois, remained mostly dry. In 1971, Rock Island had built levees to protect low-lying areas of the town, whereas Davenport had not built levees. Hannibal, Missouri, had just completed levee construction to protect the town when the flood struck. The $8 million project in Hannibal saved the Mark Twain home and museum and protected the town and surrounding land from flooding.

Unfortunately, two major problems plague flood control projects that rely on artificial levees: Levees are temporary solutions to flooding, and in some cases they cause higher floods along nearby reaches of the river.

In the absence of levees, when a stream floods, it deposits mud and sand on the flood plain. When artificial levees are built, the stream cannot overflow during small floods, so it deposits the sediment in its channel, raising the level of the stream bed. After several small floods, the entire stream may rise *above* its flood plain, contained only by the levees (Fig. 14–30). This configuration creates the potential for a truly disastrous flood because if the levee should be breached during a large flood, the entire stream then flows out of its channel and onto the flood plain. As a result of levee building and channel sedimentation, portions of the Yellow River in China now lie 10 meters above its flood plain. Thus, levees may solve flooding problems in the short term, but in a longer time frame they may cause even larger and more destructive floods.

Engineers have tried to solve the problem of channel sedimentation by dredging artificial channels across meanders. When a stream is straightened, its velocity increases and it scours more sediment from its channel. This solution, however, also has its drawbacks. A straightened stream is shorter than a meandering one, and consequently the total volume of its channel is reduced. Therefore, the channel cannot contain as much excess water, and flooding is likely to increase downstream.

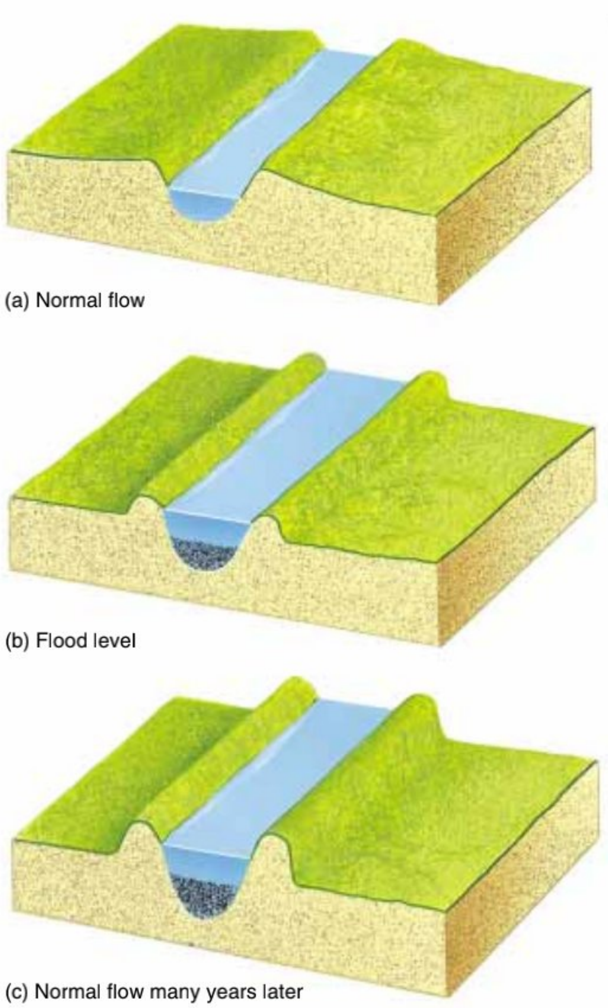

Figure 14–30 Artificial levees cause sediment to accumulate in a stream channel, eventually raising the channel above the level of the flood plain and creating the potential for a disastrous flood.

Figure 14–29 Flood waters pouring from the channel of the Missouri River through a broken levee onto the flood plain in Boone County, Missouri. (Stephen Levin)

FLOOD PLAIN MANAGEMENT

Because levees can worsen upstream and downstream flooding, the levees that save one city may endanger another. In many cases, attempts at controlling floods either do not work, or they shift the problem to a different place.

An alternative approach to flood control is to abandon some flood control projects and let the river spill out onto its flood plain in some places. Of course the question is: "What land should be allowed to flood?" Every farmer or homeowner on the river wants to maintain the levees that protect his or her land. Currently, federal and state governments are establishing wildlife reserves in some flood plain areas. Since no development is allowed in these reserves, they will flood during the next high water. However, a complete river management plan involves complex political and economic considerations.

Figure 14–31 Lago Nube in Bolivia's Cordillera Apolobamba.

14.8 LAKES

Lakes and lake shores are some of the most attractive recreational and living environments on Earth. Clean, sparkling water, abundant wildlife, beautiful scenery, aquatic recreation, and fresh breezes all come to mind when we think of going to the lake. Despite the great value that we place on them, lakes are among the most fragile and ephemeral landforms. Modern, post–ice age humans live in a special time in Earth history when the Earth's surface is dotted with numerous beautiful lakes.

THE LIFE CYCLE OF A LAKE

A **lake** is a large, inland body of standing water that occupies a depression in the land surface (Fig. 14–31). Streams flowing into the lake carry sediment, which fills the depression in a relatively short time, geologically speaking. Soon the lake becomes a swamp, and with time the swamp fills with more sediment and vegetation to become a meadow or forest with a stream flowing through it.

If most lakes fill quickly with sediment, why are they so abundant today? Most lakes exist in places that were covered by glaciers during the latest ice age. About 18,000 years ago, great continental ice sheets extended well south of the Canadian border, and mountain glaciers scoured their alpine valleys as far south as New Mexico and Arizona. Similar ice sheets and alpine glaciers existed in higher latitudes of the Southern Hemisphere. We are just now emerging from that glacial episode.

The glaciers created lakes in several different ways. Flowing ice eroded numerous depressions in the land surface, which then filled with water. The Finger Lakes of upper New York State and the Great Lakes are examples of large lakes occupying glacially scoured depressions.

The glaciers also deposited huge amounts of sediment as they melted and retreated. Because mountain glaciers flow down stream valleys, some of these great piles of glacial debris formed dams across the valleys. When the glaciers melted, streams flowed down the valleys but were blocked by the dams. Many modern lakes occupy glacially dammed valleys (Fig. 14–32).

Figure 14–32 A mountain lake dammed by glacial debris in the Sierra Nevada.

Figure 14–33 Kettle lakes in Montana's Flathead Valley formed when blocks of glacial ice melted.

In addition, the melting glaciers left huge blocks of ice buried in the glacial sediment. As the ice blocks melted, they left depressions that filled with water. Many thousands of small lakes and ponds, called **kettles** or **pothole lakes**, formed in this way. Kettles are common in the northern United States and the southern Canadian prairie (Fig. 14–33).

Most of these glacial lakes formed within the past 10,000 to 20,000 years, and sediment is rapidly filling them. Many smaller lakes have already become swamps. In the next few hundred to few thousand years, many of the remaining lakes will fill with mud. The largest, such as the Great Lakes, may continue to exist for tens of thousands of years. But the life spans of lakes such as these are limited, and it will take another glacial episode to replace them.

Lakes also form by nonglacial means. A volcanic eruption can create a crater that fills with water to form a lake, such as Crater Lake, Oregon. Other lakes form in abandoned river channels, such as the oxbow lakes on the Mississippi River flood plain, or in flat lands with shallow ground water, such as Lake Okeechobee of the Florida Everglades. These types of lakes, too, fill with sediment and, as a result, have limited lives.

A few lakes, however, form in ways that extend their lives far beyond that of a normal lake. For example, Russia's Lake Baikal is a large, deep lake lying in a depression created by an active fault. Although rivers pour sediment into the lake, movement of the fault repeatedly deepens the basin. As a result, the lake has existed for more than a million years, so long that indigenous species of seals and other animals and fish have evolved in its ecosystem.

FRESH-WATER AND SALTY LAKES

Most lakes contain fresh water because the constant flow of streams both into and out of them keeps salt from accumulating. A few lakes are salty; some, such as Utah's Great Salt Lake, are saltier than the oceans. A salty lake forms when streams flow into the lake but no streams flow out. Streams carry salts into the lake, but water leaves the lake only by evaporation and a small amount of seepage into the ground. Evaporation removes pure water, but no salts. Thus, over time the small amounts of dissolved salts carried in by the streams concentrate in the lake water. Salty lakes usually occur in desert and semiarid basins, where dry air and sunshine evaporate water rapidly.

SUMMARY

Only about 0.65 percent of the Earth's water is fresh. The rest is salty seawater and glacial ice. **Evaporation**, **transpiration**, **precipitation**, and **runoff** continuously recycle water among land, sea, and the atmosphere in the **hydrologic cycle**. About 60 times more fresh water is stored as **ground water** than as **surface water**.

A **stream** is any body of water flowing in a **channel**. A **flood** occurs when a stream overflows its banks and flows over its **flood plain**. The velocity of a stream is determined by its **gradient**, **discharge**, and channel shape and roughness.

The ability of a stream to erode and carry sediment depends on its velocity and its discharge. Stream **competence** is a measure of the largest particle it can carry. **Capacity** is the total amount of sediment a stream can carry past a point in a given amount of time. Most erosion and sediment transport occur when a stream is flooding. A stream weathers and erodes its channel and flood plain by **hydraulic action**, **abrasion**, and **solution**. A stream transports sediment as **dissolved load**, **suspended load**, and **bed load**. Most sediment is carried as suspended load. Streams deposit sediment in **channel deposits**, **alluvial fans**, **deltas**, and as **flood plain deposits**. A **braided stream** flows in many shallow, interconnecting channels.

Ultimate base level is the lowest elevation to which a stream can erode its bed. It is usually sea level. A lake or resistant rock can form a **local**, or **temporary, base**

level. A **graded stream** has a smooth, concave profile. Steep mountain streams form straight channels and V-shaped valleys, whereas lower-gradient streams form **meanders** and wide valleys. Tectonic uplift, increased rainfall, and lowering of base level all can **rejuvenate** a stream, causing it to cut down into its bed to form **incised meanders** and abandon an old flood plain to form a **stream terrace**. **Headward erosion** can cause **stream piracy**. A **drainage basin** can be characterized by **dendritic**, **trellis**, **rectangular**, or **radial** patterns, depending on bedrock geology.

Floods occur when a stream flows out of its channel and onto the **flood plain**. Floods occur periodically in all streams. Artificial levees and other flood control measures reduce flood severity in some areas but may increase flood severity at other times and places.

Many modern **lakes** were created by recent glaciers; as a result, we live in an unusual time of abundant lakes.

KEY WORDS

hydrologic cycle *236*
transpiration *236*
precipitation *236*
surface water *236*
runoff *236*
ground water *236*
stream *236*
tributary *236*
channel *236*
bed *236*
bank *236*
flood *236*
flood plain *236*
gradient *237*
discharge *237*
competence *238*
capacity *238*
hydraulic action *238*
abrasion *238*
dissolved load *239*
suspended load *240*
bed load *240*
saltation *240*
sorting *240*
channel deposits *240*
alluvial fan *240*
delta *240*
bar *241*
braided stream *241*
distributary *242*
downcutting *242*
base level *242*
ultimate base level *244*
local base level *244*
graded stream *244*
lateral erosion *245*
meander *245*
oxbow lake *246*
peneplain *246*
rejuvenation *246*
incised meander *246*
stream terrace *246*
antecedent stream *247*
superposition *247*
headward erosion *248*
stream piracy *248*
drainage basin *248*
drainage divide *248*
dendritic drainage pattern *248*
trellis pattern *249*
rectangular pattern *249*
radial pattern *250*
natural levee *251*
lake *254*

REVIEW QUESTIONS

1. What proportion of the Earth's free water is useful for drinking and irrigation? Why is the proportion so small?
2. In which physical state (solid, liquid, or vapor) does most of the Earth's free water exist? Which physical state accounts for the least?
3. Describe the movement of water through the hydrologic cycle.
4. Describe the factors that determine the velocity of stream flow and describe how those factors interact.
5. For each of the following pairs of streams (or segments of streams), which would move faster? a. Two streams have equal gradients and discharges, but one is narrow and deep while the other has a semicircular cross section. b. Two streams have equal gradients and channel shapes, but one has a greater discharge. c. Two streams have equal channel shapes and discharges, but one has a steeper gradient. d. Two streams have equal gradients, channel shapes, and discharges, but one is choked with boulders and the other is lined by smooth rock surfaces.
6. Describe the factors that control the competence of a stream.
7. Describe the factors that affect stream capacity.
8. Distinguish among the three types of stream erosion: hydraulic action, solution, and abrasion.
9. List and explain three ways in which sediment can be transported by a stream. Which type of transport is independent of stream velocity? Explain.
10. In what transport mode is most sediment carried by a stream?
11. Why do braided streams often develop in glacial and desert environments?
12. How is an alluvial fan similar to a delta? How do they differ?
13. Give two examples of natural features that create temporary base levels. Why are they temporary?
14. Draw a profile of a graded stream and an ungraded one.
15. Explain how a stream forms and shapes a valley.
16. In what type of terrain would you be likely to find a V-shaped valley? Where would you be likely to find a meandering stream?
17. What is a meander and how may it become an oxbow lake?
18. How can a stream become rejuvenated? Give an example of a landform created by a rejuvenated stream.
19. Explain the difference between an antecedent and a superposed stream.
20. Why are most lakes short-lived landforms?
21. What geologic conditions create a long-lived lake?

DISCUSSION QUESTIONS

1. In certain regions, stream discharge rises rapidly and dramatically during and after a rainfall. In other regions, stream discharge increases slowly and less dramatically. Draw a graph of these two different types of behavior, with time on the X axis and discharge on the Y axis. How do rock and soil type and vegetation affect the relationship between rainfall and discharge?
2. Gold dust settles out in regions where stream velocity slows down. If you were panning for gold, would you look for a. a graded stream or one with many temporary base levels? b. the inside or the outside of a stream bend? c. a rocky stream bed or a sandy stream bed? d. a steep gradient or a shallow gradient portion of a stream? Give reasons for each of your choices.
3. Stream flow is often reported as stream depth at a certain point. Discuss the relationship between depth and discharge. If the depth doubled, how would the discharge be affected?
4. If you were buying a house located in a flood plain, what evidence would you look for to determine past flood activity?
5. Examine Figure 14–34. If you were building a house near this river, would you choose site A or B? Defend your choice.
6. Defend the statement that most stream erosion occurs in a relatively short time when the stream is in flood.

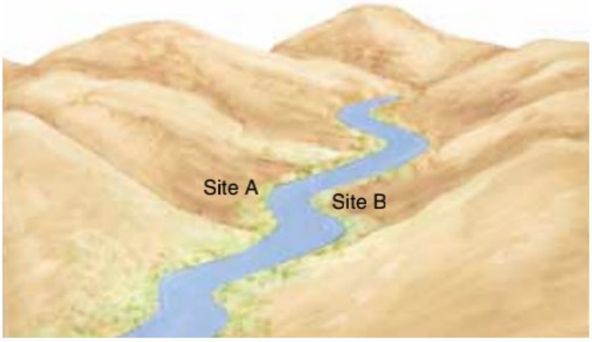

Figure 14–34 Two possible house sites along a river.

7. Imagine that a 100-year flood has just occurred on a river near your home. You want to open a small business in the area. Your accountant advises that your business and building have an economic life expectancy of 50 years. Would it be safe to build on the flood plain? Why or why not?
8. What type of drainage pattern would you expect in the following geologic environments? a. Platform sedimentary rocks. b. A batholith fractured by numerous faults. c. A flat plain with a composite volcano in the center. Defend your answers.