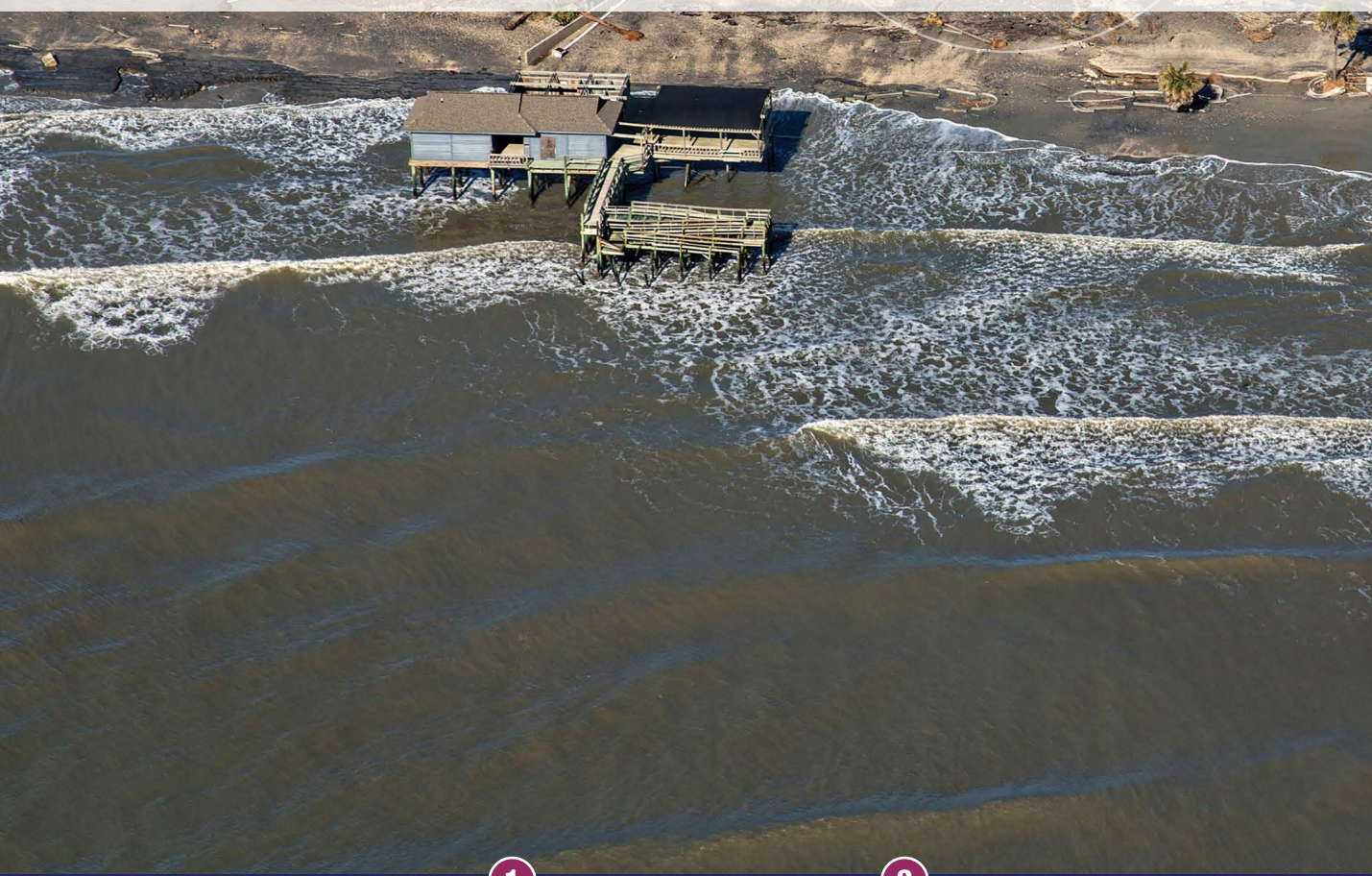
The beaches along the Eastern Seaboard are facing a serious erosion problem. Some beaches are shrinking landward by 0.3 to 1 m per year

11



APPLYING the 5 fundamental concepts Folly Island

1

Science helps us predict hazards.

Erosion of Folly Island and other coastal communities is a serious and costly natural hazard. By understanding the science behind ocean currents and sand migration along the world's coasts, we are better able to interpret the causes of coastal erosion and defend against it.

2

Knowing hazard risks can help people make decisions.

The risk of damage to land, property, and the livelihood of the 3,000 or so residents of Folly Island is being evaluated on a personal, state, and federal level.

Coastal Hazards

Folly Island

In many ways, Folly Island, 11 km (~7 mi.) south of Charleston, South Carolina, is a typical Atlantic or Gulf Coast barrier island. The island is essentially an accumulation of sand that acts as a barrier to ocean waves that would otherwise strike the mainland (Figure 11.1). A little more than 10 km (~6 mi.) long and generally less than 1 km (~0.6 mi.) wide, most of the island has an elevation of only 1.5–3 m (~5–10 ft.) above sea level. Folly Island formed 4,000 to 5,000 years ago from sand dune ridges that accumulated as the rise in sea level from the melting of Pleistocene glaciers slowed.[1] A pine forest once covered the island and was the source of its Old English name *folly*, meaning "a tree-crested dune ridge." Today Folly Island is home to about 3,000 South Carolinians.

One characteristic of Folly Island that makes it typical of Atlantic barrier islands is that it is eroding at a high rate, with some beaches shrinking landward by 0.3 to 1 m (~1 to 3 ft.) each year. The island's east-facing ocean shoreline has been retreating for at least 160 years and, in the early twentieth century, was receding at an average rate of 2 m (~7 ft.) per year.[1] In addition to natural processes that cause coastal erosion, such as hurricanes, Folly is eroding at an accelerated rate due to a pair of rocky barriers, known as jetties, that were constructed northeast of island in 1896 by the U.S. Army Corps of Engineers (Figure 11.1). The jetties were built to prevent the entrance of Charleston Harbor from being blocked by sand, which is carried southward along the coast by ocean currents. The jetties were successful

< EROSION AT FOLLY ISLAND SOUTH CAROLINA
Coastal erosion may occur slowly over tens to hundreds of years or may happen rapidly during brief periods when combined with hurricane-force winds and storm surges. Folly Island, shown here in 2012, experienced extensive erosion following Hurricanes Irene and Sandy in 2011. *(Alamy Photos)*

LEARNING Objectives

The coast, where the sea meets the land, is one of the most dynamic environments on Earth. Beaches, composed of sand or pebbles, and rocky coastlines attract tourists and new residents like few other areas, yet most of us have little understanding of how ocean waves form and change coastlines. In this chapter, we remove the mystery of the processes at work in coastal areas while retaining the wonder. We also explain the hazards resulting from waves, currents, and rising sea level and discuss how we can learn to live in the ever-changing coastal environment while sustaining its beauty.

After reading this chapter, you should be able to:

LO:1 Discuss the role of plate tectonics influencing coastal zone morphology and process.

LO:2 Explain coastal processes, such as waves, beach forms and processes, and rising sea level.

LO:3 Summarize the effects of sea-level rise on coastal processes.

LO:4 Explain why coastal erosion rates vary along different U.S. coastlines.

LO:5 Synthesize the coastal erosion hazard.

LO:6 Summarize the potential link between coastal processes and other natural hazards.

LO:7 Evaluate how human use of the coastal zone affects coastal processes.

LO:8 Summarize what we can do to minimize coastal hazards.

LO:9 List options available for coastal management.

3

Linkages exist between natural hazards.

Coastal erosion of Folly Island is linked to several other natural hazards, such as hurricanes which were responsible for extensive erosion of the island in both 2011 and 2012.

4

Humans can turn disastrous events into catastrophes.

The world's coasts are attractive places to live. Once developed, great expense is taken to preserve these narrow strips of land. Yet coastlines are some of the most dynamic landscapes on Earth, and human attempts to modify these environments often lead to unexpected negative consequences.

5

Consequences of hazards can be minimized.

When we return to Folly Island at the end of this chapter, you will learn about several strategies attempted to minimize the effects of coastal erosion on the island. But like the unexpected consequences of the Charleston jetties, some attempts only exacerbated the coastal erosion problem.

at disrupting the natural southward flow of sand down the Atlantic coast and keeping the harbor entrance open. Unfortunately, this southward flow of sand from the north regularly replenished the beaches to the south. As a consequence, severe shoreline erosion occurred on Folly and Morris Islands, which lie south of the entrance to Charleston Harbor and the jetties (Figure 11.1).

Folly Island, like coastline communities worldwide, is facing tough decisions about how to adapt to and manage coastal erosion in the future. Attempts to minimize the effects of coastal erosion of Folly Island over the past century have been diverse and have cost many tens of millions of dollars, with limited success. These investments are being made on a personal level to protect private property, at the state level to protect the island's economy, and at the federal level to reverse the damage caused by the Charleston Harbor jetties.

11.1 Introduction to Coastal Hazards

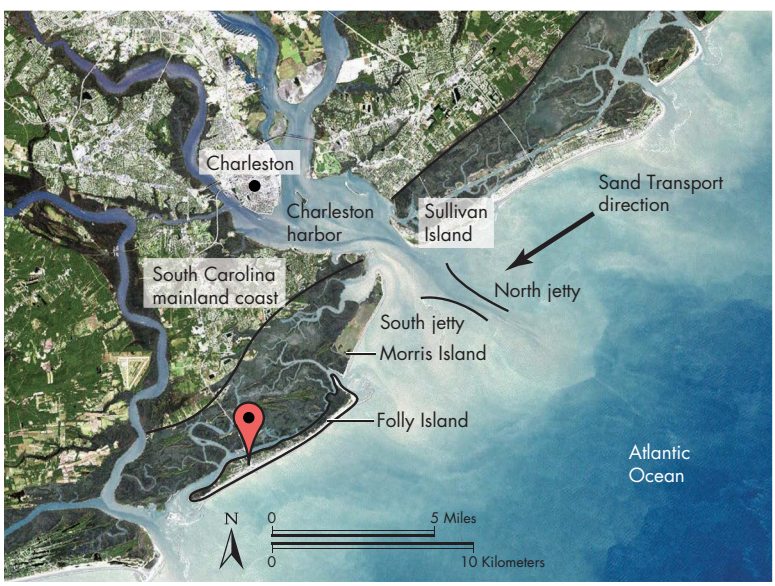
Coastal areas are dynamic environments that vary in their topography, climate, and organisms. In these areas, continental and oceanic processes converge to produce landscapes that are capable of rapid change.

Overall, coastal topography is greatly influenced by plate tectonics. The east coasts of the United States and Canada, as well as the Canadian Arctic coast, are described as tectonically passive because they are not close to a convergent plate boundary (see Chapter 2). Tectonically passive coasts typically have wide continental shelves with barrier islands and sandy beaches. Less typical are rocky shorelines, which are mostly restricted to New England, Atlantic Canada, and Arctic islands where ancient mountain ranges, such as the Appalachians, meet the Atlantic and Arctic Oceans. Along the Great Lakes, most shorelines are sandy, with rocky shores generally limited to northern areas that have experienced greater uplift following retreat of the Pleistocene glaciers.

In contrast, the west coasts of the United States and Canada are tectonically active because they are close to transform boundaries between the North American and Pacific plates (e.g., the San Andreas fault) and to convergent boundaries between the North American and Juan de Fuca or Pacific plates (e.g., the Cascadia subduction zone). Hawaii, Puerto Rico, the Virgin Islands, and southern Alaska are also tectonically active. In tectonically active regions, mountain building produces coasts with sea cliffs and rocky shorelines. Although long sandy beaches are present in these regions, they are not as abundant as along the eastern and Arctic coasts or the southern Great Lakes.

The topography of some American and Canadian coasts is significantly influenced by climate and organisms. For example, shorelines in parts of Alaska, Canada, and the Great Lakes are affected by seasonal ice or by the movement of present-day glaciers. Coastlines in temperate regions are influenced by marsh vegetation, and subtropical and tropical shores are affected by the growth of mangroves and offshore coral reefs.

The impact of hazardous coastal processes is considerable because many populated areas are located near the coast. In the United States, it is expected that most of the population will eventually be concentrated along



< FIGURE 11.1 Eroding Barrier Islands along the South Carolina Coast
Folly Island is a shrinking barrier island located south of the inlet to Charleston Harbor. One potential cause of the diminishing size of Folly Island is the jetties built to keep the harbor entrance free of sand, which consequently block sand being transported southward along the coast that would normally replenish the beaches of Folly Island. *(M-Sat Ltd./Science Source)*

the nation's 150,000 km (~93,000 mi.) of shoreline, including the Great Lakes. Today, the nation's largest cities lie in the coastal zone, and approximately 40 percent of the population lives in coastal counties, even though those counties account for only 10 percent of the land area (not including Alaska). In fact, population density for coastal counties is six times greater than that of inland counties. The population in coastal counties becomes even larger during peak vacation periods. For example, Ocean City, Maryland, receives an estimated 4 million visitors between Memorial Day and Labor Day.[2] Coastal problems will increase as more people live in coastal areas where the hazards occur. Once again, our activities continue to conflict with natural processes. Hazards along the coasts, such as coastal erosion, may become compounded by global warming, which is contributing to a worldwide rise in sea level (see Chapter 12).

The most serious coastal hazards include

- Strong coastal currents, including rip currents generated in the surf zone and tidal currents in narrow bays and channels
- Coastal erosion, which continues to produce considerable property damage that requires human adjustment
- Storm surge from tropical and extratropical cyclones, which claims many lives and causes enormous amounts of property damage every year (see Chapter 10)
- Tsunamis, which are particularly hazardous to coastal areas of the Pacific Ocean (see Chapter 4).

11.1 CHECK your understanding

1. How does plate tectonics influence coastlines?
2. What are the most serious coastal hazards?

11.2 Coastal Processes

WAVES

Waves that batter the coast are generated by offshore winds, sometimes thousands of kilometers from where the waves reach the shoreline. Wind blowing over the water produces friction along the water surface. Because the air is moving much faster than the water, the moving air transfers some of its energy to the water and produces waves. The waves, in turn, eventually expend their energy at the shoreline.

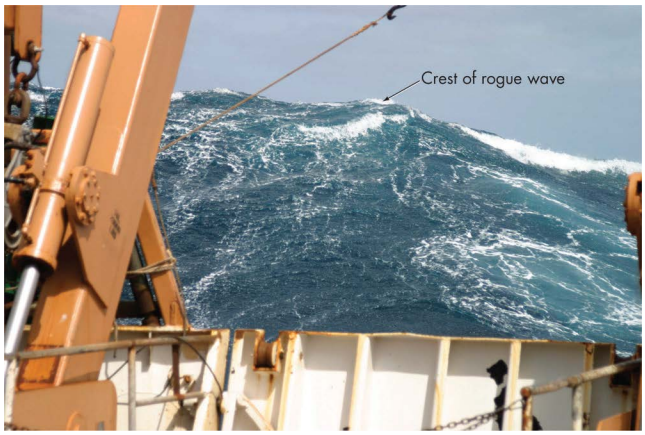
Waves vary in both their size and their shape. The size of waves in the ocean or on a lake depends on a combination of the following:

- The velocity or speed of the wind; the stronger the wind speed, the larger the waves.
- The duration of the wind. Winds that last longer, such as during storms, have more time to impart energy to the water, thereby producing larger waves.
- The distance that the wind blows across the water surface. This distance is referred to as the fetch. A longer fetch allows larger waves to form. This relationship is one reason that waves are generally larger in the ocean than in a lake.

Waves develop in a variety of sizes and shapes within an area that is experiencing a storm. As waves move away from their place of origin, they become sorted out into groups or sets of waves that have similar sizes and shapes. These sets may travel for long distances across the ocean and arrive at distant shores with little energy loss. If you stand on a beach watching the surf, you may be able to recognize these "sets" of similar-sized waves. Interactions between different sets from different sources produce a regular pattern or "surf beat." This pattern tends to repeat itself over time, allowing surfers to wait and take advantage of the sets of larger waves that they know will eventually arrive. Occasionally, however, a wave will appear that is much larger than the rest. Known as a *rogue wave*, such a huge wave is created by a number of factors.

Most rogue waves appear to form by *constructive interference*. In this process, multiple, similarly sized waves intersect to create a much larger wave. If they intersect just right, with both their crests and their troughs matching, the new wave may be as high as the sum of the intersecting waves. Undersea irregularities, as well as currents, also influence the formation of a rogue wave. Such waves can be extremely dangerous to the unsuspecting beachgoer.

When rogue waves strike the shore, lives may be lost. Such waves may appear out of nowhere, crashing down over a pier or cliff. Sadly, each summer, unsuspecting beach visitors are swept into the ocean by rogue waves and killed. Coastal zones are not the only dangerous areas. Rogue waves can also appear out of nowhere in the open ocean—in the middle of hundreds of kilometers of calm water (Figure 11.2). Such waves may be large enough to break in open water and threaten ships. In stormy seas, where almost all waves are large, rogue waves may reach 30 m (~100 ft.) in height. An initial study of three weeks of global satellite radar data found 10 separate rogue waves in the world's oceans that were taller than 25 m (~80 ft.). This is critical information for the shipping industry, since most ships



< FIGURE 11.2 Rogue Wave
This huge wave is approaching the bow of the *JOIDES Resolution*, the scientific drilling ship of the Ocean Drilling Program. Known as rogue waves, these large waves are responsible for sinking supertankers and large cargo-container ships. In April 2005, a 20 m (~65 ft.) rogue wave struck the cruise ship *Norwegian Dawn* about 400 km (~250 mi.) off the coast of Georgia. *(Personnel of NOAA Ship DELAWARE II)*

are designed to withstand 15 m (~50 ft.) waves.[3] Massive rogue waves were apparently common during the October 1991 "Perfect Storm," the intense extratropical cyclone depicted in both a book and a movie, that was responsible for sinking the fishing boat *Andrea Gail*, killing its entire six-person crew.

Waves moving across deep water have a similar basic shape or wave form (Figure 11.3a). Three parameters describe the size and movement of a wave: *wave height* (*H*), which is the difference in height between the trough and crest of a wave; *wavelength* (*L*), the distance between successive wave crests; and *wave period* (*T*), the time in seconds for successive waves to pass a reference point. Recall that we also used wavelength earlier in this book to describe the electromagnetic radiation and wave height of seismic waves as one indicator of earthquake magnitude. The reference point used to determine wave period could be a pier or similar object, which is anchored in the seafloor or lake bottom.

To understand how waves transmit energy through the water, it is useful to study the motion of an object on the water surface and one below the surface (Figure 11.3b). For example, if you were floating with a life preserver in deep water and could record your motion as waves moved through your area, you would find that you bob up, forward, down, and back in a circular orbit, always returning to the same place. If you were below the water surface with a breathing apparatus, you would still move in circles, but the circles would be smaller. That is, you would move up, forward, down, and back in a circular orbit that would remain in the same place while the waves traveled through.

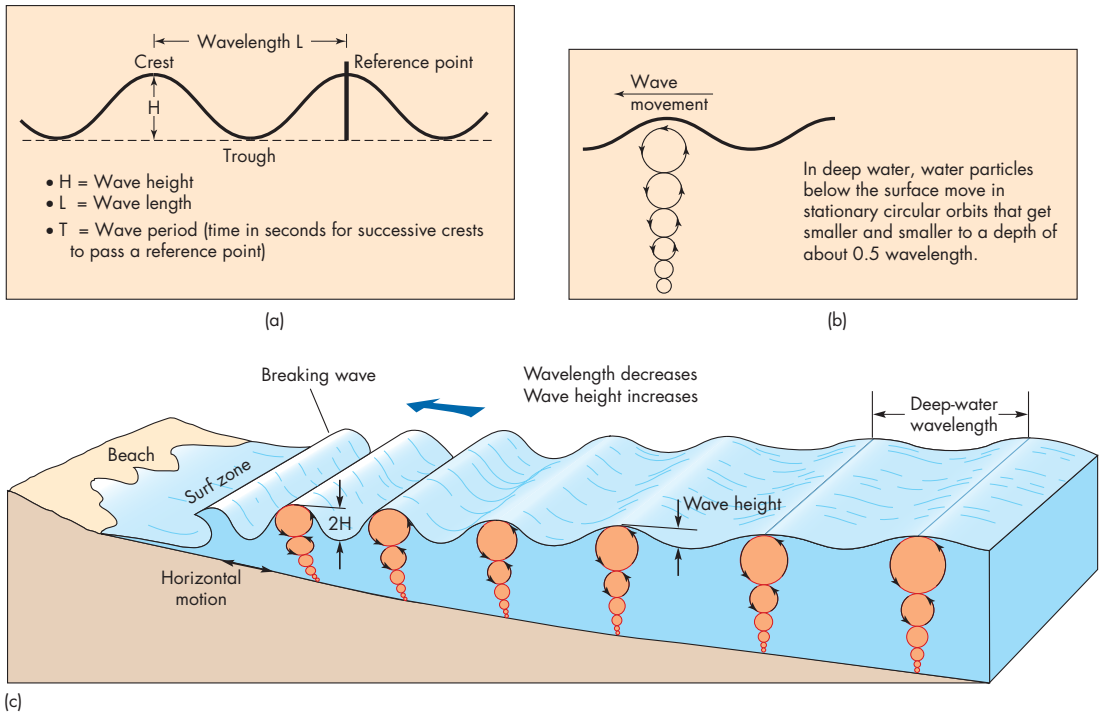
The shape of the orbital motions changes as waves enter shallow water. At a depth of less than about one-half their wavelength, the waves begin to "feel bottom." This lack of room causes the circular orbits to become ellipses. Motion at the bottom may eventually be a narrow ellipse with a back-and-forth movement that is essentially horizontal (Figure 11.3c). You may have experienced this if you have stood or swum in relatively shallow water on a beach and felt the water repeatedly push you toward the shore and then away from the shore.

Far out at sea, the wave sets generated by storms are called *swell*. As swell enters shallower and shallower water, transformations take place, and the waves eventually become unstable and break on the shore. In deep-water conditions, mathematical equations can be used to predict wave height, period, and velocity, based on the fetch, wind speed, and duration of time that the wind blows over the water. This information has important environmental consequences: By predicting the velocity and height of the waves generated by a distant storm, we can estimate when storm-generated waves with a particular erosive capability will strike the shoreline and when to expect dangerous coastal currents.

When waves enter the coastal zone and shallow water, they impinge on the bottom and become steeper. Wave steepness is the ratio of wave height to wavelength. Waves are unstable when the ratio exceeds 1/7 (~0.14). That is, waves are unstable when wave height is about 14 percent (or more) of wavelength.

As waves move into shallow water, the wave period remains constant, but wavelength and velocity decrease, and wave height increases. The waves change shape from the rounded crests and troughs in deep water to peaked crests with relatively flat troughs in shallow water close to shore. Perhaps the most dramatic feature of waves entering shallow water is their rapid increase in height. The height of waves in shallow water, where they break, may be as much as twice their deep-water height (Figure 11.3c). Waves near the shoreline, just outside the surf zone, reach a wave steepness that is unstable. The instability causes the waves to break and expend their energy on the shoreline.[4]

We have said that waves expend their energy when they reach the coastline, but just how much energy are



▲ FIGURE 11.3 Waves and Beaches

(a) Deep-water wave forms (water depth is greater than 0.5 L, where L is wavelength). The curving black line is the water surface, and the thick vertical black line is a pier or some other fixed object that can act as a reference point for determining the wave period (T). A black dashed line connects the bottom of the troughs and is the reference line for calculating wave height (H). (b) Motion of water particles associated with wave movement in deep water. The water particles follow the path of the arrows in the black circles. Wave movement is from right to left. (c) Motion of water particles as waves approach the shore. The water particles follow the path of the arrows in the circles. The waves are approaching the shore from right to left.

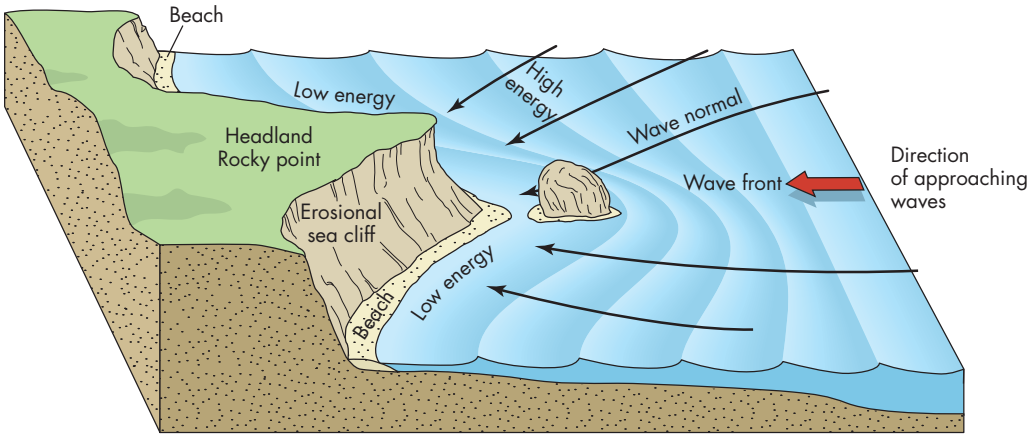
we talking about? The amount is surprisingly large. For example, the energy expended on a 400 km (~250 mi.) length of open coastline by waves with height of about 1 m (~3 ft.) over a given period of time is approximately equivalent to the energy produced by an average nuclear power plant over the same time period.[5]

Wave energy is approximately proportional to the square of the wave height. Thus, if wave height increases from 1 m (~3 ft.) to 2 m (~7 ft.), the wave energy increases by a factor of 4. If waves continue to grow to the 5 m (~16 ft.) height that is typical for large storms, then the energy expended, or wave power, will increase by 25 times as powerful as waves with a height of 1 m (~3 ft.).

Variations along a Coastline Although the heights of waves offshore from a coastline are relatively constant, the wave height along a coast may increase or decrease as waves approach the shore. These variations are caused by irregularities in the offshore topography of the seafloor and by changes in the shape of the coastline. One way to understand the variations in wave height is to examine the behavior of the long, continuous crest of a single wave, or *wave front*, as it approaches an irregularly shaped coastline (Figure 11.4a).

Irregular coastlines have small rocky peninsulas known as *headlands*. The shoreline between headlands may be relatively straight or somewhat curved. Underwater, the offshore topography surrounding the headland is similar to that of the rest of the coast; that is, the water gets progressively shallower close to shore. This shallowing means that as a wave approaches the coast, it will first slow down in the shallow water off the headland. The slowdown will cause a long wave front to bend when it reaches a headland. This bending, referred to as *refraction*, causes wave fronts to become more nearly parallel to the shoreline.

Effects of Wave Refraction To visualize the effects of wave refraction, draw a series of imaginary lines, called *wave normals*, perpendicular to the wave fronts, and add arrows pointing toward the shoreline. The resulting diagram (see Figure 11.4a) shows that wave



(a)



(b)

▲ FIGURE 11.4 Convergence and Divergence of Wave Energy
(a) Idealized diagram of the process of wave refraction and concentration of wave energy at rocky points called *headlands.* Refraction, or bending of wave fronts, causes the convergence of wave normals on the headland and their divergence in low-energy areas along the coast away from the headland. Wave normals are the imaginary long, curving black arrows. The red arrow indicates that the waves are approaching the shore from right to left. (b) Large waves striking a rocky headland along the Pacific coast at Pebble Beach in San Mateo County, California. *(Robert H. Blodgett)*

refraction causes a *convergence* of the wave normals at the headland and a *divergence* of the wave normals along the shoreline away from the headland. Where wave normals converge, both wave height and the energy expended by the waves increase. Thus, the largest waves along a shoreline are generally found at the end of a rocky headland (Figure 11.4b). The long-term effect of greater energy expenditure on protruding areas, such as headlands, is that wave energy is used to erode the coast, and the resulting erosion tends to straighten the shoreline.

Breaking Waves Waves also vary in how they break along a coastline. Breaking waves may peak quickly and plunge or surge, or they may gently spill, depending on local conditions. Waves that plunge are called *plunging breakers* (Figure 11.5a). They typically form on steep beaches and tend to be more erosive. Waves that spill are referred to as *spilling breakers* (Figure 11.5b). They commonly develop on wide, nearly flat beaches and are more likely to deposit sand. The type of breaker that occurs along a coastline can change seasonally and with changes in underwater slope and topography. Overall, large plunging breakers that form as the result of storms cause much of the coastal erosion.

BEACH FORM AND PROCESSES

A **beach** is a landform consisting of loose material, such as sand or gravel, which has accumulated by wave action at the shoreline. Beaches may be composed of a variety of loose material. For example, the color and composition of beach sand are directly tied to the source of the sand: Many white sand Pacific island beaches are made of broken bits of shell and coral, Hawaii's black sand beaches are composed of fragments of volcanic rock, and brown Carolina beaches contain grains of the minerals quartz and feldspar.

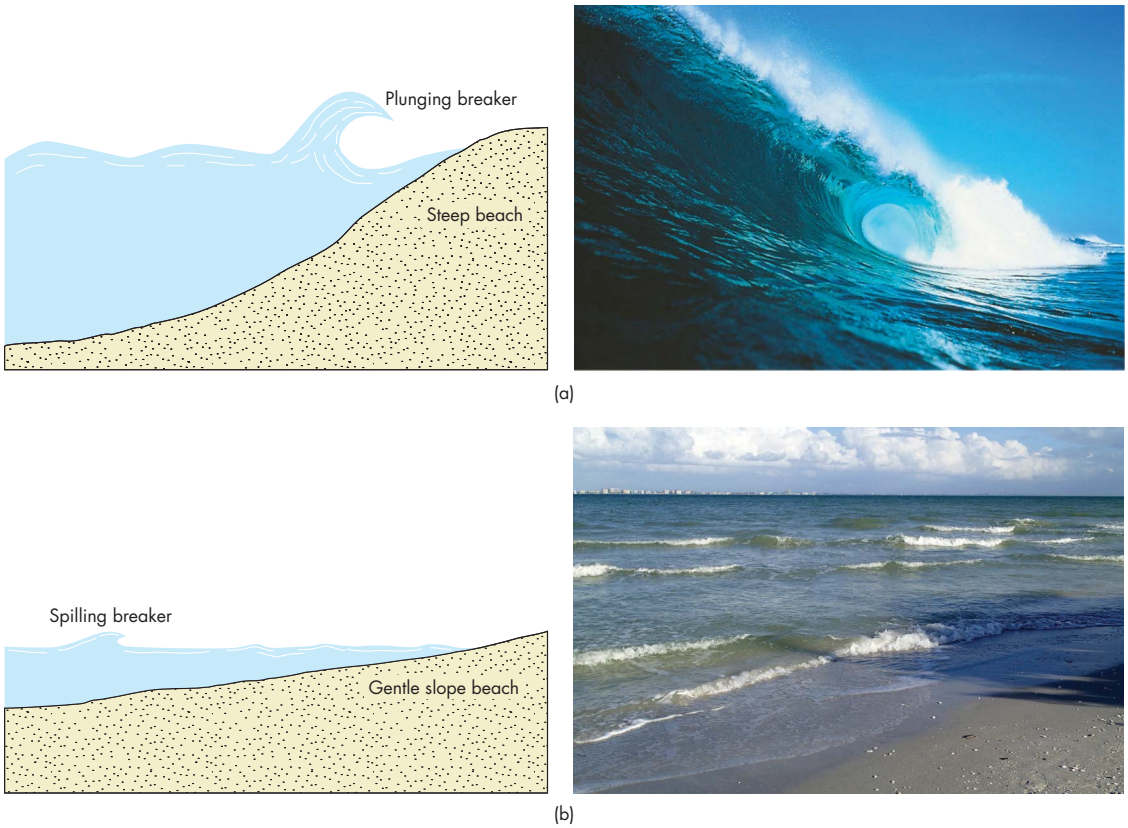


FIGURE 11.5 Types of Breakers
Idealized diagrams and photographs showing (a) plunging breakers on a steep beach and (b) spilling breakers on a gently sloping beach. *([a] Peter Cade/Stone/Getty Images [b] StockPhotosArt—Nature/Alamy Stock Photo)*

The Beach Onshore Beaches have a number of features, both onshore and offshore (Figure 11.6). Onshore, the landward extent of the beach is generally a cliff, called a **sea cliff** along the seashore and a *bluff* along a lakeshore, a line of sand dunes, or a line of permanent vegetation. Sea cliffs and lakeside bluffs develop by the erosion of rock or unconsolidated sediment. In contrast, coastal sand dunes are created by the deposition of wind-blown beach sand.

The onshore portion of most beaches can be divided into two areas: one that slopes very gently landward, called a berm, and another that slopes toward the water, called the beach face. *Berms* are nearly flat backshore areas formed by deposition of sediment as waves rush up and expend the last of their energy. They are often places where you'll find people sunbathing. Beaches may have more than one berm, or there may be no berm at all. A *beach face* begins where the beach slope changes direction and steepens toward the water. The part of the beach face that experiences the up-rush and backwash of waves is called the *swash zone*. This zone shifts in size and location with changes in water level resulting from storms or, on seacoasts, from tides.

The Beach Offshore Directly offshore from the swash zone are two distinctive zones in the water—the surf zone and breaker zone (see Figure 11.6). The *surf zone* is that portion of the nearshore environment where turbulent water moves toward the shore after the incoming waves break. Beyond the surf zone is the *breaker zone*, the area where incoming waves become unstable, peak, and break. These conditions on the water surface are reflected in the underwater topography. A sandbar, called a *longshore bar*, forms beneath each line of breakers in the breaker zone. Landward from a longshore bar is a *longshore trough*, which is formed by wave and current action. Both the bar and trough are usually elongate, parallel to the breaking waves. Wide and gently sloping beaches may have several lines of breakers and longshore bars.[4]

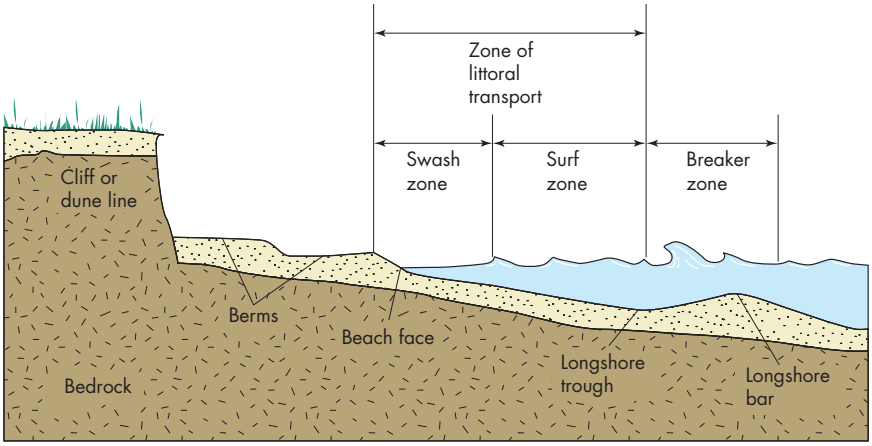


FIGURE 11.6 Beach Terms
Basic terminology for landforms and wave action in the beach and nearshore environment. A sea cliff or line of coastal sand dunes on the left marks the landward extent of the beach. Two berms are shown in the beach sand, each gently sloping toward the cliff or dunes. The beach face, where the land meets the water, is more steeply sloping toward the water. One longshore sandbar and longshore trough are shown underwater; the sandbar forms below the breaker zone. The zone of littoral transport includes both beach drift in the swash zone and longshore drift in the surf zone.

Sand Transport The sand on beaches is not static; wave action constantly keeps the sand moving in the surf and swash zones. Storms erode sand from the beach and redeposit the sand either offshore or landward from the shoreline. Most of the sand moved offshore during a storm returns to the beach during fair-weather conditions.

A great deal of sand movement occurs parallel to the shoreline by **littoral transport** (*littoral* means "shore") in the swash and surf zones (Figure 11.7). This movement includes two processes, beach drift and longshore drift. In *beach drift*, the up-and-back movement of beach material in the swash zone causes sediment to move along a beach in a zigzag path, whereas *longshore drift* refers to the transport of sediment by ocean currents that flow essentially parallel to the shoreline. These currents, called *longshore currents*, are the primary mechanism for littoral transport. Both longshore drift and beach drift occur when waves strike the coast at an angle. The terms *updrift* and *downdrift* are often used to indicate the direction in which sediment is moving or accumulating along the shore. For example, up-drift in Figure 11.7 is shown in the lower-left part of the diagram.

The direction of littoral transport along both the east and the west coasts of the United States is most often to the south, although it can be quite variable. Along U.S. seacoasts, most rates of longshore drift are between 150,000 and 300,000 m^3 (~200,000 and 400,000 $yd.^3$) of sediment per year. Although rates of longshore drift in the Great Lakes are much less, on the order of 6000 to 69,000 m^3 (~8000 to 90,000 $yd.^3$) per year, these rates are still substantial when you consider

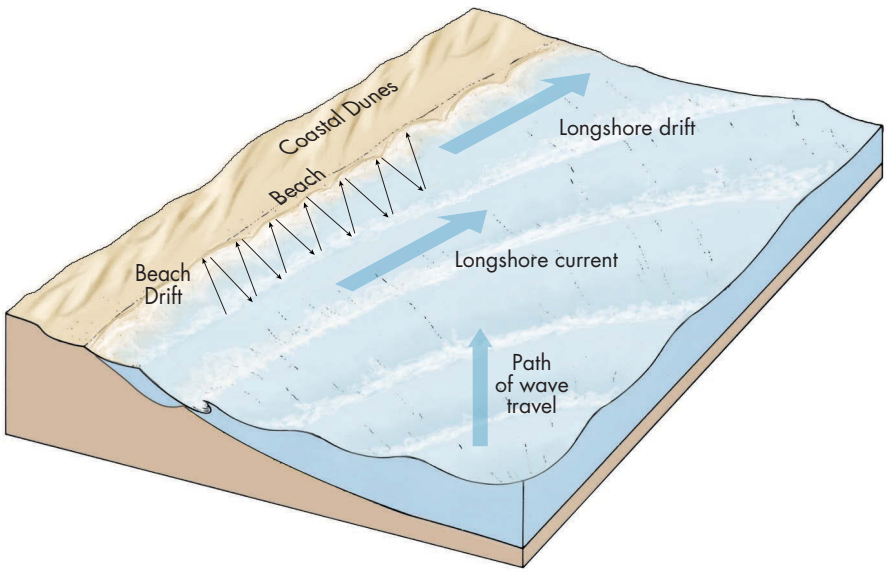


FIGURE 11.7 Transport of Sediment along a Coast
Block diagram illustrating the processes of beach drift and longshore drift. Direction of beach drift is shown by the many arrows in the swash zone. The longshore drift direction is shown by the straight, thick (dark blue) arrow in the surf zone. Collectively, these two types of drift move sand along the coast in a process known as littoral transport.

that a typical dump truck carries a meager 8 m^3 (~10 $yd.^3$) of sand. Transported sediment is eventually deposited on shore in sand dunes, deposited on sandbars or barrier islands, or carried further out to sea.

11.2 CHECK your understanding

1. What three factors determine the size of waves?
2. What are rogue waves?
3. Define wave height, wavelength, wave period, and wave energy.
4. What is wave refraction?
5. Define plunging and spilling breakers.
6. What defines a beach?
7. What is littoral transport?
8. Differentiate between beach drift and longshore drift.

11.3 Sea-Level Change

Like the beach, the level of the sea at the shore is constantly changing. This change in sea level is caused by a number of processes, some of which operate locally and others that affect all the world's oceans. The position of the sea at the shore, referred to as **relative sea level**, is influenced by both the movement of the land and the movement of the water. These movements can be local, regional, or global in extent. Global sea level, also called **eustatic sea level**, is controlled by processes that affect the overall volume of water in the ocean and the shape of the ocean basins. Changes in eustatic sea level are just one of many factors that cause a change in relative sea level.

Eustatic Sea Level Global sea-level rises or falls when the amount of water in the world's oceans increases or decreases or when there is a change in the overall shape of ocean basins. Climate, primarily the average air temperature, exerts the greatest control on the amount of water in the ocean today. Air temperature influences both the average temperature of the ocean and the amount of water that is stored in ice on land. As the average temperature of the ocean increases, the volume of water expands; as it cools, the volume of water contracts. Referred to as *thermal expansion* or *contraction*, global warming or cooling of the atmosphere is responsible for this phenomenon. For example, present eustatic rise in sea level is about 3 mm or 0.12 in. per year, and about half of the rise in eustatic sea level in the world's oceans (currently about 1.6 mm or 0.06 in. per year) results from thermal expansion caused by the warming of the atmosphere.[6]

Changes in air temperature also cause ice on land to melt or snowfall to increase. Thus, the volume of water frozen in glacial ice, ice caps, ice sheets, and permafrost is closely related to the average air temperature over years or decades. Most recently, global warming of our atmosphere has contributed to melting glaciers, ice caps, and the ice sheets in Greenland and Antarctica. This melting has increased the amount of water in the world's oceans and has contributed to about half of the eustatic rise in sea level (~1.5 mm per year).[6]

Over longer geologic time spans, ocean basins change shape as the result of plate tectonic processes. These large-scale processes, such as the rate of seafloor spreading at mid-ocean ridges (see Chapter 2), influence eustatic sea level over long periods of time and are unlikely to contribute significantly to changes in relative sea level observed over decades or centuries.

Relative Sea Level Superimposed on eustatic sea level are local or regional processes that influence the movement of the land and water. The land can rise or fall slowly, as Earth's crust responds to the weight of the now-melted Pleistocene glaciers (see Chapter 12), or rapidly, in response to tectonic movements during an earthquake. For example, on Good Friday, 1964, the shoreline of Montague Island in Prince William Sound southeast of Anchorage, Alaska, rose close to 10 m (~33 ft.) in just a few minutes during a **M** 9.2 earthquake.[7] Many coastlines that are tectonically active and that experience frequent uplift in earthquakes may be less strongly influenced by eustatic sea-level rise caused by global warming.

Movement of the shoreline is also influenced by the rates of deposition, erosion, or subsidence along the coast. Input and output factors in the beach budget described in Section 11.5 determine whether a coastline is experiencing net erosion or deposition. Rates of coastal subsidence have a major influence on relative sea level on some shorelines, such as the Louisiana coastline described in Chapter 8.

On a daily basis, astronomical tides and weather conditions primarily control relative sea level. Astronomical tides are produced by the gravitational pull of the moon and, to a lesser extent, the sun. These tides cause relative sea level to fluctuate daily and seasonally as the position of a coast relative to the moon and sun constantly shifts. Although tidal fluctuations are entirely predictable, they can create hazardous currents and affect the height of storm surges. As mentioned previously, storm surge that occurs at high tide is generally more damaging than one that occurs at low tide (see Chapter 10).

Weather conditions also change relative to sea level over a period of hours or days. Changes in wind speed and atmospheric pressure influence the level of the sea. Wind speed has a greater effect than atmospheric pressure on relative sea level. In the open ocean, high winds pile up water and increase wave height, producing the swell described earlier. This swell increases both water level and wave heights when it reaches the shore. Storm surge from tropical storms, hurricanes, and extratropical cyclones crossing the coast are extreme cases of the swell moving landward. As mentioned in Chapter 10, the significant drop in atmospheric pressure in major hurricanes can add a meter or more to the height of the storm surge. For weaker tropical and extratropical cyclones, there is a smaller drop in atmospheric pressure and, thus, less of an effect on the storm surge. Finally, over short time periods (days to months), sea level may change up to about 30 cm (~12 in.) with El Niño conditions (an atmospheric and ocean event characterized by warm water, and along the U.S. West Coast, stormy conditions; see Chapter 12).

In summary, rapid changes in relative sea level contribute to coastal flooding and hazardous nearshore currents, whereas rising eustatic sea level over decades increases hazards from storm surge and coastal erosion. Over the long term, rising sea level threatens coastal cities and the very existence of many islands (see Chapter 12). We may need to rethink how to best reduce coastal erosion in a world of rising sea level.

11.3 CHECK your understanding

1. Define relative and eustatic sea-level rise, and explain the corresponding coastal hazards.
2. How does sea level change temporarily for very short periods of hours or days?

11.4 Geographic Regions at Risk from Coastal Hazards

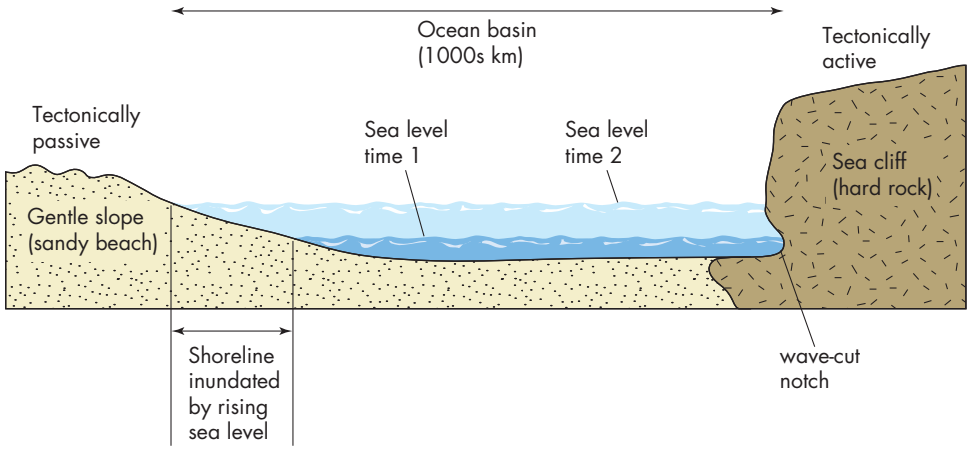
Coastal hazards are present on both seacoasts and lakeshores. In particular, large lakes, such as the Great Lakes, Great Bear Lake, Great Slave Lake, and Lake Winnipeg, develop coastal conditions similar to those on the ocean. In North America, coastal processes may have hazardous consequences along the Atlantic, Pacific, Gulf, and Arctic coasts, as well as along the shores of the Great Lakes. Strong nearshore currents, sea-level rise, storm surge from cyclones, and tsunamis are not hazards on all coastlines. For example, tsunamis and hurricanes are generally absent in lakes. In North America, only Lake Okeechobee in Florida and Lake Pontchartrain in Louisiana have experienced significant storm surges from hurricanes in historic times.

Coastal erosion is, however, a more universal hazard. As discussed later, there are various causes for this erosion, but the net effect is the horizontal retreat of the shoreline, sometimes at the rate of meters per year. All 30 U.S. states and the Canadian provinces bordering the ocean or the Great Lakes have problems with coastal erosion. Average erosion rates along some barrier islands in the southeastern United States may reach as high as 8 m (~25 ft.) per year but average closer to 0.3 to 1.0 m (~1 to 3 ft.) per year. Florida and the Gulf Coast states have highly variable erosion rates of 0.3 to 2 m (~1 to 7 ft. per year). Shorelines of the Great Lakes have experienced erosion rates up to 15 m (~50 ft.) per year[8] but average about 0.3 to 1 m (~1 to 3 ft.) per year. Along the U.S. West Coast erosion rates are also highly variable, from 0.1 to 0.3 m (~0.3 to 1 ft.) per year. Whatever the average rate of erosion at a particular coastline, local conditions (rock type and amount of sand on a beach, for example) at a particular time (when storm waves are present) and specific location (close to human structures such as a seawall) make average rates difficult to interpret.

Strong nearshore currents, especially the rip currents described later, are common on coastlines that have regular, strong surf conditions, such as those in California and Hawaii. These currents can develop on any coast with breaking waves, including the Great Lakes. Strong ocean currents are also a hazard on U.S. Gulf and East Coast beaches, where many people are rescued from rip currents each year. Strong coastal currents are especially dangerous around artificial structures, such as groins, jetties, and piers.

Astronomical tides can also produce strong currents in narrow bays and channels. On coastlines with a large range between high and low tides, the incoming flood tide can rush in rapidly. For example, the Bay of Fundy, between Nova Scotia and New Brunswick, Canada, has a tidal range that is 15 m (~50 ft.), and the incoming tide can rise 1 m (~3 ft.) in 23 minutes. Tidal currents rushing through the Golden Gate beneath the Golden Gate Bridge in San Francisco can reach 3 m per second (~7 mi. per hour). Although most tidal currents are predictable, the location and intensity of strong coastal currents can take even the strongest swimmers by surprise.[9]

The geographic areas at greatest risk for rising sea level are coastal areas and islands whose elevation is closest to present-day sea level or whose coastlines are subsiding. Coastal areas in North America that are close to sea level include most of the Gulf Coast, much



< FIGURE 11.8 Rising Sea Level Has the Greatest Effect on Low Coastlines
Low, tectonically passive coastlines are most affected by rising sea level. As sea-level rises, the shoreline shifts the farthest distance inland on shallow coastlines.

of the East Coast from Long Island south to Florida, and parts of Arctic Canada and the North Slope of Alaska. In these areas, a 0.3 m (~1 ft.) rise in sea level can result in a landward shift of the shoreline anywhere from 30 to 300 m (~100 to 1000 ft.) (Figure 11.8). Areas that are rapidly subsiding, such as parts of the Louisiana coast, may experience greater inundation from rising sea level (see Chapter 8). Many low islands in the Pacific, called *atolls*, are in danger of becoming inundated with rising sea level. Some examples associated with the United States include the Marshall Islands, the Federated States of Micronesia, and the Republic of Palau in the western Pacific Ocean (see Chapter 12).

11.4 CHECK your understanding

1. List factors that help determine the rate of coastal erosion at a particular beach.
2. Why are average rates of erosion at the regional scale useful but difficult to interpret?

11.5 Effects of Coastal Processes

Coastal processes create hazards for both individuals and communities. Individuals face safety hazards from strong coastal currents when they are swimming or wading and hazards to both safety and property during storm surges and tsunamis. Communities face long-term hazards related to coastal erosion and rising sea level. Strong coastal currents can be produced by the backflow of water in the surf zone and by the rising and falling of the tide. Coastal erosion affects natural features, such as beaches, dunes, cliffs, and bluffs, and threatens beachfront houses and businesses, lighthouses and docks, as well as roads, streets, and utility lines running close to the shore.

On *barrier islands* and sandy peninsulas called *spits*, coastal processes constantly shift the location of the shoreline, eroding material in one location and depositing material in another. This can involve movement of an entire island, the inlets between islands, or the separation of a spit from the mainland. The southern end of Hog Island along the Delmarva Peninsula of Virginia has shifted nearly 2.5 km (~1.6 mi.) in historic times (Figure 11.9).[10] In Texas, Aransas Pass, the tidal inlet that provides ships access to Corpus Christi Bay, shifted more than 3 km (~2 mi.) between 1859 and 1911 before its location was stabilized with the construction of jetties.[11] Bayocean spit near Tillamook, Oregon, and the Nauset Beach spit near Chatham, Massachusetts, were both breached by storms in the twentieth century and separated from the mainland. The continual movement of barrier islands and spits is one of several characteristics that make them poor places for coastal development.

Our discussion of the effects of coastal hazards focuses on the effects of strong nearshore currents, called rip currents, and the effects of beach and cliff erosion. Discussion of the effects of tsunamis (Chapter 4), subsiding coastlines (Chapter 8), storm surge (Chapter 10), and rising sea level (Chapter 12) appears elsewhere.

RIP CURRENTS

The longshore currents described previously are not the only currents that develop along a beach. Under specific conditions along a seacoast or lakeshore,

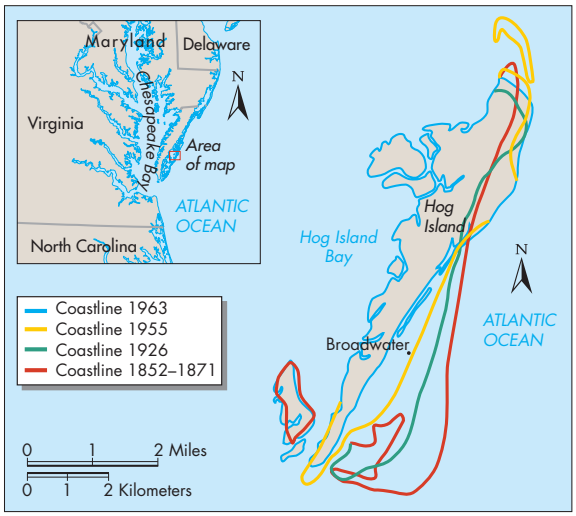


FIGURE 11.9 Barrier Islands Continually Change Shape and Location

Hog Island in Northampton County, Virginia, shifted location and changed form from the mid-nineteenth to mid-twentieth centuries. The island was once covered with pine forest and was the site of Broadwater, a town of 300 people, 50 houses, a school, church, and lighthouse. A hurricane inundated the entire island in 1933, and by the early 1940s, the inhabitants had left. The town site is now under several meters of water. *(Based on Williams, S. J., Dodd, K., and Gohn, K. K. 1991. "Coasts in Crisis," U.S. Geological Survey Circular 1075.)*



(a)

(b)

FIGURE 11.10 Rip Currents

(a) The rip current is indicated by the blue milky water spreading outward from this rocky point. The blue milky water has sediment suspended in it. Dark stringers in the water are areas of kelp. *(Edward A. Keller)* (b) The existence of a rip current on this sandy beach is indicated by an area of smooth water where no waves are breaking. *(Edward A. Keller)*

powerful currents form that carry large amounts of water away from the shore. These currents, called **rip currents**, develop when a series of large waves piles up water between the longshore bar and the swash zone. The water does not return offshore the way it came in but, instead, is concentrated in narrow zones to form rip currents (Figure 11.10). Beachgoers and lifeguards often incorrectly call this flow "riptide" or "undertow." These currents are not tides and don't pull people under the water, but they can pull people away from shore (see Case Study 11.1: Survivor Story).

In the United States, more than 100 people are killed by rip currents annually, and rip currents are the cause of more than 80 percent of the 60,000 surf rescues each year. Therefore, rip currents constitute a serious coastal hazard, on average killing more people in the United States on an annual basis than do hurricanes or earthquakes; deaths from rip currents are equivalent to those from river flooding. People drown in rip currents because they panic and fight them by trying to swim directly back to shore. This feat is nearly impossible because the current can exceed 6 km (~4 mi.) per hour, which even strong swimmers cannot maintain for long. A swimmer trying to fight a rip current soon becomes exhausted and may not have the energy to keep swimming.

Rip currents vary in width from about 15 m (50 ft.) to about 100 m (300 ft.) wide. They usually form in the surf zone at breaks in the longshore bar, but also around human structures, such as piers. They flow out perpendicular to the shoreline for a distance of tens to hundreds of meters offshore. Rip currents are fed by incoming breakers and longshore currents and may make their own channel as they pass through the longshore bar (Figure 11.11). Fortunately, they widen and dissipate once they have passed the line of breaking waves.

CASE study

11.1 Survivor Story

Rip Current: Two Experienced Swimmers Rescued on Florida Beach

It was a hot summer's day in Pensacola, Florida, and Jennifer Kleinbaum and her fiancé Ernie decided to go to the beach. The waters of the Emerald Coast were still as glass, but a red flag warned visitors that it was too dangerous to swim. To be on the safe side, the couple decided to go for a stroll instead (Figure 11.1.A).

But the sand scorched their feet, and they waded ever farther into the water to stay cool. Before they knew it, they were treading water.

Even so, neither was worried. At 26, both were strong swimmers and certified SCUBA divers. Kleinbaum was certified as a master SCUBA diver, whereas Ernie had grown up in Pensacola, swimming at this very beach.

On the horizon, they spotted a triangular fin. A marine biologist, Kleinbaum dismissed it as a harmless dogfin shark. But Ernie, unnerved, suggested returning to shore.

It took Kleinbaum some time to notice they weren't making any headway. "They say if you're swimming and not getting any closer, don't fight it; swim parallel or float out of the path of the rip current. But I was fighting without realizing it," Kleinbaum said.

They drifted into an area where the waves crashed directly over their heads and found themselves unable to swim away. "I was treading water and trying to keep myself up. I can do this for hours in a pool. But I was struggling trying to avoid the waves, and that made me much more tired," Kleinbaum said.

Fatigued and frightened, Kleinbaum began to panic. She knew she couldn't hang on to Ernie, for fear of drowning him. "But I wanted to stay close to him, because there was nothing else I could see—he was my mental life raft." Gasping, she told him she couldn't keep her head above water much longer.

Ernie began waving his arm back and forth, yelling for help. Kleinbaum joined him. "Even though I was so tired, I somehow had no problem finding energy for this; it was something I could focus on," Kleinbaum said.



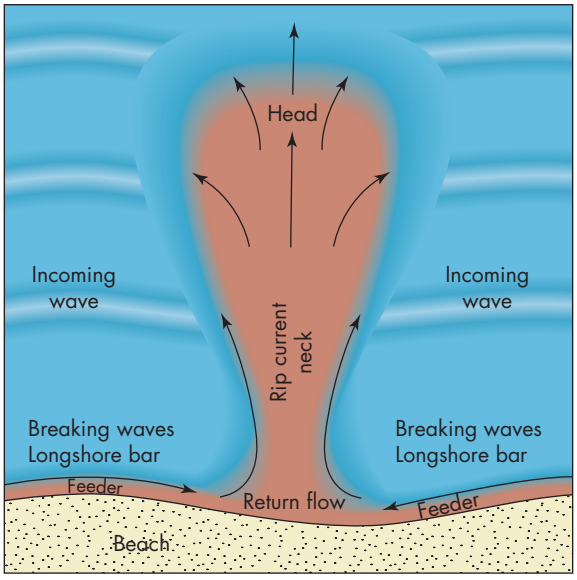
< FIGURE 11.1.A A Happier Day on the Beach
Jennifer Kleinbaum plays with her nephew Jake on a Florida beach. An earlier trip to a Pensacola, Florida, beach with her fiancé Ernie nearly ended in tragedy when they were both caught in a rip current while swimming near shore. *(Aaron Kleinbaum)*

On the beach, they saw people jump up and run away. The next thing Kleinbaum remembers, a man was pushing a red, sausage-shaped lifebuoy toward them, then helping tow the pair toward shore. An off-duty lifeguard, he sat them down on the sand to rest and called an ambulance.

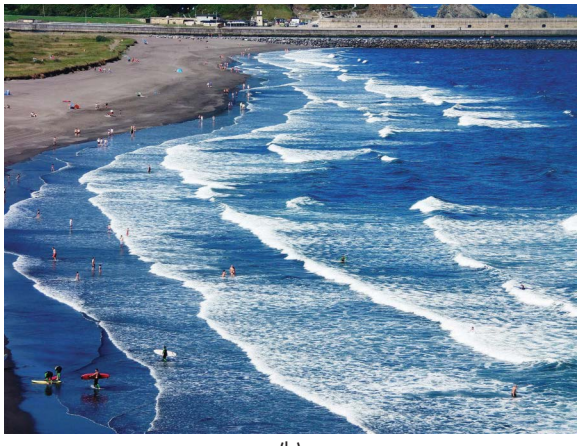
Only then did Kleinbaum realize they had been caught in a rip current. "After he got us out of the water, our overriding emotion wasn't relief or thank you—it was oh, my god, I am so embarrassed. We kept looking at each other saying, how did this happen to us?"

She had thought it couldn't happen to a strong swimmer. Ernie believed it happened only to tourists. "There couldn't have been two people who knew more about the ocean and rip tides, what they were and how to get out of them. Yet we still made all the wrong choices," she said.

— KATHLEEN WONG



(a)



(b)

To safely escape a rip current, a swimmer must first recognize the current and then swim parallel to the shore until he or she is outside the current. Only then should the swimmer attempt to swim back to shore. If you cannot reach shore, wave an arm and yell for help. The key to survival is not to panic. When you swim in the ocean, watch the waves for a few minutes before entering the water and note the "surf beat," the regularly arriving sets of small and larger waves. Rip currents can form quickly after the arrival of a set of large waves. They can be recognized as a relatively quiet area in the surf zone where fewer incoming waves break (see Figure 11.10b). You may see the current as a mass of water and debris moving out through the surf zone. The water in the current may also be a different color because it carries suspended sediment. Remember, if you do get caught in a rip current, don't panic—swim parallel to shore before heading back to the beach, and you should be able to safely escape.

COASTAL EROSION

As a result of the continuing global rise in sea level and extensive development in the coastal zone, coastal erosion is becoming recognized as a serious national and worldwide problem. Coastal erosion is generally a more

< FIGURE 11.11 Flow in a Rip Current

(a) Bird's-eye view of the surf zone showing a rip current, which is the return flow of water that forms as a result of incoming waves. Return flow starts in the surf zone and goes through a low area in the longshore bar; flow expands outward once the current gets beyond the breaker zone. (b) Large rip cell on a popular beach; notice the center of the photo where the line of breakers have a gap – that is the rip current. *(Prof. Hyeong-Dong Park, Seoul National University, Korea)*

continuous, predictable process than other natural hazards, such as earthquakes, tropical cyclones, and floods. Large sums of money are spent in attempts to control coastal erosion, but many of the fixes are only temporary. If extensive development of coastal areas for vacation and recreational living continues, coastal erosion will certainly become a more serious problem.

Beach Erosion An easy way to visualize erosion at a particular beach is to take a beach budget approach. A **beach budget** is similar to a bank account. In a bank account, deposits made to the account are input; the account balance reflects the storage of money in the account. Withdrawals by cash, check, or debit card are output from the account. Similarly, we can analyze a beach in terms of input, storage, and output of the sand or gravel that makes up the beach. Most input of sediment to a beach is caused by the coastal processes that move the sediment along the shore (see Figure 11.7) or by local wave erosion. Coastal processes, particularly beach drift and longshore drift, bring sediment from sources updrift of a beach. Local wave erosion of sand dunes or sea cliffs landward of the beach also results in inputs of sediment to the beach. Erosion of sand dunes and cliffs is generally most intense during storms when water floods the entire beach and large waves can reach inland. Sediment moving along a shoreline comes from one or more updrift sources, such as a river delta or erosion of another beach. The sediment that is in storage on a beach is what you see when you visit the site. Output of sediment occurs when coastal processes move sand or gravel away from the beach. These output processes can include littoral drift, a return bottom flow from storm waves that carries sediment into deeper water, and onshore winds that erode sand from the beach and blow it inland.

If input of sand to a beach exceeds output, the beach will grow as more sediment is stored and the beach widens. When input and output are about the same, the beach will stay fairly constant in width. If output of sediment exceeds input, the beach will erode and there will be fewer grains of sand or pieces of gravel on the beach. Thus, we see that the budget represents a balance of sediment on the beach over a period of years. Short-term changes in sediment supply from the attack of storm waves will cause seasonal or storm-related changes to the balance of sediment on a beach. Long-term changes in the beach budget caused by climate change or human impact result in either deposition or erosion of a beach.

A long-term change on some Gulf and East Coast beaches in the United States has been a reduction in sand supply from rivers. Construction of dams on rivers reaching the coast, such as the Savannah River in Georgia and the Rio Grande in Texas, has decreased the sand supply to beaches by trapping sediment behind the dam, thereby amplifying the coastal erosion problem. We now will consider the concept of the beach budget in greater detail with an idealized example.

Imagine a simple coast with rivers supplying sand, a sea cliff, a beach, and a submarine canyon (Figure 11.12). This coast defines a *littoral cell*, which is a segment of coast (a system) that includes sources and transport of sand to and along the beach (in this simple case, rivers deliver sand, as does sea cliff erosion). Sand is transported along the coast, and some is transported from the nearshore environment down a *submarine canyon* (an offshore canyon that may head in the surf zone and remove sand from the beach transport system). Now imagine that a dam was built in the area 15 years ago, which affects the amount of sediment supplied to the cell. Here, we determine the budget before and after the dam was constructed, confirming the erosion observed on beaches south of the submarine canyon where homes are threatened. Sources of sand for the beach are as follows:

(Sl) Littoral transport (+):
South (200,000 m^3/yr) – North (50,000 m^3/yr) = Net (150,000 m^3/yr) to the south

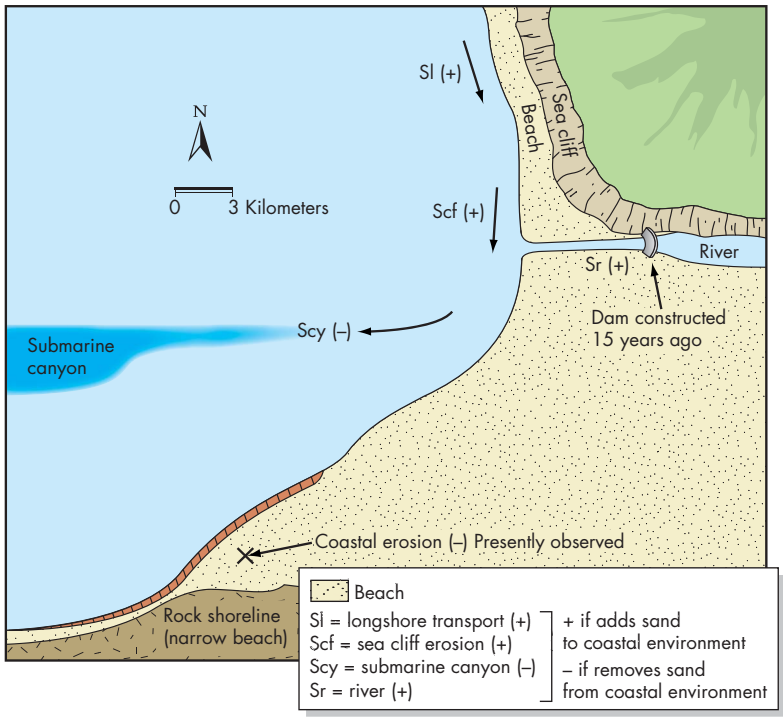
(Scf) Sea cliff erosion (+):
(0.55 m/yr)(6 m)(3000 m)(0.5) = 4500 m^3/yr
(Erosion rate is 0.5 m/yr; average height of sea cliff is 6 m; total length 3000 m. Assume 50 percent of material eroded remains on beach.)

(Scy) Down submarine canyon (–):
Estimated sediment removal from offshore observations: 220,000 m^3/yr

(Sr) River source (+):
Original drainage area of 800 km^2

To estimate the sediment delivered to the coast from the river, we can use equations (numerical models) or regional graphs. In this case, the area of the basin contributing sediment before the dam was constructed was about 800 km^2, and we estimate that the sediment delivered to the beach from the river was about 300 m^3km^2/yr. Following dam construction, the sediment-contributing area is reduced to 500 km^2 with a yield of 400 m^3km^2/yr. The increase in sediment per unit area results because smaller tributaries below the dam have a higher sediment yield.

Assuming that 30 percent of sediment delivered from the river will remain on the beach, and that it is sand sized and larger, we can calculate the sediment yield from the river before and after dam construction:



< FIGURE 11.12 Example of a Beach Budget
Beach erosion is observed at Point X. See text for calculation of the beach budget before and after construction of the dam.

Before dam:
Sr(+) = (300 m^3km^2/yr)(800 km^2)(0.3) = 72,000 m^3/yr

After dam:
Sr(+) = (400 m^3km^2/yr)(500 km^2)(0.3) = 60,000 m^3/yr

Now that we know the amount of sediment added to the system from the river before and after the dam was constructed, we can calculate the budget:

Budget before dam:

Longshore drift (Sl):	+150,000 m^3/yr
Cliff erosion (Scf):	+4,500 m^3/yr
River (Sr):	+72,000 m^3/yr
Submarine canyon (Scy):	–220,000 m^3/yr

Budget is +6500 m^3/yr because more sand was arriving at point X on Figure 11.12 than is leaving; the beach was growing before the dam was built.

Budget after dam:

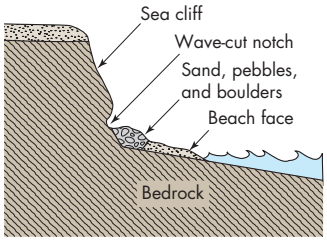
Longshore drift (Sl):	+150,000 m^3/yr
Cliff erosion (Scf):	+4,500 m^3/yr
River (Sr):	+60,000 m^3/yr
Submarine canyon (Scy):	-220,000 m^3/yr

Budget is –5500 m^3/yr; therefore, more sand is leaving point X than is arriving, and erosion is observed. The beach will get smaller over time.

Sea Cliff Erosion A sea cliff or lakeshore bluff along a coastline may be subject to additional erosion problems. Both features are exposed to a combination of wave action and land erosion by running water and landslides that erode the cliff at a greater rate than either process could do alone. The problem is further compounded when people alter a cliff through poor development.

Erosion by plunging breakers during storms causes many sea cliffs and lakeshore bluffs to retreat. This susceptibility to erosion is not always apparent during low-water periods when a beach is present at the base of the cliff (Figure 11.13). The beach sediment helps protect the cliff from wave erosion during periods between storms. On the U.S. West Coast, most of the sea cliff erosion takes place during winter storms, and in the northeastern United States and Atlantic Canada, considerable cliff erosion occurs during nor'easters (see Chapter 10). Storm waves also help erode lakeshore bluffs on the Great Lakes.

A variety of human activities can increase the erosion of sea cliffs and lakeshore bluffs. These activities create effects that include uncontrolled surface runoff, increased groundwater discharge, and the addition of weight to the top of a cliff. Increased surface runoff, as often occurs with urbanization, can enhance the erosion of coastal cliffs and bluffs unless the drainage is controlled and diverted from the cliff face. Erosion can also intensify if there is an increase in the amount



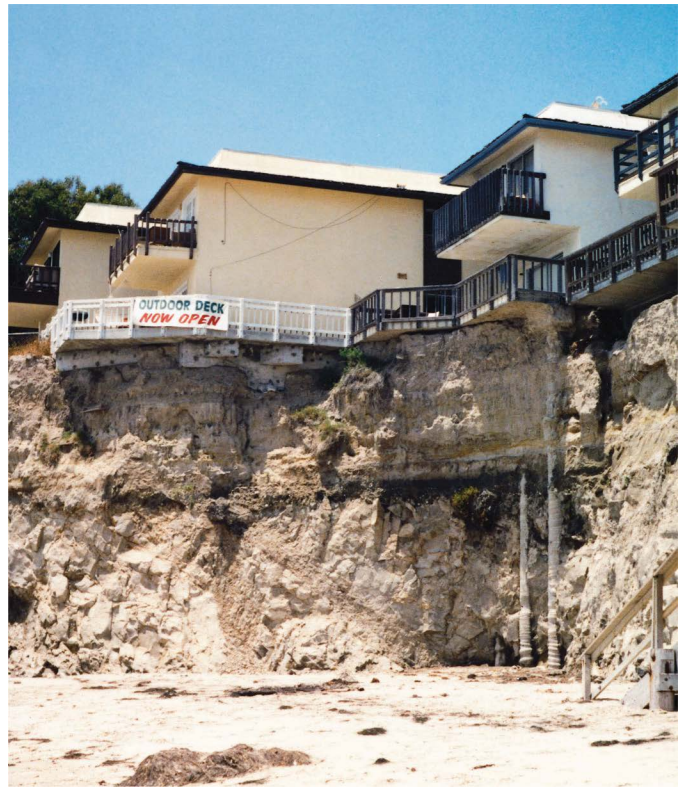
(a)



(b)

▲ FIGURE 11.13 Sea Cliff and Beach
(a) Generalized cross-section and (b) photograph of sea cliff, beach, and bedrock exposed at low tide at Santa Barbara, California. *(Donald W. Weaver)*

of groundwater discharging from the base of the cliff. Watering lawns and gardens on top of a sea cliff or lakeside bluff can increase the amount of water in the earth material. When this water emerges as seeps or springs from the cliff, it reduces its stability and facilitates both erosion and landslides.[12] Structures such as walls, buildings, swimming pools, and patios may also decrease the stability of a cliff or bluff by increasing the driving forces for mass wasting (Figure 11.14). Strict regulation of development in many areas of the coastal zone now forbids most risky construction, but we continue to live with some of our past mistakes.



▶ FIGURE 11.14 Sea Cliff Erosion
Apartment buildings on the edge of a sea cliff in the university community of Isla Vista, California. The sign states that the outdoor deck is now open. Unfortunately, the deck is not particularly safe, as it is overhanging the cliff by at least 1 m (~3 ft.). Notice the exposed cement pillars in the sea cliff, originally in place to help support the buildings. These decks and apartment buildings were in imminent danger of collapsing into the sea and were condemned in 2004. *(Edward A. Keller)*

The rate of sea cliff and lakeshore bluff erosion is variable, and few measurements have been available. More are on the way because of the increasing use of remote sensing devices, such as an aircraft-mounted laser system called "light detection and ranging" (LIDAR). This system can record several thousand elevation measurements each second with a vertical resolution of 15 cm (~6 in.). Once a baseline set of elevations is recorded, subsequent LIDAR flights can detect changes in the coastal zone, such as the shape of the beach, dunes, bluff, or cliff. For example, LIDAR flights along the coast near Pacifica, California, about 10 years apart showed beach erosion of about 1 to 2 m (~3 to 6 ft.) and sea cliff erosion of about 1 to 3 m (~3 to 10 ft.) over the 10-year period.

Moderate rates of erosion of 0.1 to 0.3 m (~4 to 12 in.) per year occur along other parts of the California coast near Santa Barbara, in comparison to 2 m (~7 ft.) per year along parts of the Norfolk coast in the United Kingdom and up to 4.6 m (~15 ft.) per year along the eastern side of Cape Cod, Massachusetts. The rate of erosion depends primarily on the resistance of earth materials and the energy of the waves,[12] as well as sand supply.

11.5 CHECK your understanding

1. How are rip currents produced, and how can you escape from one?
2. Why is the beach budget such a valuable tool in risk analysis for coastal erosion?
3. Assume there are several beach homes near point X in our beach budget example. What advice would you give them based on the calculations? What would be your response if there were high-rise coastal resorts near point X?

11.6 Linkages between Coastal Processes and Other Natural Hazards

Coastal processes such as waves and currents present numerous hazards to human life and property. These hazards are also often linked to other natural hazards, such as earthquakes, volcanic eruptions, tsunamis, cyclones, flooding, landslides, subsidence, and climate change. Earthquakes such as the **M** 9.1 Sumatran earthquake of 2004, coastal volcanic eruptions, and tsunamis can radically change the shape of the shoreline. Storm waves, storm surge, and coastal flooding from cyclones are closely linked to coastal erosion (Figure 11.15).

Intense precipitation associated with tropical storms, hurricanes, and extratropical cyclones drives many other coastal hazards, such as flooding, erosion, and landslides. As mentioned previously, storm surge and



FIGURE 11.15 Storms Contribute to Coastal Erosion
Two hurricanes, 21 days apart, eroded sand from this coastline in Vero Beach on Florida's east coast. The top picture, taken in August 1997 before the hurricanes, shows a sand dune providing some protection for the homes. In the middle picture, taken on September 8, 2004, after Hurricane Frances, the dune has migrated next to the houses. The third picture, taken on September 29, 2004, after Hurricane Jeanne, shows a house that has been undermined and damaged by storm waves. A red arrow points to the same place in all three photographs. *(USGS)*

heavy rainfall inland combine to cause widespread coastal flooding. Areas where the coast has subsided are more vulnerable to both freshwater flooding and storm surge.

Another common hazard caused by coastal processes is landslides. Wave erosion at the base of sea cliffs and lakeside bluffs undercuts the slope and frequently produces landslides. These cliffs may be more susceptible to sliding if structures, such as homes, add weight at the top (Figure 11.16).

Coastal erosion is also linked to climatic conditions that change over decades. For example, an interaction between surface winds and sea surface temperatures in the Pacific Ocean produces a climatic condition known as El Niño (see Chapter 12). Strong El Niño conditions can increase the intensity and frequency of extratropical cyclones making landfall on the U.S. West Coast. Large waves and storm surge from storms produced by a strong El Niño in 1982 to 1983 significantly increased coastal erosion in California and Oregon.[13]

Coastal erosion has significant linkages with global warming which is warming the ocean, raising sea level and increasing the energy and, thus, the intensity of high-energy storms. As sea-level rises and more intense storms occur, coastal erosion is a growing concern (see Chapter 12).

Overall, coastal processes are closely linked to other natural hazards that affect the coast: tsunamis; freshwater flooding of coastal plains, bays, and lagoons; hurricanes; and landslides of sea cliffs along the ocean and lakes.

11.6 CHECK your understanding

1. How are coastal processes linked to other hazards, such as earthquakes, tsunamis, landslides, volcanic eruptions, hurricanes, and flooding?

11.7 Natural Service Functions of Coastal Processes

As is true of many of the other hazards we have discussed, it is difficult to imagine the benefits of rip currents, coastal erosion, and sea-level rise; however, some coastal processes provide significant benefits.



FIGURE 11.16 Hazardous Room with a View
These homes perched on a sea cliff along Puget Sound west of Port Townsend, Washington, were spared in this 1997 landslide. Future landslides will cause further retreat of the cliff face. *(Geology and Earth Resources Washington)*

Although erosion is a problem for property owners in coastal areas, the attraction of the coastal zone results in part from wave action and erosion. Many tourists drive the Pacific Coast highway from Washington to California each year to experience the beauty of the coastal zone. The stunning cliffs, rocky headlands, and sea arches found along this scenic road are the direct result of erosion and are important aesthetic resources (Figure 11.17).

For many beaches, coastal erosion is the only significant input of sand. Without erosion of dunes, cliffs, and bluffs inland from the beach, or the erosion of updrift beaches, there would be little sand to form a beach. Such is the case for most beaches on the eastern shore of Cape Cod in Massachusetts.

Sandy beaches have a number of natural service functions, including:

- Transporting and storage of sand in the coastal zone
- Supplying sediment for ecosystems, such as coastal lagoons, estuaries, and sand dunes
- Dissipating waves as a buffer to coastal erosion (a thick mantle of sand helps protect the sea cliff from erosion)
- Breaking down pollutants and organic materials; cycling nutrients
- Providing nesting and roosting sites for shorebirds and seabirds
- Filtering and discharge of groundwater through beach sand and gravel
- Maintaining biodiversity in the coastal zone, including California grunion (a small fish that rides the high-tide waves to spawn in upper beach sand on summer nights)
- Providing food sources (sand crabs, beach hoppers, bloodworms, etc.) for migrating and resident shorebirds and fish, such as corvine and surf perch
- Providing a valuable cultural and aesthetic resource for people, as well as recreational opportunities.

The beach processes described earlier in the chapter maintain sandy beaches on all coasts, including lakeshores. Disturbance of the coastal zone and coral reefs by storm waves renews these ecosystems, keeping them

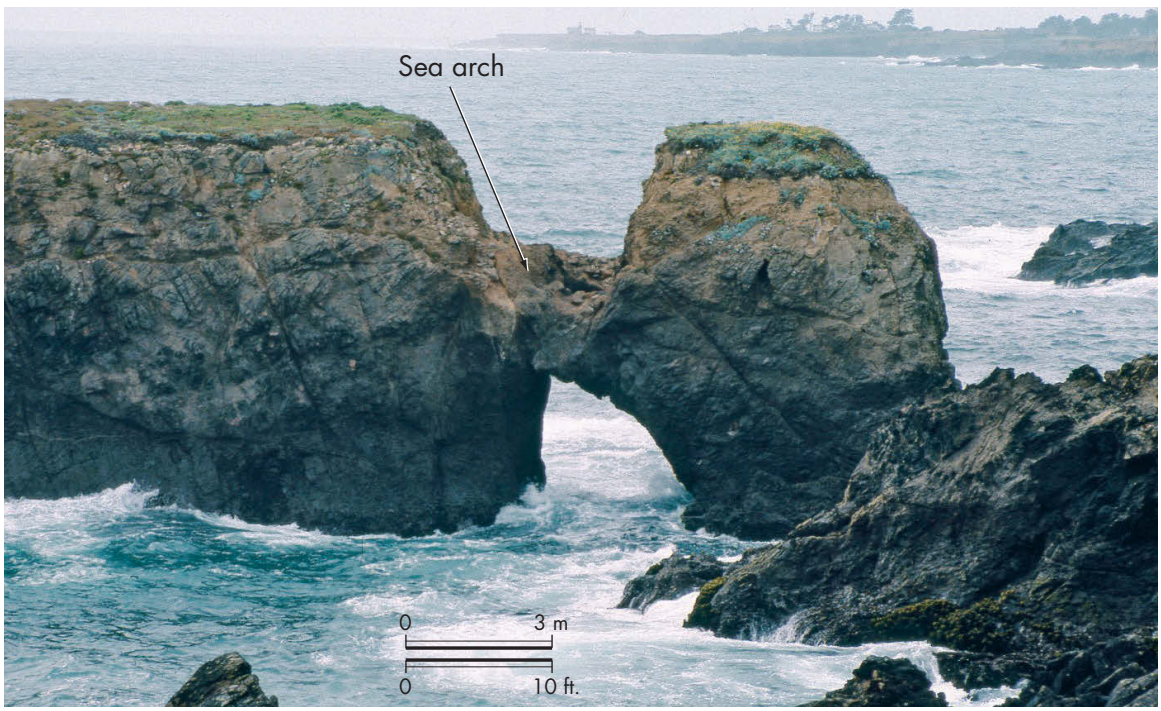


FIGURE 11.17 Sea Arch Eroded from Rocky Headland
Sea arches, like this one along the Pacific coast in Mendocino, California, are formed by the erosion of a rocky headland. Located in a public park, this coastal erosion feature, at least temporarily, adds to the beauty of the coastline. *(Robert H. Blodgett)*

healthy and maintaining their diversity. Finally, coastal processes provide aesthetic value and much-loved recreational opportunities, including swimming, surfing, sailing, fishing, and sunbathing.

11.7 CHECK your understanding

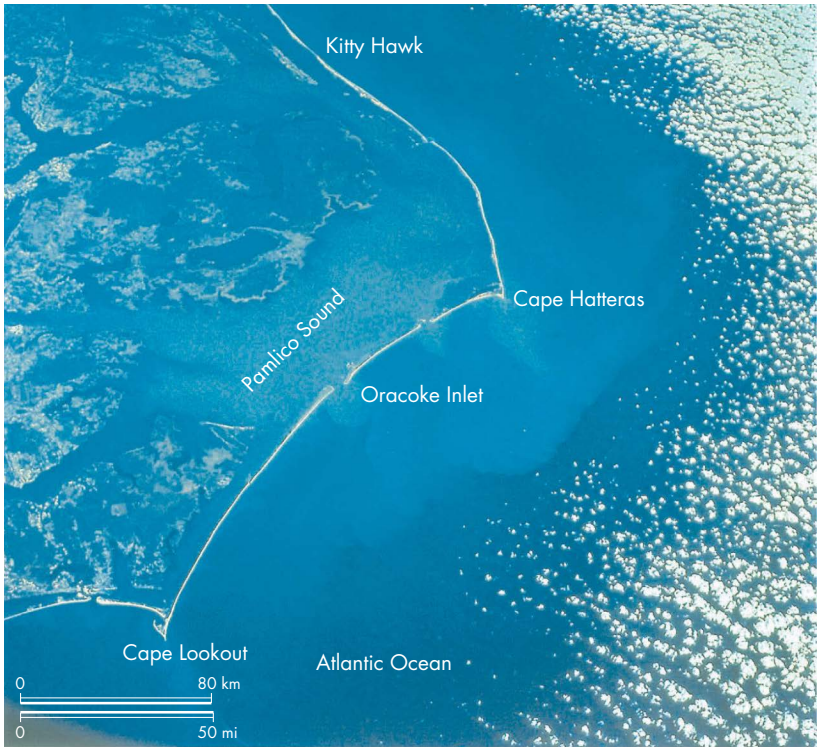
1. List some of the natural service functions of beaches.

11.8 Human Interaction with Coastal Processes

Human interference with natural shore processes has caused considerable coastal erosion. Most problems arise in areas that are highly populated and developed. Efforts to stop coastal erosion often involve engineering structures that impede littoral transport. These artificial barriers interrupt the movement of sand, causing beaches to grow in some areas and erode in others, thus damaging valuable beachfront property. This type of human interaction with coastal processes is especially prevalent along the more densely settled parts of the Atlantic, Gulf, and Pacific coasts of the United States, the Great Lakes, and in some parts of Canada.

THE ATLANTIC COAST

The Atlantic coast from northern Florida to New York is characterized by barrier islands, long narrow islands of sand that are separated from the mainland by a lagoon or bay (Figure 11.18). Many barrier islands have been altered to a lesser or greater extent by human use.

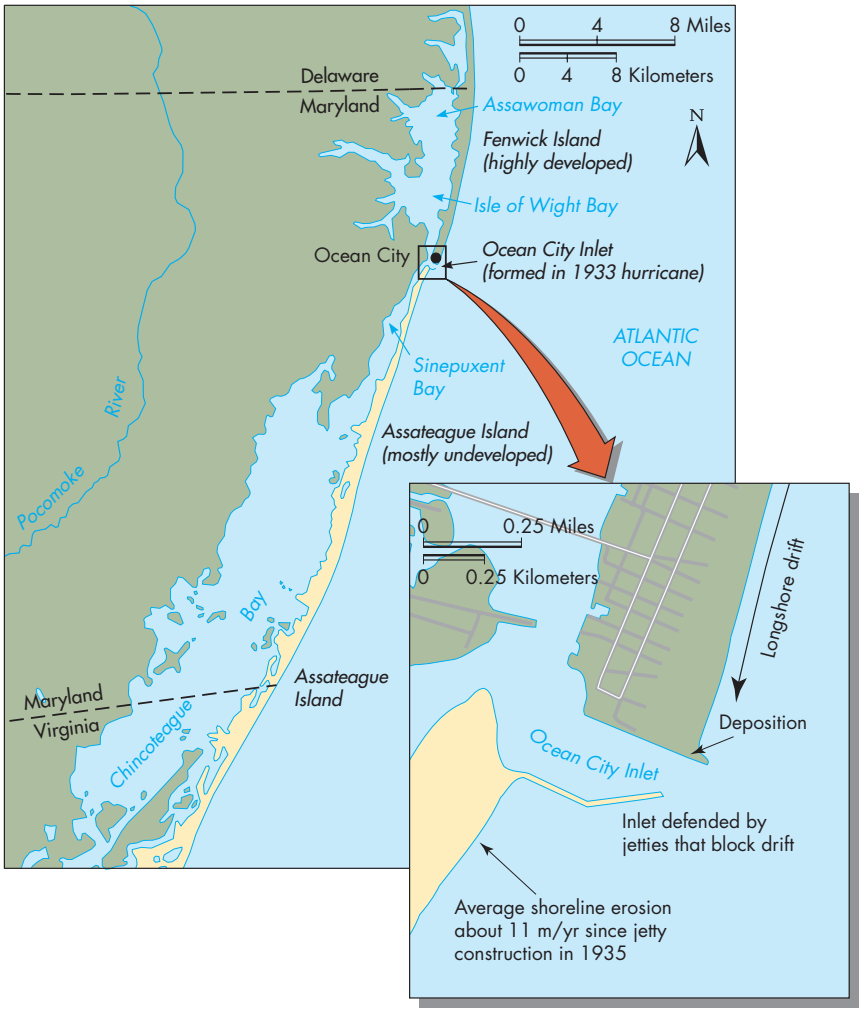


▲ FIGURE 11.18 The Outer Banks of North Carolina
View looking north from the *Apollo-9* mission. The barrier islands appear as thin white ribbons of sand separating the Atlantic Ocean on the right from Pamlico Sound and the mainland on the left. The yellowish brown color in the water is caused by suspended sediment, such as clay, moving within the coastal system. Lobe-shaped fans of suspended sediment are entering the Atlantic Ocean at Ocracoke Inlet and the inlet to the northeast. Kitty Hawk, the site of the Wright Brothers' first powered aircraft flight, is near the top of the image. The distance from Cape Lookout to Cape Hatteras is approximately 100 km (~62 mi.). *(NASA)*

11.2 CASE study

Maryland Barrier Islands

The history of barrier islands along the Maryland coast illustrates the interaction of human activity with coastal processes. Demand for the 50 km (~30 mi.) of oceanfront beach in Maryland is **very** high. This limited resource is used seasonally by residents of the Washington and Baltimore metropolitan areas (Figure 11.19). Probably the greatest repercussions from this use have taken place in Ocean City on Fenwick Island and on Assateague Island to the south of Fenwick Island. Since the early 1970s, Ocean City has promoted high-rise condominium and hotel development on its waterfront. To make way for new construction, the coastal dunes of this narrow island were removed in many locations. This activity and serious beach erosion have increased



▲ FIGURE 11.19 Urban Development with Jetty Increases Beach Erosion
Fenwick Island, a barrier island on the Maryland coast, is experiencing rapid urban development, and potential hurricane damage is a concern. What if a new inlet forms during a hurricane in Ocean City to the north of the Ocean City inlet? Inset shows details of the Ocean City inlet and effects of jetty construction. The northern end of Assateague Island, shown in yellow, is relatively undeveloped and has experienced rapid shoreline erosion since a jetty was constructed along the inlet.

the vulnerability of the island to hurricanes. As mentioned previously, coastal dunes act as natural barriers to storm waves and partially protect structures built behind them. Without coastal dunes, a shoreline has no protection from storm waves or from the formation of washover channels by storm surge.

Ocean City experienced the effects of hurricane storm surge in 1933 when the Ocean City inlet formed to the south of the city. Despite attempts to stabilize the inlet by coastal engineering, there is no guarantee that a new inlet will not destroy part of the city in the future.[14]

Assateague Island is a barrier island located to the south, across the Ocean City inlet. It encompasses two-thirds of the Maryland coastline and contrasts with the highly urbanized Fenwick Island. Assateague is in a much more natural state and is used for passive recreation, such as sunbathing, swimming, walking, and wildlife observation. However, both islands are in the same littoral cell, meaning they share the same sand supply. At least that was the case until 1935, when jetties were constructed to stabilize the Ocean City inlet. Since construction of the jetties, beaches on the north end of Assateague Island have lost about 11 m (~36 ft.) per year, nearly 20 times the long-term rate of shoreline retreat for the Maryland coastline. During the same time, beaches immediately north of the inlet became considerably wider, requiring the lengthening of a recreational pier.[15]

Observed changes on Maryland's Atlantic coast are clearly related to human interference with the longshore drift of sand. Construction of the Ocean City inlet jetties interfered with the natural southward movement of sand. The jetties diverted sand offshore rather than allowing it to continue southward to nourish the beaches on Assateague Island. Starved of sand, the northern portions of the island have experienced serious shoreline erosion during the past 50 years. This example of beach erosion associated with engineering structures has been cited as the most severe in the United States.[15]

THE GULF COAST

Coastal erosion is also a serious problem along the Gulf of Mexico, which, like the Atlantic coast, has numerous barrier islands. One study in the Texas coastal zone suggests that in the past 100 years, human modification of the coastal zone has accelerated coastal erosion by 30 to 40 percent as compared with prehistoric rates.[16] Much of the accelerated erosion appears to be caused by coastal engineering structures, subsidence as a result of groundwater and petroleum withdrawal, and damming of rivers that supply sand to the beaches.

THE PACIFIC COAST

Human modification of the Pacific coast has not had as long a history of development as the Atlantic coast. Nevertheless, in coastal development, such as highways and harbors from San Diego to Seattle and in numerous small communities in between, the trend to armor the coast (usually by building seawalls) is very evident. In the past few decades, this trend for more and accelerated coastal defenses using rock and concrete has stalled in many areas. However, with the present rise in sea level and increased human use of beaches and interest in beach development, the debate about the future of the Pacific coast beaches and what action to take continues.

THE GREAT LAKES

Erosion is a periodic problem along the coasts of the Great Lakes and has been particularly troublesome on the Lake Michigan shoreline. Damage is most severe during high lake levels caused by above-normal precipitation. Measurements by the U.S. Army Corps of Engineers since 1860 show that the level of Lake Michigan has fluctuated about 2 m (~7 ft.). During periods of high water, the considerable wave erosion has destroyed many buildings, roads, retaining walls, and other structures (Figure 11.20).[17] For example, in 1985, high lake levels from fall storms caused an estimated $15 to $20 million in damages.

During periods of below-average lake level, wide beaches develop that dissipate energy from storm waves and protect the shore. However, as lake levels rise, beaches become narrower, and storm waves exert considerable energy against coastal areas. Even a small rise in water level on a gently sloping shore will inundate a surprisingly wide section of beach.[17]

Erosion of lakeshore bluffs has also been a problem. Many bluffs along Lake Michigan have eroded back at an average rate of 0.4 m (~1.3 ft.) per year.[18] Severity of erosion at a particular site depends on several factors:

- Coastal dunes—dune-protected bluffs erode at a slower rate
- Coastline orientation—sites exposed to high-energy storm winds erode faster
- Groundwater seepage—seepage at the base of a bluff causes slope instability and increased erosion
- Protective structures—engineering structures are locally beneficial but often accelerate coastal erosion in adjacent areas.[17,18]

In recent years, sand has been artificially added to some Great Lakes beaches. For some projects, the added

sands have been deliberately chosen to be coarser and heavier than the natural sands, theoretically reducing erosion potential.

CANADIAN SEACOASTS

Canada has the longest ocean coastline in the world, and like the United States, it faces a serious erosion problem. As is true elsewhere, Canadian sandy and muddy beaches are eroding more rapidly than rocky beaches. Although most erosion rates are less than 1 m (~3 ft.) per year, some areas of Atlantic Canada are eroding at rates of up to 10 m (~30 ft.) per year! Even at close to the average rate of erosion, entire islands off Nova Scotia have disappeared into the sea. In the Canadian Arctic along the Beaufort Sea, erosion rates are a bit higher, at 1 to 2 m (~3 to 7 ft.) per year. Each year, the Canadian government spends about $1 billion on projects related to the coastline, including erosion control.[19]

11.8 CHECK your understanding

1. Describe the main causes of erosion at Assateague Island, located just south of Ocean City on Fenwick Island.
2. What factors affect the severity of erosion on Great Lake shorelines? How applicable are these factors to general coastal erosion?

11.9 Minimizing the Effects of Coastal Hazards

On the surface, it may appear that coastal hazards would be much easier to control than other natural hazards that release tremendous amounts of energy, such as earthquakes, volcanoes, and hurricanes. In practice, interactions among coastal processes are complex, and efforts to combat coastal erosion and rising sea level have often met with failure or unintended consequences. The following discussion focuses on minimizing beach erosion, one of the most widespread coastal hazards.

Most efforts to minimize beach erosion focus on stabilizing a beach at its present location. These efforts use two approaches:

- Hard stabilization: engineering structures to protect a shoreline from direct wave erosion
- Soft stabilization: adding sand to replace sand that has been eroded from the beach, a process known as beach nourishment.

HARD STABILIZATION

Engineering structures in the coastal environment, such as seawalls, groins, breakwaters, and jetties, are generally constructed to improve navigation or retard erosion. However, because these structures interfere with the littoral transport of sediment along the beach, they all too often cause undesirable deposition and erosion in their vicinity.

Seawalls Seawalls (or sea walls) are structures built on land parallel to the coastline to help retard erosion and protect buildings from damage. They may be constructed with concrete, large stone blocks called *riprap*, pilings of wood or steel, cemented sandbags, or other materials. Such walls are also called rock revetments. The construction of a seawall at the base of a sea cliff or lakeside bluff may not be particularly effective because the sea cliff is eroded from both the land and the water. Seawalls can fail for several reasons. For example, rock seawalls (riprap), unless carefully engineered, may fail as the rock blocks are washed away by large waves. Also, they may be overtopped (if not properly keyed in at the top) and erode behind the wall, leaving the rock intended to protect the coast stranded on the beach (Figure 11.20).



FIGURE 11.20 Rock seawall (rock revetment) at Goleta Beach in Southern California
This seawall was overtopped by waves in 2017 and a ~2m (6 ft) sea cliff constructed on decades old fill is eroding back, stranding the rock blocks (riprap) on the beach. The failure of the seawall reflects a poor design and engineered structure. There is controversy as to whether or not the seawall should ever have been constructed. *(Edward A. Keller, 2017)*

The use of seawalls has been criticized because their vertical design reflects incoming storm waves and redirects their energy to the shore. Therefore, seawalls, over a period of decades, promote beach erosion and produce a narrower beach with less sand (Figure 11.21). Unless carefully designed to complement existing land uses, seawalls generally cause environmental and aesthetic degradation. The design and construction of seawalls must be carefully tailored to specific sites. Because of these difficulties, many geologists believe that seawalls cause more problems than they solve and should be used rarely, if ever, where beach preservation is a goal.

Groins Groins are linear structures placed perpendicular to the shore, usually in groups called *groin fields*. Each groin is designed to trap a portion of the sand from the longshore drift (Figure 11.22). A small amount of sand accumulates updrift of each groin, thus building an irregular but wider beach.

However, there is an inherent problem with groins—although trapped sand is deposited updrift of a groin, erosion occurs downdrift of these structures because the longshore drift has been depleted of sand. Thus, a groin or groin field results in a wider, more protected beach in a desired area but causes erosion of the adjacent shoreline. Once a groin has trapped all the sediment it can hold, sand in the groin is transported around its offshore end to continue its journey along the beach. Therefore, erosion may be minimized by artificially filling each groin. Known as **beach nourishment**, this process requires extracting sand from

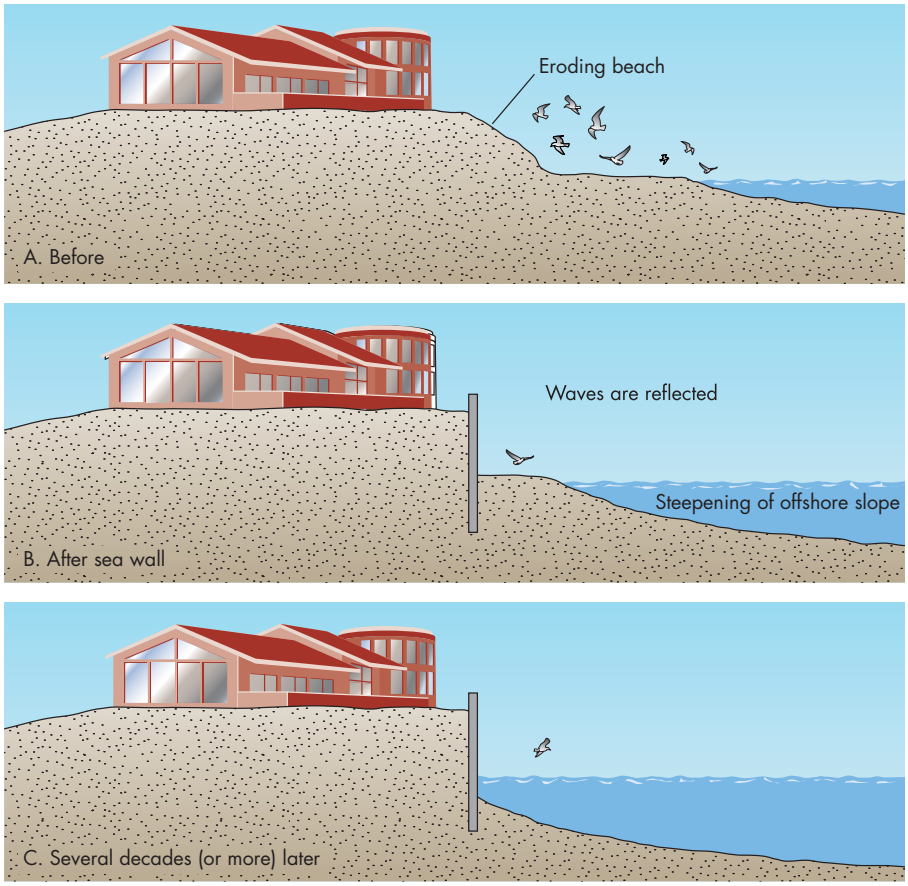
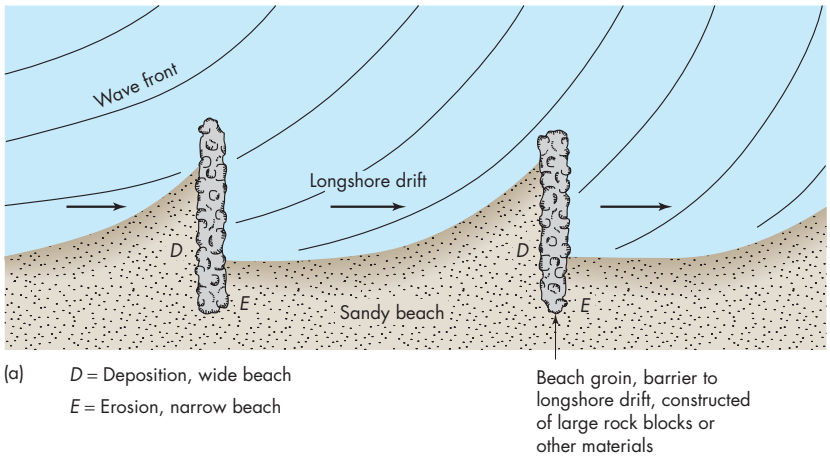
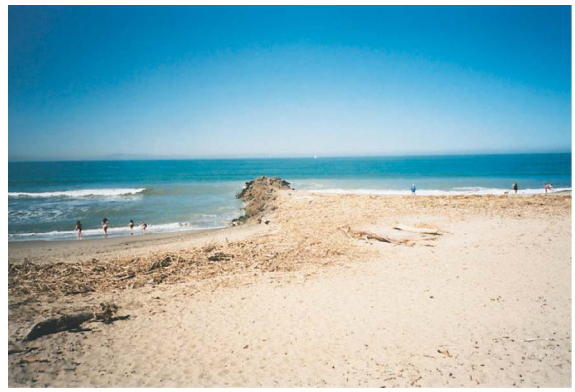


FIGURE 11.21
Seawalls Increase Beach Erosion
Construction of seawalls to mitigate coastal erosion and protect buildings from rising sea level results in beach erosion. A seawall acts as a reflector for storm waves and can result in the permanent loss of a beach.



< FIGURE 11.22 Beach Groins
(a) Diagram of two beach groins built to trap sand; updrift depositional areas (D) are on the left, and the downdrift erosional areas (E) are on the right of the groins. Waves approach from the upper left, and longshore drift is from left to right. (b) Close-up of the eroded area downdrift of a groin. *(Edward A. Keller)* (c) A groin extends seaward in the center of the photograph; contrast the width and height of the beach on the updrift side to the right and the downdrift side to the left. *(Edward A. Keller)*


(b)


(c)

the ocean floor and placing it onto the beach. When nourished, the groins will draw less sand from the longshore drift, and the downdrift erosion will be reduced.[4,13] Despite beach nourishment and other precautions, groins often cause undesirable erosion in the downdrift area; therefore, their use should be carefully evaluated.

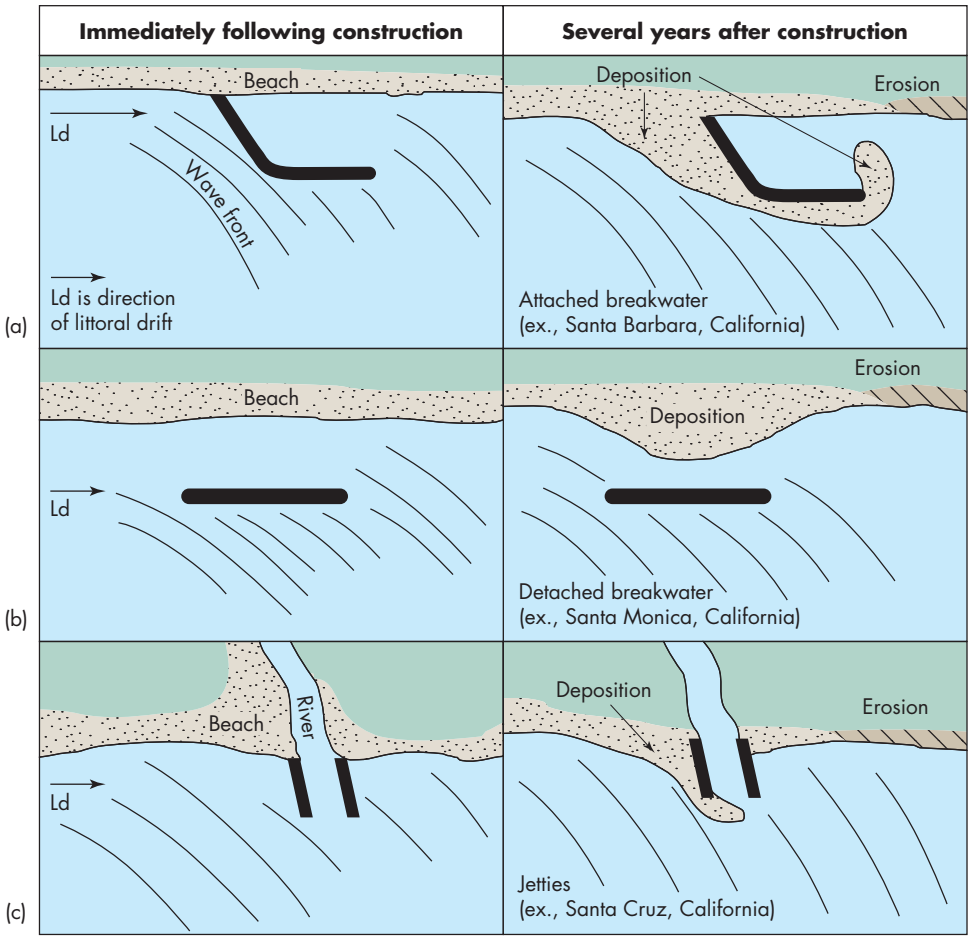
Breakwaters and Jetties Breakwaters and jetties are linear structures of riprap or concrete that protect limited stretches of the shoreline from waves. A **breakwater** is designed to intercept waves and provide a protected area or harbor for mooring boats or ships. This structure may be attached to, or separated from, the beach (Figure 11.23a,b). In either case, a breakwater blocks littoral transport and alters the shape of the coastline as new areas of deposition and erosion develop. This can cause serious erosion, or it can block a harbor entrance with newly trapped sand. The trapped sand may have to be moved by *artificial bypass*, that is, the dredging and pumping out of sand from around the breakwater to redeposit it downdrift.

Jetties are usually built in pairs, perpendicular to the shore at the mouth of a river or at the entrance of an inlet to a bay or lagoon (Figure 11.23c). They are designed to keep a ship or boat channel open and in a fixed location, with minimal dredging to remove sediment. Jetties also shelter a channel from large waves. Like groins, jetties block littoral transport, thus causing the updrift beach adjacent to one jetty to widen while contributing to erosion of downdrift beaches.

Unfortunately, it is impossible to build a breakwater or jetty that will not interfere with longshore movement of beach sediment. These structures must, therefore, be carefully planned and incorporate protective measures that eliminate or at least minimize adverse effects. Protective measures may include a dredging and artificial sediment-bypass system, a beach-nourishment program, seawalls, or some combination of these measures.[4,13]

SOFT STABILIZATION

Beach Nourishment The use of beach nourishment to reduce rates of shoreline retreat is not limited to adding sand to engineering structures. In fact, in



< FIGURE 11.23

Engineering Structures Built in the Surf Zone Cause Change

Diagrams illustrating the effects of breakwaters (the thick black lines in (a) and (b)) and jetties (the short black lines in (c)) on local patterns of deposition (tan) and erosion (brown). The left column of the diagrams shows the structures immediately following their construction, and the right column shows deposition and erosion after the structures were built. Curved, thin black lines show approaching waves, and the arrows indicate the direction of littoral transport (Ld).

most cases, it is used as an alternative to engineering structures. In its purest form, beach nourishment consists of artificially placing sand on beaches in the hope of constructing a positive beach budget, where more sand remains in storage than leaves in output. Beach nourishment is sometimes referred to as the "soft solution" to coastal erosion, as contrasted with "hard solutions" such as groins or seawalls. Ideally, a nourished beach will protect coastal property from the attack of waves. Beach nourishment is aesthetically preferable to many engineering structures, and it provides a recreational beach as well as some protection from shoreline erosion. Unfortunately, beach nourishment is expensive and must be repeated at regular intervals to stabilize a beach. Considerable care must be taken in selecting the appropriate range of sand sizes for a beach replenishment project, and locating a nearby source for this sand is sometimes difficult.

In the mid-1970s, the city of Miami Beach, Florida and the U.S. Army Corps of Engineers began an ambitious beach nourishment program to reverse serious beach erosion that had plagued the area since the 1950s. The program was designed to produce a positive beach budget that would widen the beach and protect coastal resort areas from storm damage.[20] At a cost of approximately $62 million over 10 years, the project added

about 160,000 m^3 (~210,000 $yd.^3$) of sand per year to replenish erosion losses. By 1980, about 18 million m^3 (~24 million $yd.^3$) of sand had been dredged and pumped from an offshore site onto the beach, producing a 200 m (~660 ft.) wide beach.[21] The change that took place over a decade is dramatic (Figure 11.24).

Part of the Miami project included building vegetated coastal dunes to function as a buffer to wave erosion and storm surge (Figure 11.25). Special wooden walkways allow public access through the dunes, but other areas of the dunes are protected. The successful Miami Beach nourishment project has functioned for more than 20 years and survived major hurricanes in 1979 and 1992; it is certainly preferable to the fragmented erosion control methods that preceded it.[4]

More than 600 km (~370 mi.) of U.S. coastline has received some sort of beach nourishment. Not all this nourishment has had the positive effects reported for Miami Beach. For example, in 1982, Ocean City, New Jersey, nourished a stretch of beach at a cost of just over $5 million. A series of storms that subsequently struck the beach eroded the sand in just 2½ months. The beach sands of Miami may yet be eroded and require replacement at a greater cost. Beach nourishment remains controversial, and some consider it nothing more than "sacrificial sand" that will eventually be washed away by coastal erosion.[21] Most beaches require frequent nourishments to remain intact. Nevertheless, beach nourishment has become a preferred method of restoring or even creating recreational beaches and protecting the shoreline from coastal erosion around the world. Additional case histories are needed to document the success or failure of the projects. Public education is also needed to inform people about what can be expected from beach nourishment.[4]

Coastal Zone Bioengineering

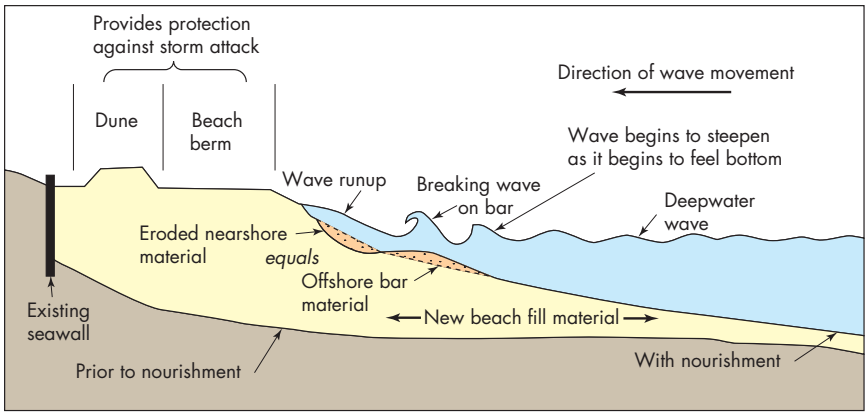
Coastal zone bioengineering (CZB) is an emerging coastal defense that uses living or dead plants to assist in erosion control. CZB is a relatively new concept being tested. Sand dunes constructed along a coast to provide a barrier to ocean intrusion have been used many times, often as part of beach nourishment. The dunes may be stabilized with native dune grassland or other vegetation, insofar as the plants help hold the dune in place.

The Sargasso Sea, located in the North Atlantic Ocean east of the Carolinas, is the only sea without a land boundary. The sea is bounded by clockwise rotation of ocean currents, including the Gulf Stream, and is named after the free-floating Sargassum seaweed (algae) that grows there. Some of the seaweed is eventually carried westward to Galveston, Texas, where it periodically piles up on beaches. The seaweed provides valuable nutrients to the beach, but it is a nuisance to people visiting the beach, and crews often collect the decaying seaweed. Galveston is experimenting with utilizing the seaweed to help retard coastal erosion. The seaweed is collected with machinery similar to that used to gather and roll hay in fields. It is then



(a) (b)

Figure 11.24 Beach Nourishment
Miami Beach (a) before and (b) after beach nourishment. *(New Orleans District, U.S. Army Corps of Engineers)*



< Figure 11.25 Miami Beach Shape after Nourishment
Diagrammatic cross-section of the Miami Beach nourishment project. The dune and beach berm system provides protection against storm attack. An existing seawall is indicated by the thick black line on the left. New beach fill material is in yellow. Orange areas are beach sand that may be eroded and deposited during a storm. A dashed line shows a pre-storm profile of the beach. *(From the U.S. Army Corps of Engineers)*

compressed and buried with sand to form a kind of dune. The dune provides a first, although not a very strong, defense from storm waves and high tides.

Another example of CZB can be found at Refugio State Beach near Santa Barbara, California, where palm trees are located near the high-tide line. We do not know if the palms were planted with erosion control in mind, but the palm trees have a dense, strong root system that retards erosion. The tough, interwoven roots provide a first defense against beach erosion from high tides and storms.

11.9 CHECK your understanding

1. How can a seawall increase beach erosion?
2. Why are beach groins used? What problems can groins cause?
3. Why do breakwaters and jetties cause beach erosion problems?
4. What are the advantages and disadvantages of beach nourishment?
5. What is coastal zone bioengineering, and what are its advantages and possible shortcomings?

11.10 Perception of and Adjustment to Coastal Hazards

PERCEPTION OF COASTAL HAZARDS

People generally perceive land as being stable, and, in many cultures, it is viewed as a permanent asset that can be bought and sold.[10] This perception of stability is appropriate for most land where geologic changes are relatively slow and alterations to the land can take centuries or millennia. Coastlines, however, are dynamic, and shorelines erode, accumulate, and move in time frames of months and years (see Figure 11.15).

Even if individuals understand that erosion can be rapid, their past experience, proximity to the coastline, and the probability of suffering property damage influence their perception of coastal erosion as a natural hazard. One study of sea cliff erosion near Bolinas, California, 24 km (~15 mi.) north of the entrance to San Francisco Bay, found that coastal residents in an area that was likely to experience damage in the near future were generally well-informed and saw the erosion as a direct and serious threat.[22] Other people living a few hundred meters from a possible hazard, although aware of the hazard, knew little about its frequency, severity, and predictability. Still further inland, people were aware that coastal erosion exists but had little perception of it as a hazard.

Many people do not perceive waves and currents as hazards. Often, their first visits to beaches are as children, where their parents closely limit their activities. In fact, waves that have large heights and wavelengths and plunging waves can be dangerous for wading and swimming. These waves are considerably more powerful than the spilling waves that generally provide safe conditions for waders and swimmers. Rip currents, which are commonly produced by plunging waves with large wavelengths, are responsible for about 80 percent of all lifeguard rescues on the seashore. Many beachgoers do not recognize the danger and try to enter the water where there are few breaking waves (see Figure 11.10b), only to be caught in a rip current.[23]

ADJUSTMENT AND MANAGEMENT OF COASTAL HAZARDS

Coastal erosion is usually a complex problem involving natural coastal processes of sand supply and people interfering with natural sand flow by building

jetties, seawalls, rock revetments, small boat harbors, and other structures. Social, economic, and political forces often are present, so decisions about what to do about an erosion problem can be controversial. As a result, coastal erosion is often viewed as a wicked problem (see Chapter 1) for which a simple solution is elusive and difficult. A problem is that the various interests and values regarding a particular beach often are in conflict. Some people (e.g., property owners) want to protect the homes and other developments such as a beach park, while others are more interested in preserving a natural beach for recreational and ecologic reasons. Two sorts of mistakes are often made: implementation of a simple hard solution, such as sea walls (that may damage the beach), and doing little or nothing while declaring that the problem is too complex. The proper response is often to take an incremental approach with monitoring and periodic review. This may not be acceptable to homeowners or parks that want to preserve development at all costs.

Adjustments As with most other natural hazards, there is a variety of ways that we can adjust to shorelines with strong currents, coastal erosion, and rising sea level. Since strong currents cannot be prevented—they exist naturally, as well as around engineering structures—the best adjustments are improving education about and awareness of the conditions that create this hazard. For many ocean beaches and some beaches on large lakes, it may be best to restrict swimming to supervised locations when lifeguards are on duty. On these beaches, warnings about rip currents and tidal currents are often posted. In the United States, general beach and surf forecasts are issued by the National Weather Service. Information about coastal wave and weather conditions is also available through NOAA's now-COAST website (nowcoast.noaa.gov).

For the coastal erosion hazard, adjustments generally fall into one of three categories:[24]

1. Beach nourishment that tends to imitate natural processes—a "soft solution."
2. Land-use change that attempts to avoid the problem by not building in hazardous areas or by relocating threatened buildings—the "managed retreat solution" (also a soft solution).
3. Shoreline stabilization through structures such as groins and seawalls—a "hard solution." For example, a seawall may be constructed along an entire beach, or a coastal point of particular interest may be defended by coastal engineering.

Management Management of the coastal zone includes *adaptive management* and *integrated coastal zone management*. **Adaptive management** is a structured management concept with the following features:[25]

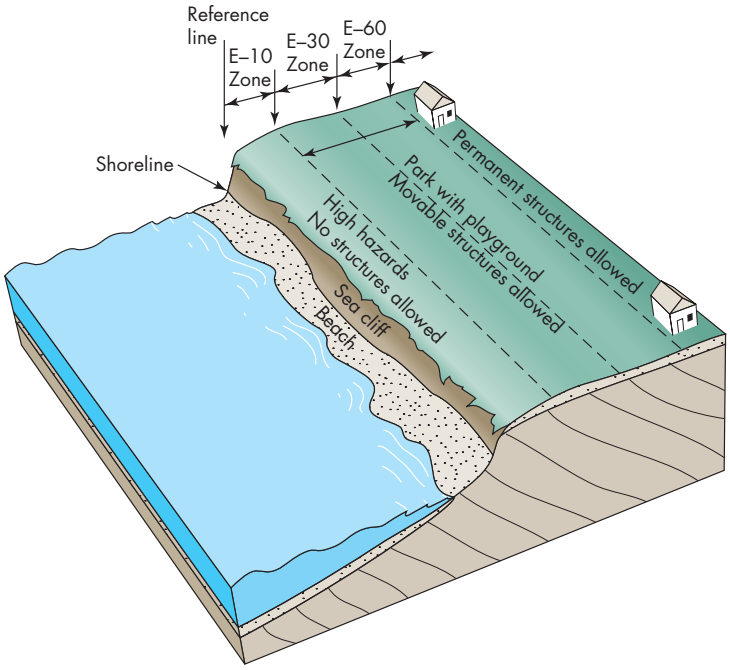
- Includes the use of science, statistical analysis, and modeling with the goal of reducing management uncertainty
- Promotes sustainable coasts and beaches—sustainability is a long-term intergenerational process to help ensure that future generations inherit a quality environment
- Communicates alternatives for discussion and negotiation—that is, the management is an open process
- Recognizes that future change is inevitable and that management can change as conditions change.

Integrated coastal zone management is similar to adaptive management and has the following goals:[26]

- To maintain the ecological function and integrity of the coastal zone
- To encourage sustainable solutions to coastal zone management
- To reduce or minimize potential and present conflicts resulting from development in the coastal zone, use of coastal resources, and recreational use of the coastal zone.

One of the first tasks in managing coastal erosion is determining the rates of erosion. Estimates of future erosion rates are based on historic shoreline change or on statistical analysis of the oceanographic environment, such as the waves, wind, and sediment supply that affect coastal erosion. Once local erosion rates have been determined, the Committee on Coastal Erosion Management, a special committee of the National Research Council (NRC), recommends that maps be made showing erosion lines and zones, referred to as *E-lines and E-zones*[24] (Figure 11.26). An *E-line* is the location of expected erosion in a given number of years; for example, the E-10 line is the location in 10 years. *E-zones* are similar to hazard zones in floodplains; that is, the E-10 zone would be the area between sea level and the E-10 line. Rising sea level is considered to be an imminent hazard in the E-10 zone, and no new habitable structures should be allowed in such areas.

NRC recommendations are then made concerning setbacks, which are considered to be minimum standards for state or local coastal erosion management programs. A *setback* is the distance from the shoreline beyond which development, such as the construction of homes, is allowed. The system of E-lines and E-zones



< FIGURE 11.26 E-Lines and E-Zones
Conceptual diagram of E-lines and E-zones, based on the rate of coastal erosion from a reference point, such as the sea cliff or dune line. Width of the zones depends on the rate of erosion and defines setback distances. After 60 years of erosion, the structures will be much closer to the shoreline and vulnerable to erosion. It is a form of planned obsolescence. *(Based on National Research Council,* Managing Coastal Erosion. *Washington, DC: National Academy Press, 1990)*

can be used to establish setback distances. For example, if the erosion rate is 1 m (~3.3 ft.) per year, the E-10 setback is 10 m (~30 ft.). Movable structures are allowed in the intermediate and long-term hazard zones (E-10 to E-60), while permanent large structures are allowed at setbacks greater than the E-60 line. With the exception of those on high bluffs or sea cliffs, all new structures built seaward of the E-60 line should be constructed on pilings. Their design should withstand erosion associated with a high-magnitude storm with a recurrence interval of 100 years.

Only a few states, such as California, Florida, New Jersey, New York, North Carolina, and South Carolina, use a setback distance for buildings based upon the rate of erosion.[27] Nevertheless, the concept of E-lines and E-zones has real merit in coastal zone management and is at the heart of land-use planning that minimizes damage from coastal erosion.

We are at a crossroads today with respect to adjustment to coastal erosion. One road leads to ever-increasing coastal defenses in an attempt to control erosion. The second path involves learning to live with coastal erosion through flexible environmental planning and wise land use in the coastal zone.[24,28] The first path follows history in our attempt to control erosion by building engineering structures, such as seawalls. In the second path, most structures in the coastal zone are considered temporary and expendable; only a few critical facilities may be considered permanent. Development in the coastal zone must be in the best interests of the general public rather than for a few who profit from it. This concept is at odds with the attitude of developers who consider the coastal zone "too valuable not to develop." In fact, development in the coastal zone is not the problem; rather, the problem lies in building in hazardous areas and areas better suited for other uses. In other words, beaches belong to all people to enjoy, not only those fortunate enough to purchase beach-front property. The states of Hawaii and Texas have taken this philosophy to heart. In Hawaii, all beaches are public property, and local property owners cannot deny access to others. Likewise, in Texas, virtually all of the ocean beaches are public property, and coastal zoning now requires avenues for public access.

Accepting the philosophy that, with minor exceptions, coastal zone development is temporary and expendable and that consideration should first be given to the general public requires an appreciation of the following five principles:[28]

1. Coastal erosion is a natural process rather than a natural hazard.
2. Any shoreline construction causes change. Such change interferes with natural processes and produces a variety of adverse secondary and tertiary changes.
3. Stabilization of the coastal zone through engineering structures protects property, not the beach itself. Most protected property belongs to relatively few people, at a large expense to the general public.

4. Engineering structures designed to protect a beach may eventually destroy it.
5. Once constructed, shoreline engineering structures produce a costly trend in coastal development that is difficult, if not impossible, to reverse.

If you consider purchasing land in the coastal zone, remember these guidelines: (1) allow for a good setback from the beach, sea cliff, or lakeshore bluff; (2) be high enough above the water level to avoid flooding and take into account rising sea level in making this determination; (3) construct buildings to withstand adverse weather, especially high winds; and (4) if hurricanes are a possibility, be sure there are adequate evacuation routes.[28] Remember that it is always risky to buy property where land meets water.

We conclude our discussion of coastal processes and hazards with two case histories: Cape Hatteras Lighthouse, where the decision was to move the structure, and Pointe du Hoc, France, where the decision was very different.

11.3 CASE study

The Cape Hatteras Lighthouse

Managed retreat is one method for dealing with coastal erosion and rising sea level. That was the option chosen by the National Park Service for protecting the historic Cape Hatteras Lighthouse. When the North Carolina lighthouse was built in the late nineteenth century—the tallest brick lighthouse in the world—it was approximately 500 m (~1650 ft.) from the Atlantic Ocean. By the early 1990s, it was only 100 m (~330 ft.) from the sea and in danger of being destroyed by a major storm. As you may recall from Chapter 10, Cape Hatteras is frequently a target for both hurricanes and nor'easters.

One probably would not expect the task of moving a 4400-ton lighthouse to be a matter of simple hydraulics. But this is how Rick Lohr, president of the International Chimney Corporation (ICC), described the task of moving the Cape Hatteras Lighthouse more than 800 m (~2700 ft.) when coastal erosion threatened to claim the historic structure (Figure 11.27).

The ICC was contracted to move the lighthouse to a safe location away from the shoreline in 1998, and it immediately set about making the necessary calculations to ensure that the project would go smoothly.

Among the preparatory tasks was testing the 880 m (~2900 ft.) path to the structure's new location for any



(a)



(b)

FIGURE 11.27 Lighthouse Moved
The historic Cape Hatteras Lighthouse was moved during summer 1999 to keep it from being destroyed by coastal erosion. (a) Cape Hatteras Lighthouse before it was moved. Only around 100 m (~330 ft.) from the water, the lighthouse could have been destroyed in a major storm. *(Don Smetzer/PhotoEdit)* (b) Cape Hatteras lighthouse being moved; at its new location, the lighthouse should be safe for the next 50 to 100 years. *(AP Photo/Bob Jordan)*

hidden regions, such as subsurface holes that could collapse during the move. In order to find out about possible subsidence, the ICC conducted what is known as "proof rolling," in which a similar amount of weight (in this case the weight of the lighthouse) was hauled across the move route to test for any such holes. This did not require an extraordinary amount of weight. The total surface area of the structure (lighthouse) at ground level, including the hydraulic jacks and rollers the ICC installed, was about 455 m^2 (~4900 $ft.^2$), making the average pressure at any given point roughly 10 tons per m^2 (~1 ton per $ft.^2$).

As for the move itself, the company used a system known as the "Unified Jack System," invented in the 1950s by ICC employee Pete Freisen, who, in his mid-80s, served as a technical director for the Hatteras project. The system used 120 individual jacks, which allowed for every point to rise equally, no matter what the pressure.

After cutting the lighthouse from its foundation, the 120 jacks were placed under the structure and divided into three groups of 40 jacks each so that, during transport, a downward tip in any of the three groups would not stress the structure. The same method was used to move an entire terminal at Newark International Airport in 2000.

Even though computers now aid companies such as ICC in their initial calculations, such as determining the center of gravity of a structure, the science of moving large objects has existed since the turn of the century. Thanks to Rick Lohr and his engineers, the lighthouse is expected to be safe in its new location until the middle or end of the twenty-first century.

—CHRIS WILSON

11.4 CASE study

Pointe du Hoc, France

Pointe du Hoc is a promontory on the English Channel, several hundred kilometers northwest of Paris on the Normandy coast. The point is a historical site located on a coastal plain of low relief. The ocean side is a sea cliff, approximately 30 m (~98 ft.) high (Figure 11.28). Each year, many thousands of people come to see the location where the invasion to free Europe in World War II began on June 6, 1944. However, the point has experienced as much as 10 m (~33 ft.) of erosion in the past 60 years. As a result, there is concern that the observation post (OP) might actually fall into the sea. Some predictions indicated that the OP could not last more than a few decades at most.

The site is considered by many to be so important that expending a large amount of money to preserve the most vulnerable parts of the point is worthwhile. Of course, this is a value judgment. Those who wanted to preserve the last bit of rock on the point, rather than move some of the structures, obtained funding to evaluate whether the point could be preserved for another few decades by reinforcing it. This is an interesting approach to coastal erosion because it is a site-specific solution to a particular problem that involves coastal stabilization, rather than adjustment to the hazard, such as managed retreat. The case is also interesting because it involves detailed geologic evaluation and study of processes of sea cliff retreat, linked to a specific strategy to reduce the rate of coastal erosion, which has been estimated at 0.1–0.2 m per year.[29] Scientists and engineers studying the sea cliff realized that any attempt to absolutely stop sea cliff erosion was futile, but their objective was a temporary solution to buy as much as 50 years. Total erosion in the past 60 years has been approximately 10 m (~33 ft.), but in future decades, that rate might be significantly reduced.

The sea cliff was carefully evaluated and its geology studied in detail. The idealized profile of the sea cliff is shown in Figure 11.29, illustrating three geologic layers:[29]

- The top layer, which is up to about 9.0 m (~30 ft.) thick, is a silty, gravelly, sandy, clay soil. This layer has relatively low strength and is prone to small landslides and grain-by-grain erosion resulting from precipitation.
- The middle layer is a fractured limestone about 15 m (~50 ft.) thick that, with depth, becomes sandy and enriched with calcium carbonate muds. The limestone beds are nearly horizontal but have numerous nearly vertical fractures that are filled, to a lesser or greater extent, with weathered products of the limestone that are rich in clay. Precipitation from the surface can remove some of the clay, resulting in the fractures being more open. The fractured limestone is vulnerable to larger slope failures, particularly if the rock is underlain by areas of coastal erosion that have produced wave-cut notches and sea caves. In fact, investigators studying the site have observed that this is the dominant failure mechanism that results in the most rock being lost from the sea cliff. When wave erosion undermines the rocks at the base, they may fail along the fractures, falling onto the beach or into the sea.
- The lowest layer present is a black marl, which is a calcium carbonate–rich mudstone. Both the



(a)



(b)

< FIGURE 11.28 Pointe du Hoc
(a) Location of Pointe du Hoc. (b) The historical site of Pointe du Hoc is on a coastal plain underlain by cretaceous limestone. Pits are bomb craters from World War II. *(Forget Patrick/Sagaphoto. com/Alamy)*

fractured limestone and the black marl have relatively high rock strength, compared to that of the overlying soil.

The sea cliff study suggested that the attack of waves at the rock face near the beach dislodges blocks of rock and creates caverns or sea caves. These are clearly visible along the base of the sea cliff and can be quite large, as illustrated in Figure 11.29. The caves grow larger and deeper with time and, eventually, leave the overlying rock unsupported, and a failure may occur along the fractures. The study concluded that the primary reason for collapse of the sea cliff was the presence of the caverns at the base of the cliff. As a result, the primary recommendation for reducing the rate of erosion was to fill the caverns and stabilize the base of the sea cliff.

Work on this project began in 2010 with the goal of filling the caverns with several hundred cubic meters of concrete. Rock bolts were also used to secure the concrete and stabilize the rocks. After filling the caverns, an outermost layer of cement, which was specially designed to look like native rock, would be added. This was obviously a temporary solution because new sea caves could form, and the cement itself might be undermined and eroded. As a result, the study recommended a maintenance program based on inspections, recognizing that future work would undoubtedly be necessary. It is also important to recognize that the development of sea caves and large landslides was not the only process

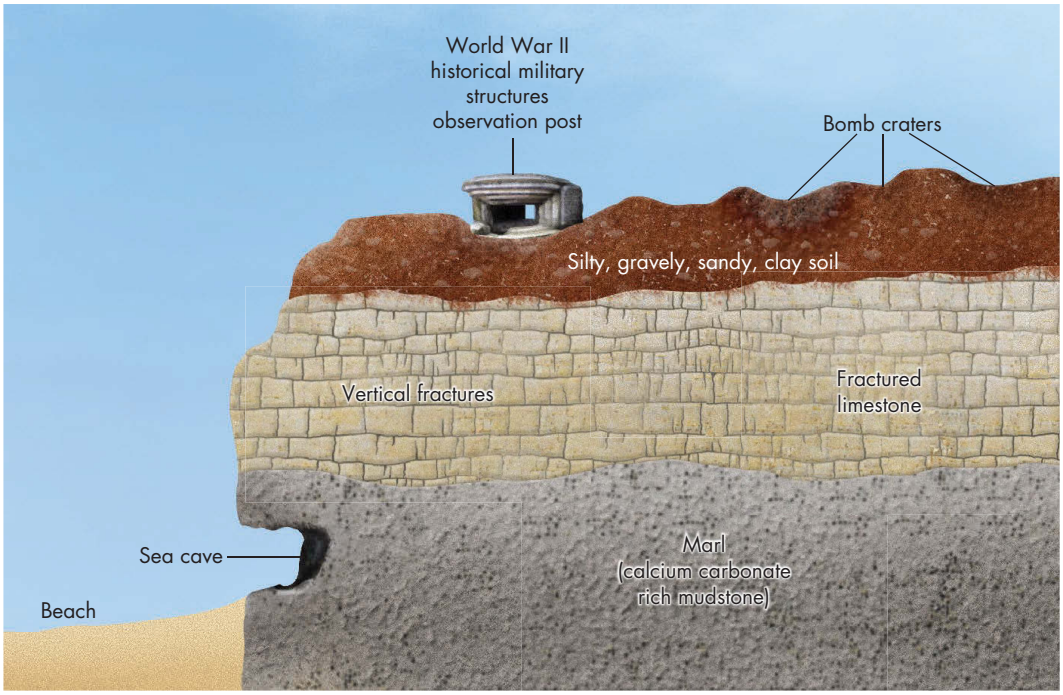


FIGURE 11.29 Idealized Geology at Pointe du Hoc (Observation Point)
(Data from Briand, J.-L., Nouri, H. R., and Darby, C., Pointe du Hoc Stabilization Study. *Texas A&M University, 2008.)*

affecting the sea cliff. The top unit of the sea cliff is weak soil, and numerous small landslides were occurring on a regular basis. In fact, the top of the sea cliff has a wavy form, resulting from the many small landslides. Therefore, stabilizing the base of the sea cliff would not completely eliminate sea cliff retreat but would probably reduce it by about one-half. Thus, the work on the lower part of the sea cliff, which was completed by September 2010, was a temporary solution at best.

The decision to use a "hard solution" at Pointe du Hoc is an interesting one, based on the value judgment that the historical significance of the physical site is so great that measures needed to be taken to preserve it. The cost of the work is modest to date, at about $6 million; however, future maintenance costs will be incurred, and structures that are built in the sea cliff environment are often fortified even more in subsequent years, so the total cost in the future is unknown. The solution to coastal erosion and the decision to minimize it at Pointe du Hoc are obviously special circumstances for stabilizing a small length of sea cliff. Should such an approach be applied to a long section of sea cliff, the cost would be far too great to maintain. For now, the point is better protected, and the erosion rate will probably decrease, but, in the long run, the environmentally preferable solution will be to move historically important structures back from the edge of the cliff. This is essentially the same solution that was implemented for the Cape Hatteras Lighthouse.

11.10 CHECK your understanding

1. What are the main adjustments to managing coastal erosion?
2. What are the attributes of adaptive management?
3. What are the goals of integrated coastal zone management?
4. What are E-lines and E-zones?
5. Why was moving the Cape Hatteras Lighthouse successful?
6. Could erosion control measures for Pointe du Hoc in France be widely applied to other eroding sea cliffs? Why or why not?

APPLYING the 5 Fundamental Concepts

Folly Island

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

Coastal erosion along much of the world's coastlines is a serious and costly problem, and nowhere is this truer than on Folly Island, South Carolina, where some beaches are receding at a rate of 2 m (~7 ft.) per year. The high rates of shoreline retreat on Folly Island is the result of both natural and human-caused changes to the environment that began in the late nineteenth century with the construction of the Charleston jetties, as discussed at the beginning of this chapter. Just 7 km (~4.3 mi.) northeast of Folly Island, the rock jetties are perpendicular to the coastline and extend for 5 km (~3 mi.) into the Atlantic Ocean from the entrance to the Charleston Harbor (see Figure 11.1). By impeding the south-flowing longshore drift, which for thousands of years replenished Folly, the jetties upset the natural balance between sand supply and beach erosion on the island. The effects of this seemingly minor imbalance due to human attempts to minimize nature's will has combined with sea-level rise to create Folly's coastal erosion problem.

Folly Island has seen not only conflict between civilization and nature, but also conflicting approaches to long-term solutions to coastal erosion. By the middle of the twentieth century, it was clear that Folly's beaches were washing away, so construction of walls both perpendicular (groins) and parallel (seawalls) to the shoreline began following World War II. Between 1949 and 1970, the state highway department built 40



< FIGURE 11.30 Groins on Folly Island
Pictured are eight of the more than 40 groins on Folly Island, South Carolina, that trap sand moving by coastal currents. Groins create an irregular pattern of shoreline erosion and deposition and, in the end, contribute to coastal erosion downdrift from Folly Island. *(Bob Krist/Corbis)*



< FIGURE 11.31 Attempts to Mitigate Coastal Flooding and Erosion on Folly Island

Property owners use a variety of methods to mitigate the effects of storms and coastal erosion on Folly Island, South Carolina, including this seawall constructed of large boulders, called riprap, and wood and the elevation of this house on wood pilings. Although seawalls may help protect buildings, they generally contribute to beach erosion. *(Robert H. Blodgett)*

groins along Folly's coast, which were composed of wood pilings sunk deep into the sandy island coastline (Figure 11.30).[1] Although the groins resulted in updrift beach deposition, they caused accelerated erosion downdrift of their locations. Property owners have also built walls of concrete, boulders, or wood parallel to the beach or have added sand on the beach in front of their homes to protect the houses from erosion and flooding (Figure 11.31). Although the seawalls provided temporary protection for buildings, over the long term these structures similarly led to excess erosion and damage elsewhere by locally amplifying the effects of storm waves.[1] For example, in 1985, a North Carolina land developer was permitted to construct a nine-story hotel on the Folly coast if a seawall was constructed to protect it. However, the hotel's seawall ultimately caused excess beach erosion and failed to protect the building from the 3.7 m (~12 ft.) storm surge of Hurricane Hugo in 1989.[1] State regulations have since been put in place to limit the construction of such coastal erosion structures.

Folly Island homeowners sued the U.S. Army Corp of Engineers in 1979 for constructing the Charleston jetties, and in 1987, the federal government agreed to pay for more than 70 percent of the cost of stabilizing Folly's beaches through the year 2037. To mitigate this erosion, engineers, business interests, and some politicians have favored beach nourishment, the periodic addition of sand to the beach. Sand was added to the beach three times, in 1979, 1993, and 2005, by contractors for the Corps (Figure 11.32). In fact, in 1996, Congress made promotion of beach nourishment part of the Corp's mission.[30] The Corps estimates that, on average, sand will have to be added to Folly Beach every eight years. Although this frequency may seem high, it is not as high as estimated for Jupiter Beach, Florida, and Ocean City, New Jersey, where beach nourishment is projected for every three years![31] A study of sand added to Folly Beach in 1993 indicates that significant quantities of the sand placed on the beach are being carried out onto the continental shelf and completely removed from the beach system.[32]

Beach nourishment was again deemed necessary in 2012 after sustaining severe erosion on both ends of the island, due to Hurricanes Irene and Sandy in 2011 and 2012 (see opening photograph). However, federal budget battles have hindered procurement of the funds to pay for the replenishment. Beach nourishment on Folly Island has cost more than $24 million to date, up from the $15 million originally estimated. The Corps announced that $2 million in federal funds would be available



▲ FIGURE 11.32 Nourishment of Folly Beach
(a) A floating hydraulic cutter-head suction dredge in the distance sucked sand from the continental shelf and pumped a sand-and-water slurry to the shore in 2005. The slurry flowed along the beach in the steel pipe that appears in the foreground. *(Robert H. Blodgett)* (b) Sand and water discharged from the pipe on the beach, and the sand was moved in position by the bulldozer shown in (a). The U.S. Army Corps of Engineers spent more than $12 million to add approximately 1.7 million m^3 (~2.3 million yd^3) of sand to the beach in 2005. An estimated 1.9 million m^3 (~2.5 million yd^3) was added at a cost of $12.5 million in 1993. *(Robert H. Blodgett)*

for the project, but as of late 2013, the funds had not yet been provided.[31] With so much beach erosion and no certain plan for funding beach nourishment, residents began to fight regulations that limited construction of seawalls by private landowners. Ultimately the South Carolina Department of Health and Environmental Control overruled the coastal regulations in the spring of 2013, making it possible for a small number of residents to build mitigation structures to protect their homes. By that summer, the City of Folly Beach also decided it could no longer wait for federal assistance and announced that it would move forward with its own $3 million nourishment plan. Beach nourishment finally occurred in 2014 when about 765,000 cubic meters (1 million cubic yards) of sand was added to the beaches of the island. Unfortunately, Hurricane Joaquin hit Folly Island in October of 2015 with high waves and flooding. The storm removed about one-third of the sand just added in 2014. Beach nourishment is a gamble, insofar as the sand is considered sacrificial. Sometimes it lasts for a few years, but one large storm can remove it at any time.

Geologists study shoreline behavior over the long term and take into account the natural movement of barrier islands and rising sea level. They have observed that without hard structures, such as seawalls and groins, beaches generally do not disappear; they just shift location. Although shifting location may sound better than severe coastal erosion, shifting is just as serious once humans populate and develop these islands. Sea level in Charleston, just north of Folly Island, has been rising on average 3 mm (~0.12 in.) per year since 1920,[33] which is causing sand deposition to shift westward toward mainland South Carolina. Therefore, even in the absence of man-made structures such as the Charleston jetties or the groins on the island, natural processes are adding to Folly's coastal erosion problem. Moreover, the rate of sea-level rise is likely to increase as the effects of humans increase the rate of global warming.[6]

Although most ocean beaches in the United States are eroding like Folly Beach, few states and coastal communities are considering sea-level rise in their planning.[34] South Carolina's Beachfront Management Act, implemented in 1990, recognizes the coastal erosion hazard and establishes setback distances for new construction from the shoreline. However, because it has been developed since the



▲ FIGURE 11.33 New Home Construction on Folly Island
After Hurricane Hugo's 3.7 m (~12 ft.) storm surge in 1989, more recent construction on Folly Island has been on higher piers. The base flood elevation on the 2004 FEMA Flood Insurance Rate Maps is 4.9 to 7 m (~16 to 23 ft.) above sea level for most of the island. With coastal erosion and rising sea level, this elevation may be too low to protect this house from storm surge for the remainder of the century. *(Robert H. Blodgett)*

1920s, Folly Beach is at least temporarily exempted from the setback provision.[1] What has yet to be addressed is the effect of rising sea level. New houses built on Folly Island are elevated on tall piers (Figure 11.33) at a height that is determined from the base flood elevation shown on FEMA flood insurance rate maps. This base flood elevation is based on present-day sea level, not the rise in sea level that is likely to occur during the lifetime of the structure.

Erosion on Folly Island varies from place to place, and there are erosion hot spots (particularly at the east and west ends). Although beach nourishment is a big part of management at Folly Island and additional hard structures, such as seawalls and beach groins, are also being considered, some homeowners are angry that regulations do not allow or encourage them to protect private property. Individual homes are now essentially on the high-tide beach and vulnerable to erosion and flooding.

The challenge for Folly Island, and much of the Atlantic and Gulf coasts, will be adopting coastal management policies and regulations that are forward-looking and take into consideration coastal erosion, local subsidence, and rising sea level. In some areas, difficult choices will have to be made between preserving beaches and coastal wetlands and protecting buildings and infrastructure.

APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. How can we better predict the amount of coastal erosion Folly Island will experience by 2050?
2. Assuming we can predict the amount of erosion that will occur on Folly Island in the next decade, how can this prediction be used by the city of Folly Beach and property owners to define the risk?
3. How is coastal erosion of Folly Island linked to hurricanes, flooding, and rising sea level from climate change?
4. In what ways have human processes impacted coastal erosion at Folly Island?
5. Given the history and information about Folly Island presented here, what would you suggest to minimize the erosion hazard?

CONCEPTS in review

11.1 Introduction to Coastal Hazards

LO:1 Discuss the role of plate tectonics influencing coastal zone morphology and process.



- The coastal environment is incredibly dynamic and capable of rapid change.
- Coastal morphology around the globe is greatly influenced by plate tectonics, and there are major differences between a coast on the leading edge of a continent and near a plate boundary (such as the U.S. West Coast) and a more passive coastline far from a major plate boundary (such as the U.S. East Coast).
- Impacts of coastal hazards are increasing for a variety of reasons, including the fact that about 50 percent of the population of the United States today lives in large cities in the coastal zone, or at least in coastal counties.
- The most serious coastal hazards include strong coastal currents, coastal erosion of beaches and sea cliffs, storm surge from hurricanes and cyclones (see Chapter 10), and tsunamis (see Chapter 4).

11.2 Coastal Processes

LO:2 Explain coastal processes, such as waves, beach forms and processes, and rising sea level.



- Waves that arrive at coastlines are generated by offshore winds, and the size of the waves is related to the velocity or speed of the waves, the duration that the wind blows in the storm area, and the distance that the wind blows across the water surface (fetch).
- Waves develop in a variety of sizes and shapes. Rogue waves are unusually large waves formed by currents and undersea irregularities.
- As waves enter shallow coastal water, remarkable transformations take place. Wave period remains constant, but velocity decreases and height increases. When a wave reaches a critical steepness, it is no longer stable at the surface, and the wave breaks.
- Waves seldom arrive at the coasts with their wave fronts perfectly parallel to the coast. Because they arrive at an angle, a component of the wave power is directed along the shore, producing the littoral transport system, which includes beach drift along the beach face, as well as longshore drift in the surf zone.
- The two main types of breakers are spilling and plunging breakers. Spilling breakers build beaches, while plunging breakers are more destructive and may erode a beach.
- Basic terms used to describe a beach are *berms*, *beach face*, *longshore trough*, *longshore bar*, *swash zone*, *surf zone*, and *breaker zone*. At the back of a beach, there may be either sand dunes or, sometimes, a sea cliff.

KEY WORDS

beach (p. 444), **littoral transport** (p. 446), **sea cliff** (p. 445)

11.3 Sea-Level Change

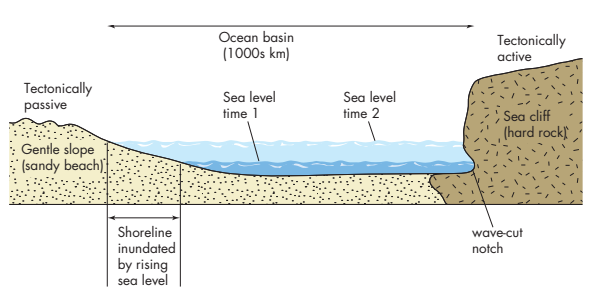
LO:3 Summarize the effects of sea-level rise on coastal processes.

KEY WORDS
eustatic sea level (p. 447), **relative sea level** (p. 447)

- Sea level is always changing, and it can change over time scales of hours and days to many thousands of years.
- Relative sea level refers to sea level influenced by tectonic movements of the land, as well as movements of the water and climatic factors. Relative sea level may change very rapidly in response to storm surge from hurricanes or to storm events, such as El Niño events, which can move a mass of warmer water toward the western coast of the United States.
- Eustatic sea-level curves refer to worldwide changes that are linked to climatic factors and global change affecting the overall volume of water in the ocean.

11.4 Geographic Regions at Risk from Coastal Hazards

LO:4 Explain why coastal erosion rates vary along different U.S. coastlines.



- Coastal erosion is essentially a worldwide hazard. This results because most coastlines are experiencing a rise in sea level, and that may drive coastal erosion.
- Rates of coastal erosion related to beaches and sea cliffs are highly variable. Coastal erosion along the east and west coasts of the United States vary from about 0.3 m (~1 ft.) per year to as much as 2 m (~7 ft.) or more per year. The lower rates, however, tend to dominate in the United States, with notable exceptions that are usually related to human processes that affect erosion.

11.5 Effects of Coastal Processes

LO:5 Synthesize the coastal erosion hazard.

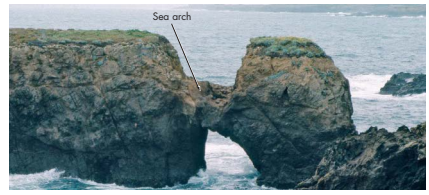


KEY WORDS
beach budget (p. 453), **rip current** (p. 450)

- Individual hazards for people swimming in the ocean are related to strong currents. The most familiar of these is the rip current that develops as incoming breakers pile up water at the coast on the beach. This water moves out in discrete flow paths known as rip currents.
- Coastal erosion is a serious natural hazard. It is a generally continuous predictable process. The changes may be dramatic during storms, but, over a period of years, it is a relatively slow process.
- One way to visualize erosion at a particular beach is to compute the beach budget, which accounts for sources and sinks of sand at a particular beach. If input of sand exceeds output, then the beach will grow, and if output exceeds input, then erosion occurs.

- Sea cliff erosion occurs along many coastlines in the United States and around the world, as well as along the U.S. Great Lakes. Human processes can increase coastal erosion and sea cliff erosion through uncontrolled surface runoff, increased groundwater discharge, and added weight to the top of a sea cliff.

11.6 and 11.7 Linkages between Coastal Processes and Other Natural Hazards Natural Service Functions of Coastal Processes



LO:6 Summarize the potential links between coastal processes and other natural hazards

- Coastal erosion is typically linked to other natural hazards such as earthquakes, volcanic eruptions, tsunamis, cyclones, flooding, landslides, and subsidence, as well as climate change.
- The coastal zone provides a variety of service functions for the natural and human-built environment. For example, coastlines provide aesthetic resources for people, but they do much more in terms of maintaining ecosystems, eroding and transporting sands, and building coastal sand dunes.

11.8 Human Interaction with Coastal Processes



LO:7 Evaluate how human use of the coastal zone affects coastal processes.

- Human use of and interest in the coastal zone is a major driving force that affects coastlines around the world. Human processes have caused considerable coastal erosion, particularly near highly populated and developed coastlines.
- Humans often attempt to control coastal erosion by building structures that are designed to minimize erosion. Often, these end up causing damage and further erosion to beaches.
- Coastal processes include both physical and human-induced factors. The physical factors include the existence of coastal dunes or sea cliffs, as well as the orientation of the coastline (exposure of the coast to waves); human factors include constructing protective structures (engineering structures) that might be locally beneficial but might accelerate erosion at adjacent areas.

11.9 Minimizing the Effects of Coastal Hazards

LO:8 Summarize what we can do to minimize coastal hazards.

- The two major approaches to coastal erosion and attempts by people to minimize it are the so-called hard solutions and the soft solutions.
- Examples of hard stabilization include construction of seawalls, groins, breakwaters, and jetties. Examples of soft stabilization include beach nourishment, land-use planning, and bioengineering approaches.



KEY WORDS

adaptive management (p. 468), **integrated coastal zone management** (p. 468)

11.10 Perception of and Adjustment to Coastal Hazards

LO:9 List options available for coastal management.

- People have attempted to adjust to coastal erosion in a variety of ways, and the predominant ones fall into three categories: beach nourishment, shoreline stabilization through engineering structures, and land-use change.
- Management of coastlines and beaches encourages the use of adaptive management, which utilizes science as an integral part, and integrated coastal zone management, which may include a mixture of hard and soft solutions.
- A number of general principles related to coastal erosion and processes must be considered: Coastal erosion is a natural process; any shoreline construction causes change; stabilizing coastal zones through engineering may protect property but not the beach; engineering structures designed to protect the beach may eventually damage or destroy it, and, once constructed, shoreline engineering structures produce a trend that is difficult to reverse.



KEY WORDS

beach nourishment (p. 464), **breakwater** (p. 464), **jetties** (p. 465)

CRITICAL thinking questions

1. Do you think that human activity has increased coastal erosion? Outline a research program that could test this question.
2. Do you agree or disagree with the following statements: (1) All structures in the coastal zone, with the exception of critical facilities, should be considered temporary and expendable. (2) Any development in the coastal zone must be in the best interest of the general public rather than the few who developed the oceanfront. Explain your position on both statements.
3. You have been asked by a coastal community to evaluate the feasibility of a beach nourishment project. Describe the types of information that you would require for your evaluation and how you would determine how often nourishment will be needed in the future.
4. Compare and contrast the shoreline features of the tectonically active and passive coasts of the United States and describe how coastal hazards differ in the two coasts that you have evaluated.

5. Assume you are living on a barrier island in the Gulf of Mexico that is experiencing rapid urbanization. Nearly everyone wants to live near the edge of the ocean, in other words, as close to the water as possible. It is expected that, in 10 years, the number of homes and people will increase dramatically from a few hundred now to a few thousand. You are hired by the community to help evaluate land use and potential effects of coastal erosion. What advice would you give to the communities on the barrier island, and what sorts of data would you need to gather to make conclusions concerning future land use? In addition, how would you handle the people problems? That is, how would you talk to people about erosion and what the consequences are likely to be and how the process might be minimized?

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