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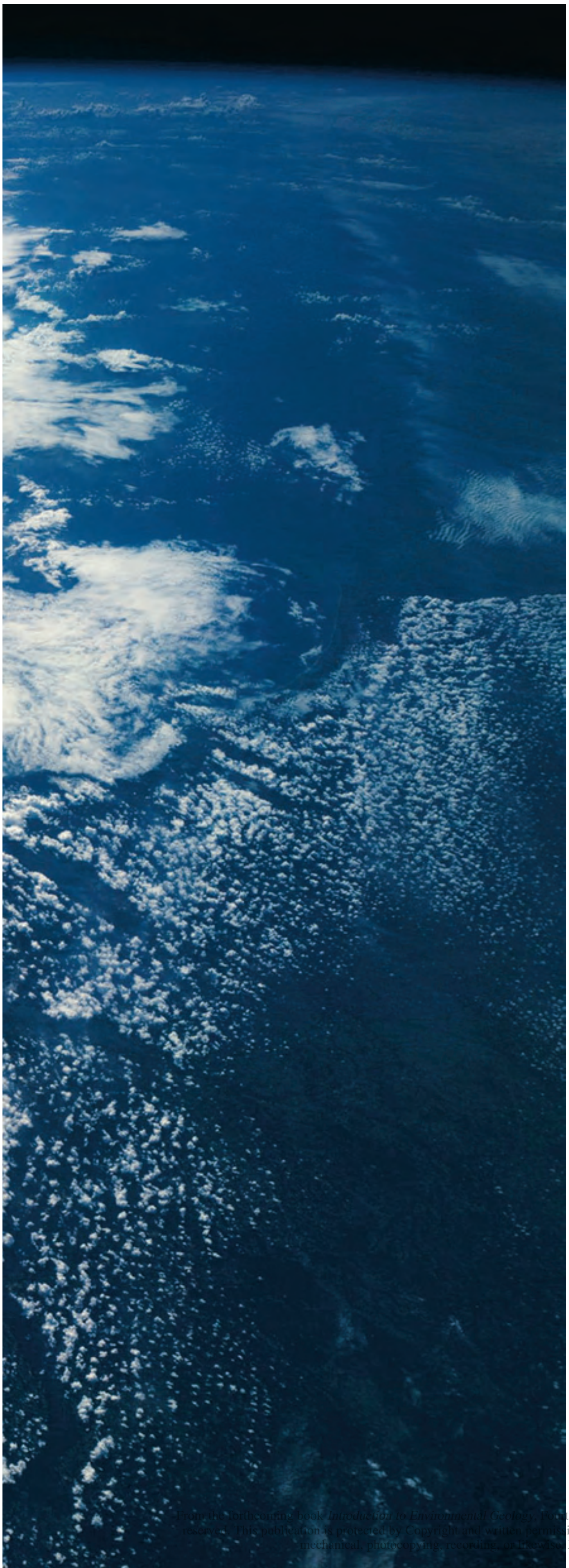
Coastal Processes



Learning Objectives

In this chapter we focus on one of the most dynamic environments on Earth—the coast, where the sea meets the land. The beauty of the coastal zone, with its salty smells and the sight and sound of wind and waves striking the land, has inspired poets and artists for thousands of years. Beaches composed of sand or pebbles and rocky coastlines continue to attract tourists like few other areas. Yet most of us have little understanding of how ocean waves form and change the coastlines of the world. A major purpose of this chapter is to remove the mystery of how coastal areas are formed and maintained while retaining the wonder. We seek to understand the hazards resulting from wind, waves, and storms, and how we can learn to live in the ever-changing coastal environment while sustaining its beauty. We will focus on the following learning objectives:

- Know the basic terminology of waves, and processes of waves
- Be able to define the basic components of a beach
- Understand the process of littoral transport of sediment
- Know what rip currents are and why they are a serious hazard to swimmers
- Know the major processes related to coastal erosion
- Understand the various engineering approaches to shoreline protection
- Understand how human activities affect coastal erosion
- Understand why we are at a crossroads with respect to adjustments to coastal erosion
- Understand what tropical cyclones are and the hazards they produce

The Outer Banks View to the south of Cape Hatteras and the Outer Banks of North Carolina. The Outer Banks extend far out in the Atlantic. They are a ribbon of sand tied to a continent, ever shifting and changing in response to wind and waves, pounded by storms and warmed by the sun. A magical place!

(NASA/The Image Bank/Getty Images Inc.)

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CASE HISTORY | The Cape Hatteras Lighthouse Controversy

In North Carolina, a dramatic collision of opinions concerning beach erosion is now being played out. Historically, North Carolina has adhered to the philosophy that beach erosion is a natural process with which its residents can live. When erosion began to threaten the historic Cape Hatteras Lighthouse (Figure 10.1a), this philosophy was tested. The lighthouse is located near Buxton, on North Carolina's barrier islands known as the Outer Banks. When the lighthouse was originally constructed in the late nineteenth century, it was approximately 0.5 km (0.3 mi) from the sea. By the early 1990s it was only 100 m (328 ft) away from the sea and in danger of being destroyed by a major storm. Officials in the area had to weigh the following options:

- Artificially control coastal erosion at the site, and reverse state policy of yielding to erosion. The U.S. Army Corps of Engineers originally proposed to protect the lighthouse by constructing a $5.6 million seawall around the base.[1]
- Do nothing and eventually lose the lighthouse and, thus, an important bit of American history.
- Move the lighthouse inland. Many local people opposed this plan, fearing the lighthouse would collapse if moved.[1]

Following much discussion, argument, and controversy over what to do, the decision was made by the National Park Service to move the lighthouse inland approximately 500 m (1,640 ft) from the eastern shore of Hatteras Island at a cost of about $12 million. The decision to move the lighthouse was based on several factors. It was consistent with the philosophy of flexible coastal zone planning to avoid hazardous zones rather than attempting to control natural processes. It was also consistent with North Carolina's policy to preserve historic objects, such as the lighthouse, for the enjoyment of future generations. The lighthouse was successfully moved during the summer of 1999 (Figure 10.1b). Given the present rate of coastal erosion, the lighthouse should be safe in its new location until the middle or end of the twenty-first century. Hurricane Dennis struck the island in 1999 after the lighthouse was moved, and the historic structure was not significantly damaged.

Another lighthouse battle is looming on the East Coast. Hundreds of homes and other buildings along the coast on Long Island, New York, are now close to the actively eroding shoreline. Included is the famous Montauk Lighthouse, which was constructed in 1746 on a bluff 100 m (300 ft) from the ocean and is now about 25 m (75 ft) from the ocean. One group argues for a hard structure consisting of a multimillion dollar, 280 m (840 ft) long rock revetment (rock seawall) to protect the base of the bluff from erosion. Another group is arguing to move the lighthouse inland. Moving the lighthouse would be a challenge and the rock revetment might change the coastline, causing problems in adjacent areas. The rock solution might also set a precedent for hard structural control of beach erosion on Long Island and other East Coast areas.


(a) (b)

Figure 10.1 **Lighthouse is moved** (a) Cape Hatteras Lighthouse before being moved. *(Don Smetzer/Getty Images Inc.)* (b) Cape Hatteras Lighthouse being moved in the summer of 1999. *(Hart Matthews/Reuters/Getty Images Inc.)*

10.1 Introduction to Coastal Hazards

Coastal areas are dynamic environments that vary in their topography, climate, and vegetation. Continental and oceanic processes converge along coasts to produce landscapes that are characteristically capable of rapid change. The East Coast of the United States is a passive margin coastline far from a convergent plate

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boundary (see Chapter 2). The coastline is characterized by a wide continental shelf with barrier islands (see opening photograph) with wide sandy beaches. Rocky coastlines are mostly restricted to the New England coast where the Appalachian Mountains merge with the Atlantic Ocean. The west coast is close to the convergent boundary between the North American and Pacific plates (active margin coast). Mountain building has produced a coastline with sea cliffs and rocky coastlines. Long sandy beaches are present, but not as abundant as along the East Coast.

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 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 75 percent of the population lives in coastal states.[2] Coastal problems will thus increase because so many more people will live in coastal areas where the hazards occur. Once again, our activities continue to conflict with natural processes! Hazards along the coasts may become compounded by the fact that global warming and the accompanying global rise in sea level are increasing the coastal erosion problem. (Climate change and sea level rise are discussed in Chapter 19.)

The most serious coastal hazards are the following:

- Rip currents generated in the surf zone
- Coastal erosion, which continues to produce considerable property damage that requires human adjustment
- Tsunamis, or seismic sea waves (discussed in Chapter 5), which are particularly hazardous to coastal areas of the Pacific Ocean
- Tropical cyclones, called hurricanes in the Atlantic and typhoons in the Pacific, which claim many lives and cause enormous amounts of property damage every year

10.2 Coastal Processes

Waves

Waves that batter the coast are generated by offshore storms, sometimes thousands of kilometers from the shoreline where they will expend their energy. Wind blowing over the water produces friction along the air-water boundary. Since the air is moving much faster than the water, the moving air transfers some of its energy to the water, resulting in waves. The waves, in turn, eventually expend their energy at the shoreline. The size of the waves produced depends on the following:

- The velocity, or speed, of the wind. The greater the wind velocity, the larger the waves.
- The duration of the wind. Storms of longer duration have more time to impart energy to the water, producing larger waves.
- The distance that the wind blows across the surface, or *fetch.* The longer the fetch, the larger the waves.

Within the area of the storm, the ocean waves have a variety of sizes and shapes, but as they move away from their place of origin, they become sorted out into groups of similar waves. These groups of waves may travel for long distances across the ocean and arrive at distant shores with very little energy loss.

The basic shape, or wave form, of waves moving across deep water is shown in Figure 10.2a. The important parameters are *wave height,* which is the difference in height between the wave's trough and its peak, and *wave length,* the distance between successive peaks. The *wave period* (P) is the time in seconds for successive waves to pass a reference point. If you were floating with a life preserver in deep

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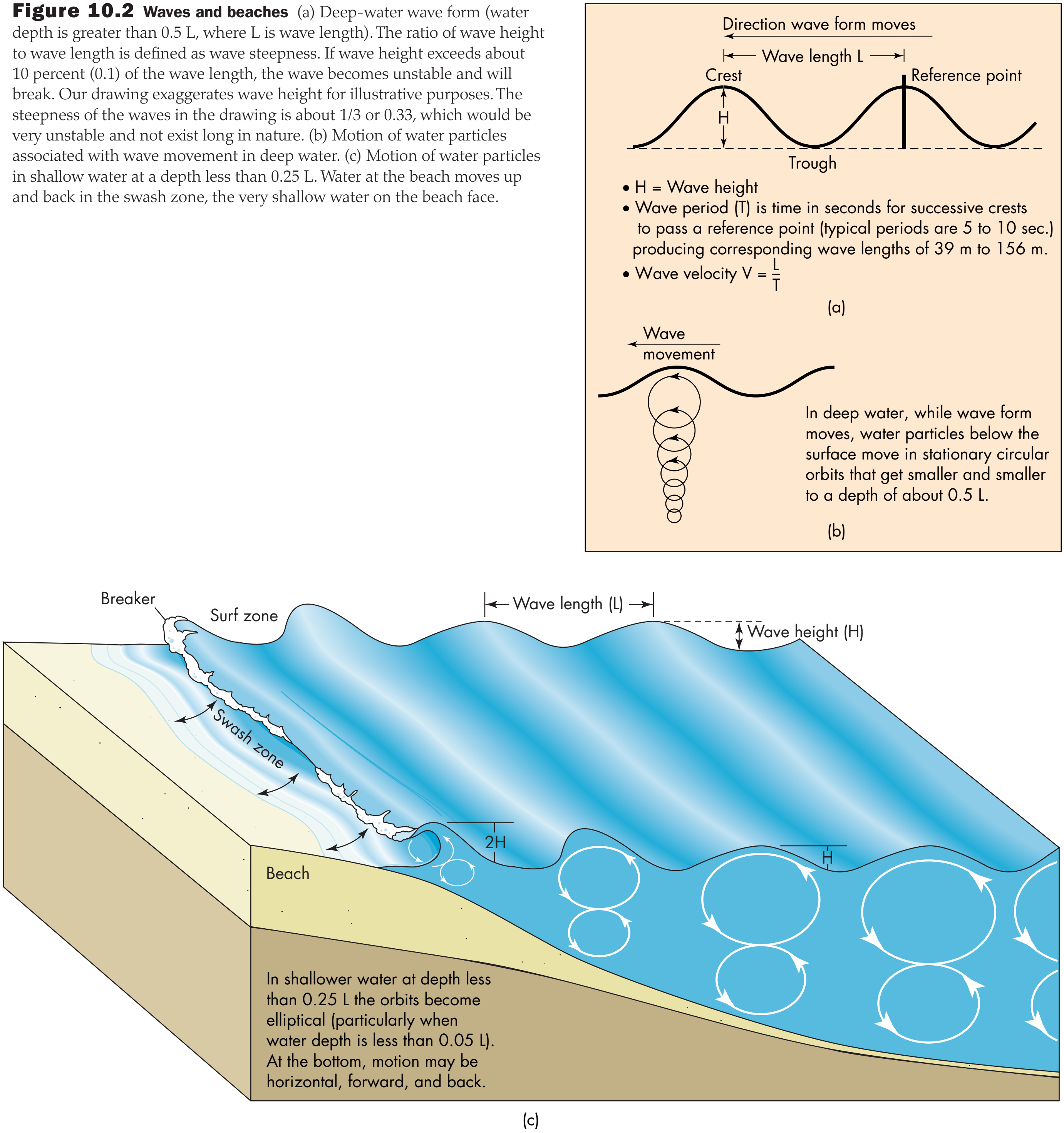

Figure 10.2 **Waves and beaches** (a) Deep-water wave form (water depth is greater than 0.5 L, where L is wave length). The ratio of wave height to wave length is defined as wave steepness. If wave height exceeds about 10 percent (0.1) of the wave length, the wave becomes unstable and will break. Our drawing exaggerates wave height for illustrative purposes. The steepness of the waves in the drawing is about 1/3 or 0.33, which would be very unstable and not exist long in nature. (b) Motion of water particles associated with wave movement in deep water. (c) Motion of water particles in shallow water at a depth less than 0.25 L. Water at the beach moves up and back in the swash zone, the very shallow water on the beach face.

- H = Wave height
- Wave period (T) is time in seconds for successive crests to pass a reference point (typical periods are 5 to 10 sec.) producing corresponding wave lengths of 39 m to 156 m.
- Wave velocity $V = \frac{L}{T}$

(a)

In deep water, while wave form moves, water particles below the surface move in stationary circular orbits that get smaller and smaller to a depth of about 0.5 L.

(b)

In shallower water at depth less than 0.25 L the orbits become elliptical (particularly when water depth is less than 0.05 L). At the bottom, motion may be horizontal, forward, and back.

(c)

water and could record your motion as waves moved through your area, you would find that you bob up, down, forward, and back in a circular orbit, returning to about the same place. If you were below the surface with a breathing apparatus, you would still move in circles, but the circle would be smaller. That is, you would move up, down, forward, and back in a circular orbit that would remain in the same place while the waves traveled through. This concept is shown in Figure 10.2b. When waves enter shallow water at a depth of less than about one-half their wavelength (L), they "feel bottom." The circular orbits change to become ellipses; the motion at the bottom may be a very narrow ellipse,

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or essentially horizontal, that is, forward and back (Figure 10.2c). You may have experienced this phenomenon if you have stood or have swum in relatively shallow water on a beach and felt the water repeatedly push you toward the shore and then back out toward the sea.

The wave groups generated by storms far out at sea are called *swell.* As the swell enters shallower and shallower water, transformations take place that eventually lead to the waves' breaking on the shore. For deep-water conditions, there are equations to predict wave height, period, and velocity based on the fetch, wind velocity, and length of time that the wind blows over the water. This information has important environmental consequences: by predicting the velocity and height of the waves, we can estimate when waves with a particular erosive capability generated by a distant storm will strike the shoreline.

We have said that waves expend their energy when they reach the coastline. But just how much energy are 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 a height of about 1 m (3.3 ft) over a given period of time is approximately equivalent to the energy produced by one average-sized nuclear power plant over the same time period.[3] Wave energy is approximately proportional to the square of the wave height. Thus, if wave height increases to 2 m (6.6 ft), the wave energy increases by a factor of 2^2, or 4. If wave height increases to 5 m (16 ft), which is typical for large storms, then the energy expended, or wave power, increases 5^2, or 25 times over that of waves with a height of 1 m (3.3 ft).

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 wave length. Waves are unstable when the wave height is greater than about 10 percent (0.1) of the wave length. As waves move into shallow water, the wave period remains constant, but wave length 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 10.2c). 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]

Although wave heights offshore are relatively constant, the local wave height may increase or decrease when the *wave front* (see Figure 10.3a) reaches the nearshore environment. This change can be attributed to irregularities in the offshore topography and the shape of the coastline. Figure 10.3a is an idealized diagram showing a rocky point, or headland, between two relatively straight reaches of coastline. The offshore topography is similar to that of the coastline. As a wave front approaches the coastline, the shape of the front changes and becomes more parallel to the coastline. This change occurs because, as the waves enter shallow water, they slow down first where the water is shallowest, that is, off the rocky point. The result is a bending, or *refraction,* of the wave front. In Figure 10.3a, the lines drawn perpendicular to the wave fronts, with arrows pointing toward the shoreline, are known as *wave normals.* Notice that, owing to the bending of the wave fronts by refraction, there is a *convergence* of the wave normals at the headland, or rocky point, and a *divergence* of the wave normals at the beaches, or embayments. Where wave normals converge, wave height increases; as a result, wave energy expenditure at the shoreline also increases. Figure 10.3b shows a photograph of large waves striking a rocky headland.

The long-term effect of greater energy expenditure on protruding areas is that wave erosion tends to straighten the shoreline. The total energy from waves reaching a coastline during a particular time interval may be fairly constant, but there may be considerable local variability of energy expenditure when the waves break on the shoreline. In addition, breaking waves may peak up quickly and plunge or surge, or they may gently spill, depending on local conditions such as

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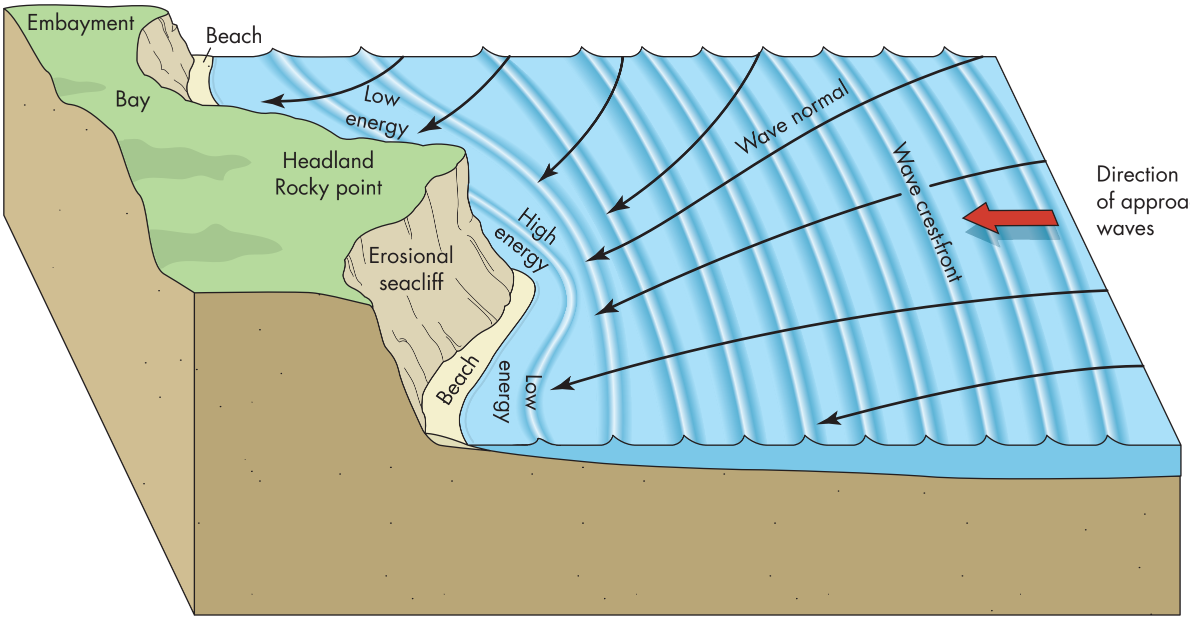

(a)

(b)

Figure 10.3 Convergence and divergence of wave energy (a) Idealized diagram of the process of wave refraction and concentration of wave energy at rocky points, or headlands. The refraction, or bending of the wave fronts causes the convergence of wave normals on the rocky point and divergence at the bay. (b) Photograph of large waves striking a rocky headland. *(Douglas Faulkner/ Photo Researchers, Inc.)*

the steepness of the shoreline (Figure 10.4) and the height and length of waves arriving at the shoreline from a distant storm. *Plunging breakers* tend to be highly erosive at the shoreline, whereas *spilling breakers* are more gentle and may facilitate the deposition of sand on beaches. The large plunging breakers that occur during storms cause much of the coastal erosion we observe.

Beach Form and Beach Processes

A **beach** is a landform consisting of loose material, such as sand or gravel, that has accumulated by wave action at the shoreline. Beaches may be composed of a variety of loose material in the shore zone, the composition of which depends on the environment. For example, many Pacific island beaches include broken bits of shell and coral; Hawaii's black sand beaches are composed of volcanic rock; and grains of quartz and feldspar are found on the beaches of southern California. Figure 10.5 shows the basic terminology of an idealized nearshore environment. The landward extension of the beach terminates at a natural topographic and morphologic change such as a seacliff or a line of sand dunes. The *berms* are flat backshore areas on beaches formed by deposition of sediment as waves rush up and expend the last of their energy. Berms are where you will find people sunbathing. The *beach face* is the sloping portion of the beach below the berm, and the part of the beach face that is exposed by the uprush and backwash of waves is

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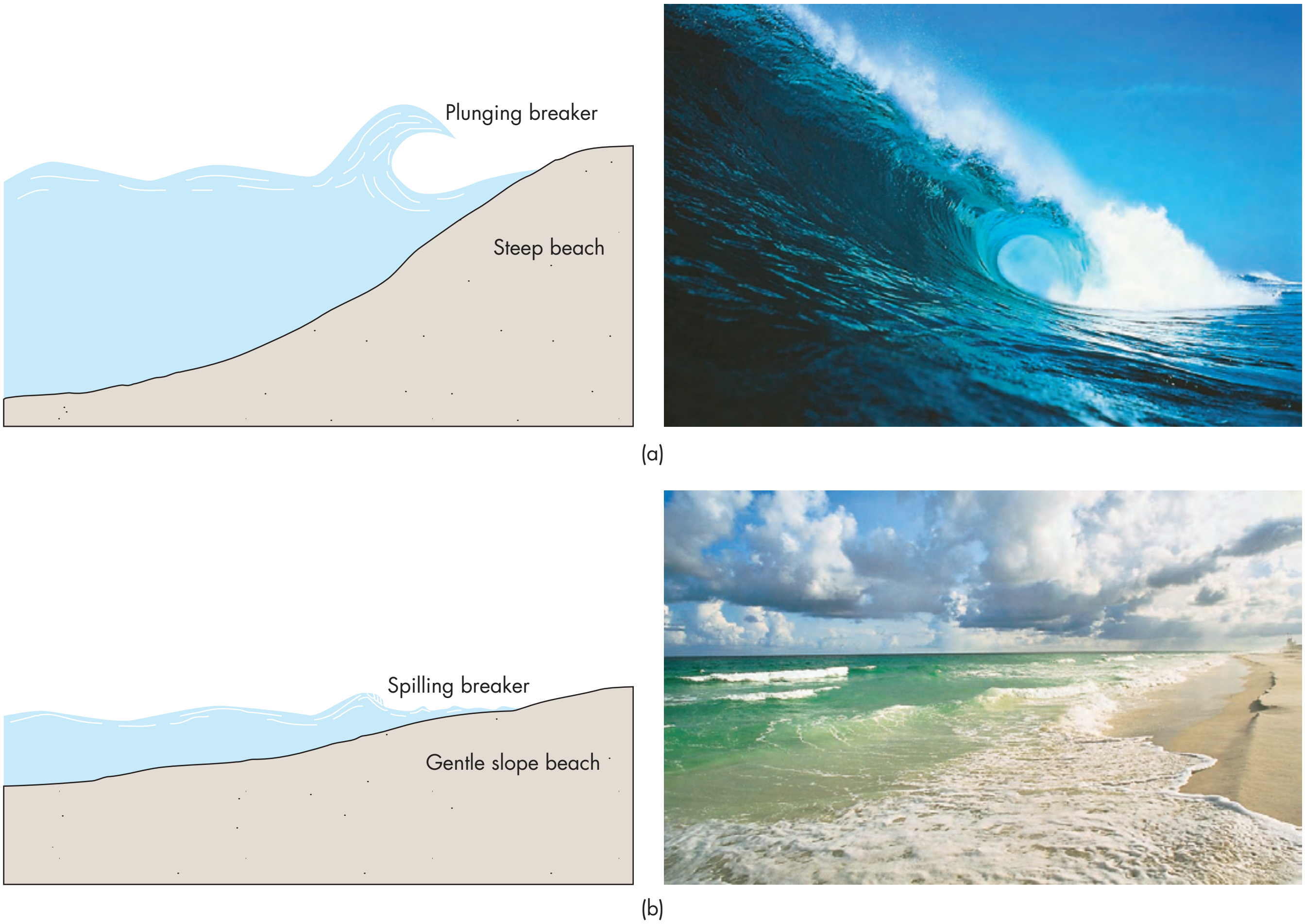

Figure 10.4 **Types of breakers** Idealized diagram and photographs showing (a) plunging breakers on a steep beach and (b) spilling breakers on a gently sloping beach. *([a] Peter Cade/Getty Images Inc.; [b] Penny Tweedie/Getty Images Inc.)*

called the *swash zone.* The *surf zone* is that portion of the seashore environment where turbulent translational waves move toward the shore after the incoming waves break; the *breaker zone* is the area where the incoming waves become unstable, peak, and break. The *longshore trough* and *longshore bar* are an elongated depression and adjacent ridge of sand produced by wave action. A particular beach, especially if it is wide and gently sloping, may have a series of longshore bars, longshore troughs, and breaker zones.[4]

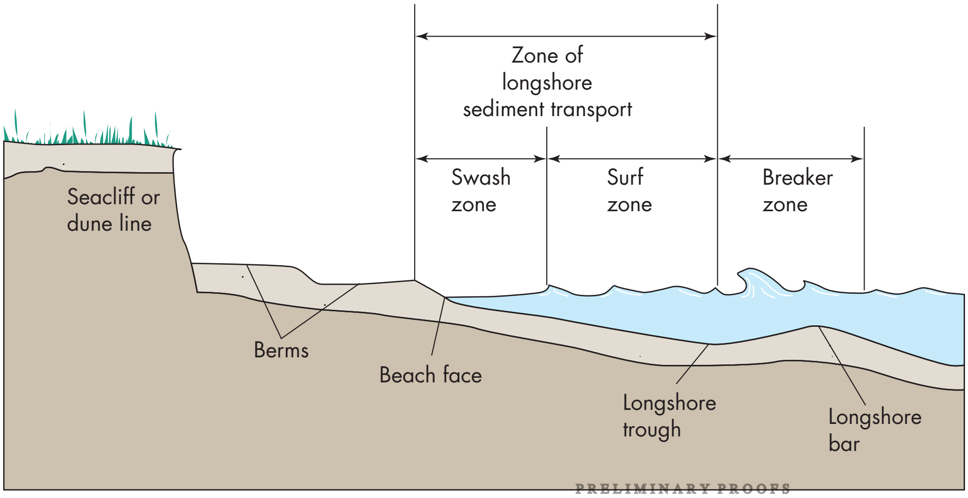

Figure 10.5 **Beach terms** Basic terminology for landforms and wave action in the beach and nearshore environment.

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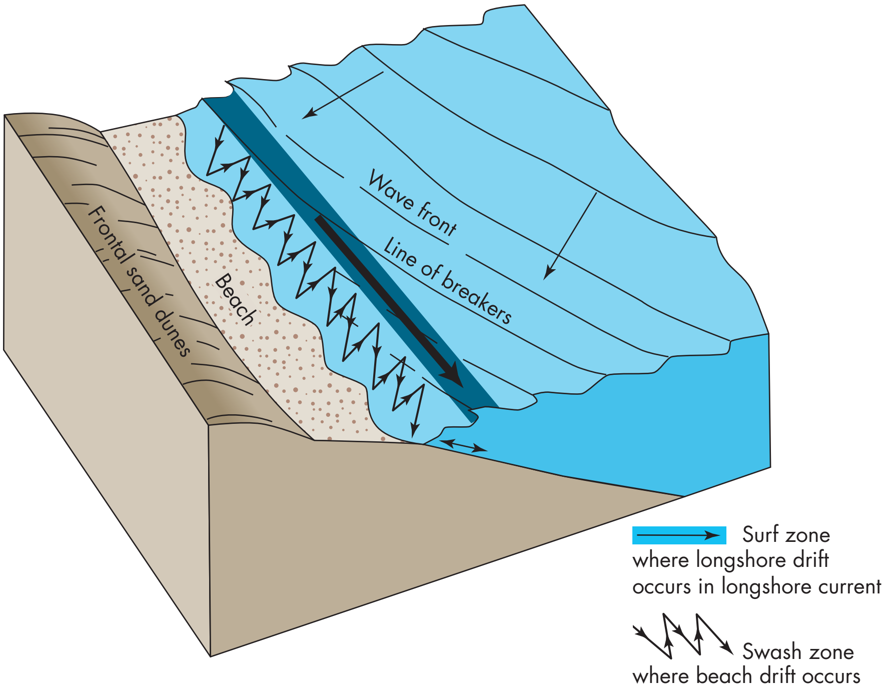

Figure 10.6 **Transport of sediment along a coast** Block diagram showing the processes of beach drift and longshore drift, which collectively move sand along the coast in a process known as longshore sediment transport. Sediments transported in the swash zone and surf zone follow paths shown by the arrows.

Transport of Sand

The sand on beaches is not static; wave action keeps the sand moving along the beach in the surf and swash zones. A longshore current is produced by incoming waves striking the coast at an angle (Figure 10.6). Because the waves strike the coast at an angle, a component of wave energy is directed along the shore. If waves arrive at a beach perfectly parallel to the beach, then no longshore current is generated. The longshore current is a stream of water flowing parallel to the shore in the surf zone. This current can be surprisingly strong. If you are swimming on a beach and wading in and out of the surf zone, you may notice that the longer you go in and out through the surf zone the further away you are from where you started and left your beach towel and umbrella. As you move in and out through the surf and swash zone, the current will move you along the coast, and the sand is doing exactly the same thing.

The process that transports sand along the beach, called **longshore sediment transport,** has two components: (1) Sand is transported along the coast with the longshore current in the surf zone; and (2) the up-and-back movement of beach sand in the swash zone causes the sand to move along the beach in a zigzag path (Figure 10.6). Most of the sand is transported in the surf zone by the longshore current.

The direction of transport of sand along beaches in the United States is generally from the north to the south for beaches on both the East and West Coasts of the country. Although most of the transport is to the south, it can be variable and depends upon the wave action and in which direction they strike the shore. The amount of sand transported along a beach, whether we are talking about Long Island, New York, or Los Angeles, California, is surprisingly large, at several hundred thousand cubic meters of sediment per year. Having said this, the amount of sand transported on a given day or period of days is extremely variable. On many days little sand is being transported and on others the amount is much larger. Most of the sediment is transported during storms by the larger waves.

Rip Currents

When a series of large waves arrives at a coastline and breaks on the beach, the water tends to pile up on the shore. The water does not return as it came in, along the entire shoreline, but is concentrated in narrow zones known as **rip currents**

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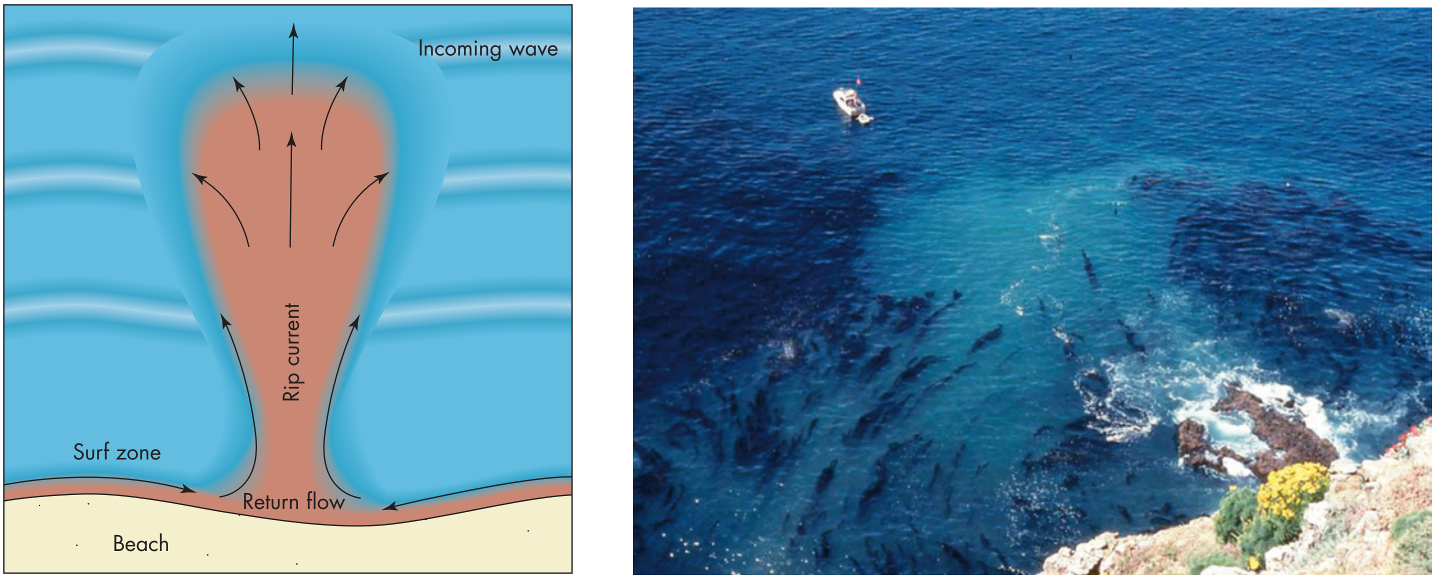

(a)

(b)

Figure 10.7 **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. (b) Rip current at Santa Cruz Island, CA. The floating kelp shows the rip current. *(Edward A. Keller)*

(Figure 10.7). Beachgoers and lifeguards call them riptides or undertow. They certainly are not tides, and they do not pull people under the water, but they can pull people off shore. In the United States, up to 200 people are killed and 20,000 people are rescued from rip currents each year. Therefore, rip currents constitute a serious coastal hazard to swimmers, killing more people in the United States on an annual basis than do hurricanes or earthquakes; the number of deaths caused by rip currents is equivalent to the number caused by river flooding. People drown in rip currents because they do not know how to swim or because they panic and fight the current by trying to swim directly back to shore. Winning a fight with a rip current is nearly impossible because the current can exceed 6 km per hour (4 mi per hour), a speed that 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. Fortunately, rip currents are usually relatively narrow, a few meters to a few tens of meters wide, and they dissipate outside of the surf zone, within tens to hundreds of meters offshore. 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. 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. You may see the current as a mass of water moving out through the surf zone. The water in the current may also be darker, carrying suspended sediment. Remember, if you do get caught in a rip current, don't panic; swim parallel to the shore until you are outside the current, then head back to the beach. If there are lifeguards in the area, yell for assistance!

10.3 Coastal Erosion

As a result of the global rise in sea level and inappropriate development in the coastal zone, coastal erosion is becoming recognized as a serious national and worldwide problem. Coastal erosion is generally a more continuous, predictable process than other natural hazards such as earthquakes, tropical cyclones, or

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floods, and large sums of money are spent in attempts to control it. If extensive development of coastal areas for vacation and recreational living continues, coastal erosion will certainly become a more serious problem.

Beach Budget

An easy way to visualize beach erosion at a particular beach is to take a **beach-budget** approach. An analogy to the budget is your bank account. You deposit money at regular or not so regular times. Some money is in storage and that's your account balance, and you periodically withdraw funds, which is output. Similarly, we can analyze a beach in terms of input, storage, and output of sand or larger sediment that may be found on the beach. Input of sediment to a beach is by coastal processes that move the sediment along the shoreline (Figure 10.6) or produce sand from erosion of a sea cliff or sand dunes on the upper part of a beach. The sediment that is in storage on a beach is what you see when you visit the site. Output of sediment is that material that moves away from the site by coastal processes similar to those that brought the sediment to the beach. If input exceeds output, then the beach will grow as more sediment is stored and the beach widens. If input and output are relatively equal to one another, the beach will remain in a rough equilibrium at about the same width. If output of sediment exceeds input, then the beach will erode and there will be fewer grains of sediment on the beach. Thus we see the budget represents a balance of sand on the beach over a period of years. Short-term changes in sediment supply due to the attack of storm waves will cause seasonal or storm-related changes to the supply of sediment on a beach. Long-term changes in the beach budget caused by climate change or human impact cause long-term growth or erosion of a beach.

Erosion Factors

The sand on many beaches is supplied to the coastal areas by rivers that transport it from areas upstream, where it has been produced by weathering of quartz- and feldspar-rich rocks. We have interfered with this material flow of sand from inland areas to the beach by building dams that trap the sand. As a result, some beaches have become deprived of sediment and have eroded.

Damming is not the only reason for erosion. For example, beach erosion along the East Coast is a result of tropical cyclones (hurricanes) and severe storms, known as Northeasters or Nor'easters;[3] a rise in sea level; and human interference with natural shore processes.[5] Sea level is rising around the world at the rate of about 2 to 3 mm (0.08 to 0.12 in.) per year, independent of any tectonic movement. Evidence suggests that the rate of rise has increased since the 1940s. The increase is due to the melting of the polar ice caps and thermal expansion of the upper ocean waters, triggered by global warming that is in part related to increased atmospheric carbon dioxide produced by burning fossil fuels. Sea levels could rise by 700 mm (28 in.) over the next century, ensuring that coastal erosion will become an even greater problem than it is today.

Seacliff Erosion

When a **seacliff** (a steep bluff or cliff) is present along a coastline, additional erosion problems may occur because the seacliff is exposed to both wave action and land erosion processes such as running water and landslides. These processes may work together to erode the cliff at a greater rate than either process could alone. The problem is further compounded when people interfere with the seacliff environment through inappropriate development.

Figure 10.8 shows a typical southern California seacliff environment at low tide. The rocks of the cliff are steeply inclined and folded shale. A thin veneer of sand and coarser material, such as pebbles and boulders, near the base of the cliff covers the wave-cut platform, which is a nearly flat bench cut into the bedrock by wave action. A mantle of sand approximately 1 m (3.3 ft) thick covers the beach during the summer, when long, gentle, spilling breakers construct a wide berm

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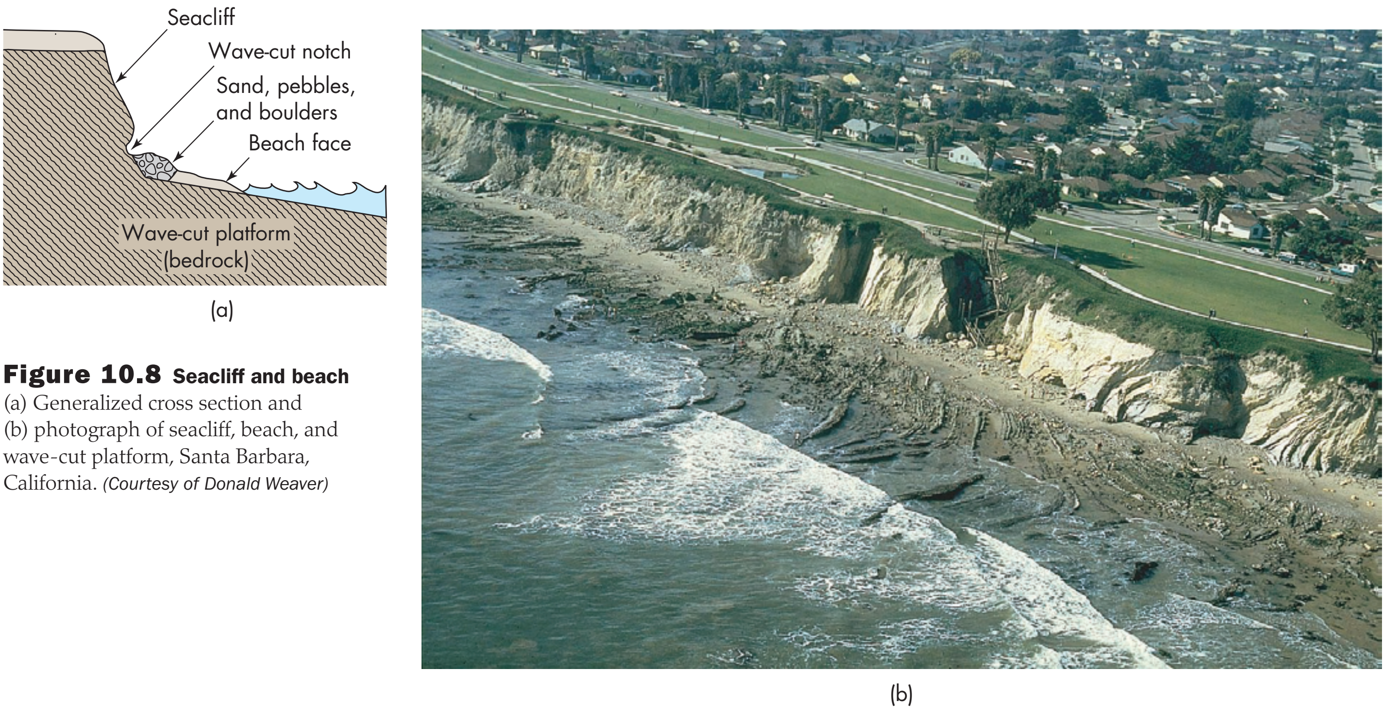

Figure 10.8 **Seacliff and beach** (a) Generalized cross section and (b) photograph of seacliff, beach, and wave-cut platform, Santa Barbara, California. *(Courtesy of Donald Weaver)*

while protecting the seacliff from wave erosion. During the winter, plunging breakers, which have a high potential to erode beaches, remove the mantle of sand and expose the base of the seacliff. Thus, it is not surprising that most erosion of the seacliffs in southern California takes place during the winter.

A variety of human activities can induce seacliff erosion. Urbanization, for example, results in increased runoff. If the runoff is not controlled, carefully collected, and diverted away from the seacliff, serious erosion can result. Drainpipes that dump urban runoff from streets and homes directly onto the seacliff increase erosion. Drainpipes that route runoff to the base of the seacliff on the face of the beach result in less erosion (Figure 10.9a). Watering lawns and gardens on top of a seacliff may add a good deal of water to the slope. This water tends to migrate downward through the seacliff toward the base. When water emerges as small

Figure 10.9 **Seacliff erosion** (a) The pipe in this photograph, from the early 1990s, carries surface runoff from the top of the seacliff down to the beach. Notice that the house at the top of the seacliff has a layer of cement partway down the cliff. The purpose of the cement is to retard erosion. (b) The same location in 2001. Note the landslide that has occurred, removing some of the cement and rock of the seacliff. *(Edward A. Keller)*

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Figure 10.10 Students living on the edge Apartment buildings on the edge of the seacliff 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 because it is overhanging the cliff by at least 1 m (3.3 ft). Notice the exposed cement pillars in the seacliff, which were intended to help support the houses. These decks and apartment buildings are in imminent danger of collapsing into the sea. *(Edward A. Keller)*

seeps or springs from a seacliff, it effectively reduces the stability of the seacliff, facilitating erosion, including landslides (Figure 10.9b).[6]

Structures such as walls, buildings, swimming pools, and patios near the edge of a seacliff may also decrease stability by adding weight to the slope, increasing both small and large landslides (Figure 10.10). 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.

The rate of seacliff erosion is variable, and few measurements are available. Near Santa Barbara, California, the rate of seacliff erosion averages 15 to 30 cm (6 to 12 in.) per year. These erosion rates are moderate compared with those in other parts of the world. Along the Norfolk coast of England, for example, erosion rates in some areas are about 2 m (6.6 ft) per year. The rate of erosion is dependent on the resistance of the rocks and the height of the seacliff.[6] The rate of coastal erosion can be determined by a new remote sensing technique (see A Closer Look: Measuring Coastal Change).

Seacliff erosion is a natural process that cannot be completely controlled unless large amounts of time and money are invested, and even then there is no guarantee that erosion will cease. Therefore, it seems we must learn to live with some erosion. It can be minimized by applying sound conservation practices, such as controlling the water on and in the cliff and not placing homes, walls, large trees, or other structures that contribute to driving forces close to the top edge of a cliff.

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A CLOSER LOOK | Measuring Coastal Change

Technology has recently provided a remote sensing method of measuring and monitoring changes in the coastal environment. Light Detection and Ranging (LIDAR) is an aircraft-mounted laser system that can record several thousand elevation measurements per second, with vertical resolution of better than 15 cm (6 in.). Once a baseline set of elevations is recorded, subsequent flights can detect changes in the coastal zone such as change in shape of the beach coastal dunes or seacliff. Figure 10.A shows a digital elevation model determined by LIDAR for the Hilton Head, South Carolina, coastal area in the vicinity of a hotel which is very close to the active beach. Figure 10.B shows the seacliff environment near Pacifica, California, where 12 homes were condemned as unsafe following winter storms in early 1998. The amount of seacliff erosion from LIDAR from October 1997 to April 1998 is shown on Figure 10.C. Total erosion was about 10 m (30 ft) landward and a meter or two on the beach.

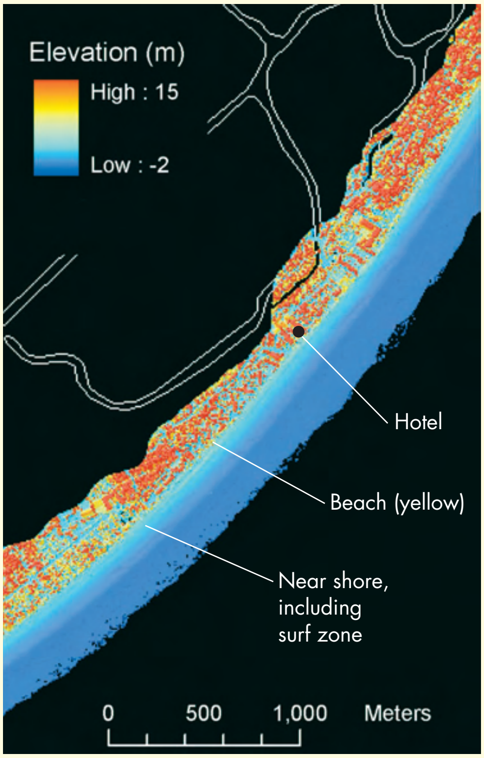

Figure 10.A **Coastal Topography** Digital elevation map of part of Hilton Head, South Carolina. Data from Light Detection and Ranging (LIDAR), an aircraft mounted laser remote sensing technique. The hotel is very close to the beach source—modified from NOAA. *(http://www.csc.noaa.gov/products/sccoasts/html/tutlid.htm)*

Figure 10.B **Severe coastal erosion** near Pacifica, California, that occurred early in 1998. *(Courtesy of Monty Hampton, USGS http://coastal.er.usgs.gov/lidar/AGU_fall98/)*

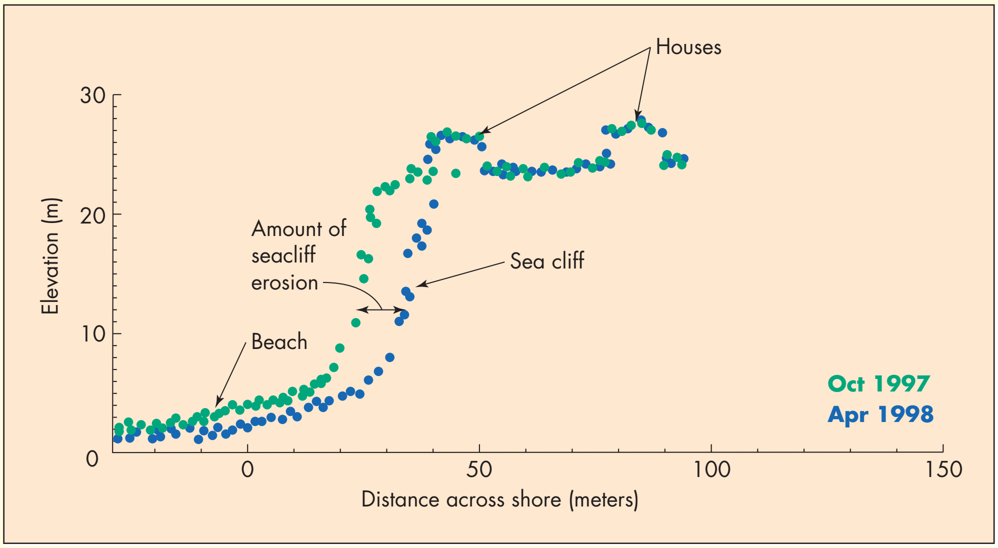

Figure 10.C **About 10 meters (30 ft) of seacliff erosion** near Pacifica, California (LIDAR data). Several houses were condemned and seven were torn down. *(Modified after USGS 1998 http://coastal.er.usgs.gov/lidar/AGU_fall98)*

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10.4 Coastal Hazards and Engineering Structures

Efforts to stabilize a beach can be generalized into three approaches.

- Hard stabilization: Engineering structures to protect a shoreline from waves
- Soft stabilization: Adding sand to a beach (beach nourishment)
- Managed retreat: Living with beach erosion with perhaps a mixture of hard and soft stabilization

Hard Stabilization

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

Seawalls. **Seawalls** are structures constructed parallel to the coastline to help retard erosion. They may be constructed of concrete, large stones, wood, or other materials. Seawalls constructed at the base of a seacliff may not be particularly effective; considerable erosion of the seacliff results from mass-wasting processes on the cliff itself (see Figure 10.9b) as well as wave erosion at the base. Seawall use has been criticized because seawalls are often vertical structures that reflect incoming waves, or bounce them back from the shore. The reflection of waves enhances beach erosion and over several decades produces a narrower beach with less sand. Unless carefully designed to complement existing land uses, seawalls generally cause environmental and aesthetic degradation. Seawalls, in addition to causing a narrowing of a beach, may result in a reduction in biodiversity of the beach ecosystem (see Chapter 4). The design and construction of seawalls must be carefully tailored to specific sites. Some geologists believe that seawalls cause more problems than they solve and should be used rarely, if ever.[7]

Groins. **Groins** are linear structures placed perpendicular to the shore, usually in groups called *groin fields* (Figure 10.11). Each groin is designed to trap a portion of the sand that moves in the littoral transport system. A small accumulation of sand will develop updrift of each groin, thus building an irregular but wider beach. The wider beach protects the shoreline from erosion.

However, there is an inherent problem with groins: Although deposition occurs updrift of a groin, erosion tends to occur in the downdrift direction. Thus, a groin or a groin field results in a wider, more protected beach in a desired area but may cause a zone of erosion to develop in the adjacent downcoast shoreline. The erosion results because as a groin traps sediment on its updrift side, the downdrift area is deprived of sediment. 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. This process, known as **beach nourishment,** requires extracting sand from the ocean or other sources and placing it onto the beach. When nourished, the groins will draw less sand from the natural littoral transport system, and the downdrift erosion will be reduced.[4] Despite beach nourishment and other precautions, groins may still cause undesirable erosion; therefore, their use should be carefully evaluated.

Breakwaters. Breakwaters and jetties protect limited stretches of the shoreline from waves. **Breakwaters** are designed to intercept waves and provide a protected area, or harbor, for boat moorings; they may be attached to, or separated from, the beach (Figure 10.12a, b). In either case, a breakwater blocks the natural littoral transport of beach sediment, causing the configuration of the coast to

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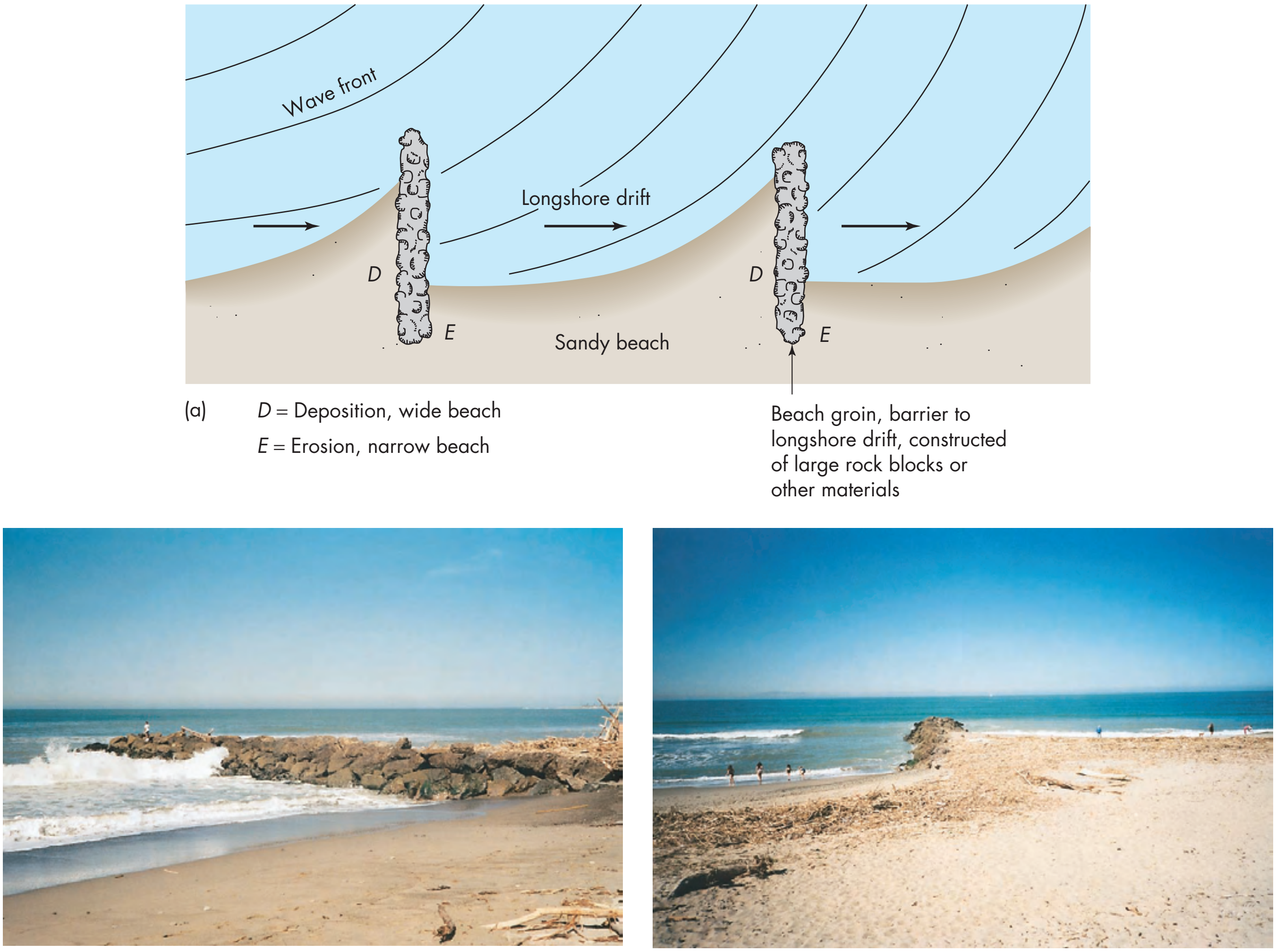

(b)

(c)

Figure 10.11 **Beach groins** (a) Diagram of two beach groins. (b) Closeup of downdrift zone of erosion. (c) Updrift deposition (right) and downdrift erosion (left). Deposited sediment builds a wide beach in the updrift direction; in the downdrift direction, the sparse amount of sediment for transport can cause erosion. *(Edward A. Keller)*

change locally as new areas of deposition and erosion develop. In addition to possibly causing serious erosion problems in the downdrift direction, breakwaters act as sand traps that accumulate sand in the updrift direction. Eventually the trapped sand may fill or block the entrance to the harbor as a deposit called a *sand spit* or *bar* develops. As a result, a dredging program, with an *artificial bypass,* is often necessary to keep the harbor open and clear of sediment. The sand that is removed by dredging, unless it is polluted, is transported in a pipe with water and released on the beach downdrift of the breakwater to rejoin the natural littoral transport system, thus reducing the erosion problem. It is the transport of the sand from the site where it is dredged to the downdrift location that is referred to as an artificial bypass.

Jetties. **Jetties** are often constructed in pairs at the mouth of a river or inlet to a lagoon, estuary, or bay (Figure 10.12c). They are designed to stabilize the channel, prevent or minimize deposition of sediment in the channel, and generally protect it from large waves.[4] Jetties tend to block the littoral transport of beach sediment, thus causing the updrift beach adjacent to the jetty to widen while downdrift beaches erode. The deposition at jetties may eventually fill the channel, making it useless,

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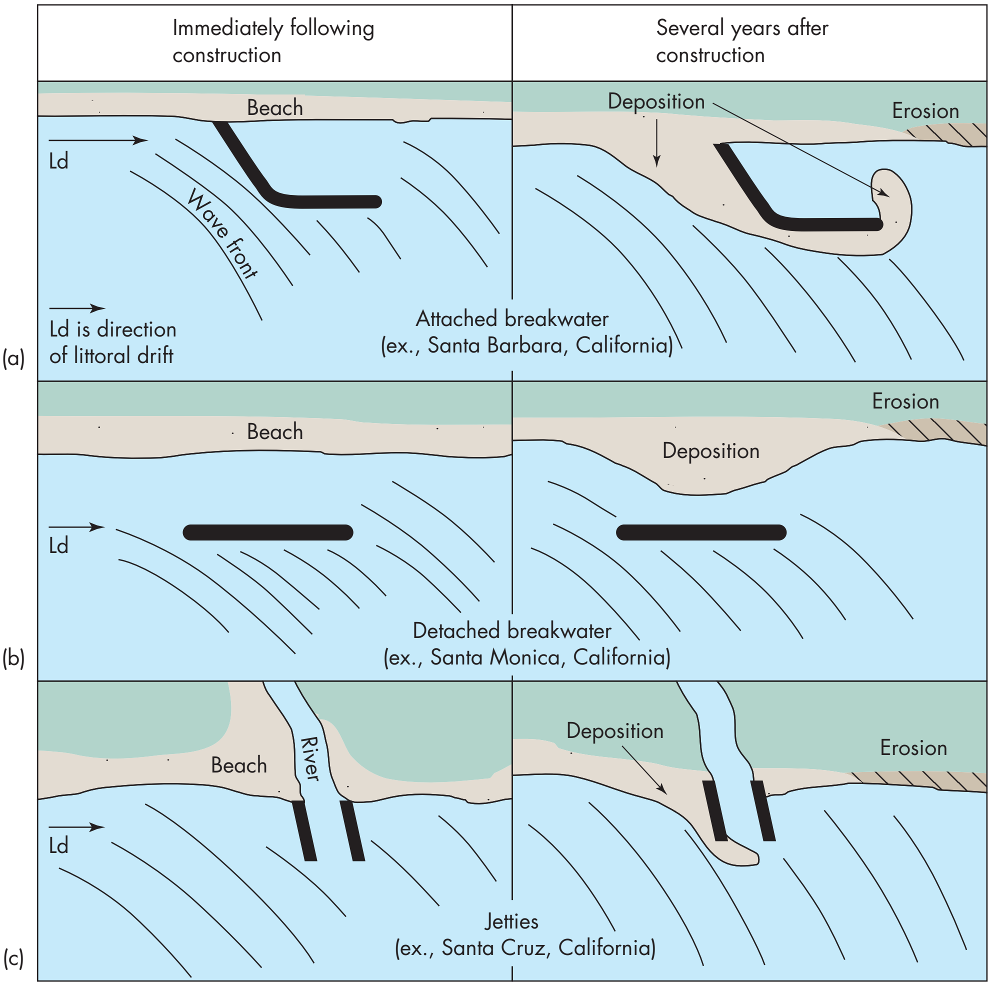

Figure 10.12 Engineering structures constructed in the surf zone cause change Diagrams illustrating the effects of breakwaters and jetties on local patterns of deposition and erosion.

while downcoast erosion damages coastal development. Dredging the sediment minimizes but does not eliminate all undesirable deposition and erosion.

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 must incorporate protective measures that eliminate or at least minimize adverse effects. These protective measures may include installation of a dredging and artificial sediment-bypass system, a beach nourishment program, seawalls, riprap (large rocks), or some combination of these.[4]

Soft Stabilization

Beach Nourishment: An Alternative to Engineering Structures. In the discussion above, we introduced the topic of beach nourishment as an adjunct to engineering structures in the coastal zone. Beach nourishment can also be 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*. When you budget your money you probably hope for a positive budget, allowing you some extra cash. Similarly, a positive beach budget means that when all the sand that enters and leaves the beach is accounted for, there is enough sand left to maintain the beach itself. Beach nourishment is sometimes referred to as "soft" stabilization to control beach erosion, as contrasted with "hard" stabilization, such as constructing groins or seawalls. Ideally, the presence of the nourished beach protects coastal property from the attack of waves.[4] The procedure has distinct advantages: It is aesthetically preferable to many engineering

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Figure 10.13 **Beach nourishment** Miami Beach (a) before and (b) after beach nourishment. *(Courtesy of U.S. Army Corps of Engineers)*

structures, and it provides a recreation beach as well as some protection from shoreline erosion.

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 a serious beach erosion problem that had plagued the area since the 1950s. The program was also intended to provide protection from storms. The natural beach had nearly disappeared by the 1950s, and only small pockets of sand could be found associated with various shoreline protection structures, including seawalls and groins. As the beach disappeared, coastal resort areas, including high-rise hotels, became vulnerable to storm erosion.[8] The nourishment program was designed to produce a positive beach budget, which would widen the beach and provide additional protection from storm damage. The project cost approximately $62 million over 10 years and involved nourishment of about 160,000 m^3 (209,300 yd^3) of sand per year to replenish erosion losses. By 1980, about 18 million m^3 (23.5 million yd^3) of sand had been dredged and pumped from an offshore site onto the beach, producing a 200 m wide (656 ft wide) beach.[8] Figure 10.13 shows Miami Beach before and after the nourishment. The change is dramatic.

A cross-sectional design of the project shows the wide berm and frontal dune system, which is a line of sand dunes just above the high-tide line that functions as a buffer to wave erosion and storm surge (Figure 10.14). The Miami project was expanded in the mid- to late 1980s to include dune restoration, which involved establishing native vegetation on the dune. Special wooden walkways allow public access through the dunes while other areas of the dunes are protected. The successful Miami Beach nourishment project has functioned for more than 20 years, surviving major hurricanes in 1979 and 1992,[4] and is certainly preferable to the fragmented erosion-control methods that preceded it.

More than 600 km (373 mi) of coastline in the United States have received some sort of beach nourishment. Not all of 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. After a series of storms that struck the beach, the sand was eroded in just two and a half months. The beach sands at Miami may be eroded at a much greater cost. Beach nourishment remains

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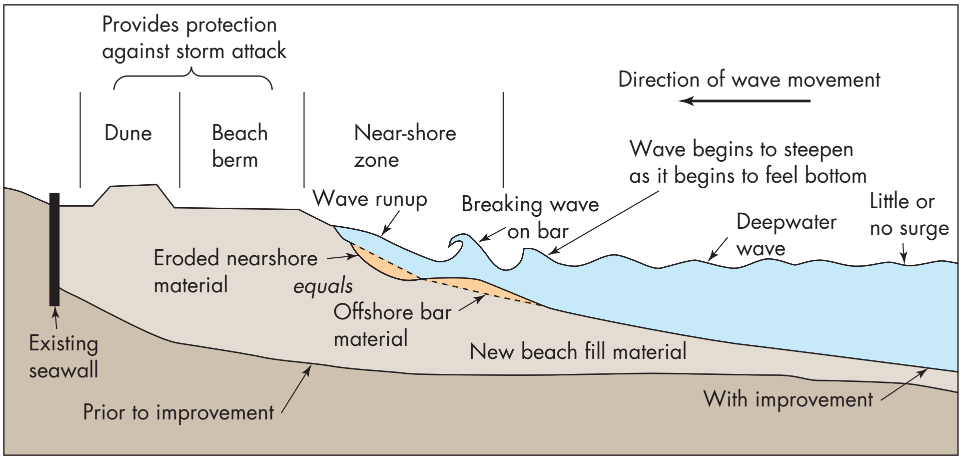

Figure 10.14 **Miami Beach shape after nourishment** Cross section of the Miami Beach nourishment project. The dune and beach berm system provide protection against storm attack. *(Courtesy of U.S. Army Corps of Engineers)*

controversial, and some consider beach nourishment nothing more than "sacrificial sand" that will eventually be washed away by coastal erosion.[7] Miami Beach is an exception with respect to its apparent success and our discussion oversimplifies positive aspects of nourishment. The annual cost to nourish Miami Beach is about $3 million. Over 20 million tourist visit the beach each year. Foreign tourism alone brings in about $2 billion per year, over 650 times the cost of the nourishment.

Important issues of finding sand compatible with the site, how the nourishment will be paid for, and possible disruption of beach ecosystems must be carefully evaluated prior to any nourishment project. 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. Also needed is more public education to inform people of what can be expected from beach nourishment.[4]

10.5 Human Activity and Coastal Erosion: Some Examples

Human interference with natural shore processes has caused considerable coastal erosion. Most problems arise in areas that are highly populated and developed. As we have discussed, artificially constructed barriers often retard the movement of sand, causing beaches to grow in some areas and erode in others, resulting in damage to valuable beachfront property.

The Atlantic Coast

The Atlantic Coast from northern Florida to New York is characterized by *barrier islands*, long narrow islands separated from the mainland by a body of water (Figure 10.15). Many barrier islands have been altered to a lesser or greater extent by human use and interest.

The barrier island coast of Maryland illustrates some effects of human activity on coastal processes. Demand for the 50 km (30 mi) of Atlantic oceanfront beach in Maryland is very high, and the limited resource is used seasonally by residents of Washington, D.C., and Baltimore, Maryland (Figure 10.16). Since the early 1970s, Ocean City on Fenwick Island has promoted high-rise condominium and hotel development on its waterfront. The natural frontal dune system of this narrow island has been removed in many locations, resulting in a serious beach erosion problem. Even more ominous is the almost certain possibility that a future hurricane will cause serious damage to Fenwick Island. The Ocean City inlet found to the south of Ocean City formed during a hurricane in 1933. There is no guarantee, despite attempts to stabilize the inlet by coastal engineering, that a new inlet will not form, destroying, by erosion, part of Ocean City in the future.[9]

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Figure 10.15 **The Outer Banks** of North Carolina appear in this image from the *Apollo 9* as a thin white ribbon of sand. The Barrier Islands are separated from the mainland by the Pamlico Sound. The brown color in the water is the result of sediment suspended in the water moving within the coastal system. Notice the fan-shaped plume of sediment just seaward of Ocracoke Inlet. The distance from Cape Lookout to Cape Hatteras is approximately 100 km (62 mi). *(National Aeronautics and Space Administration)*

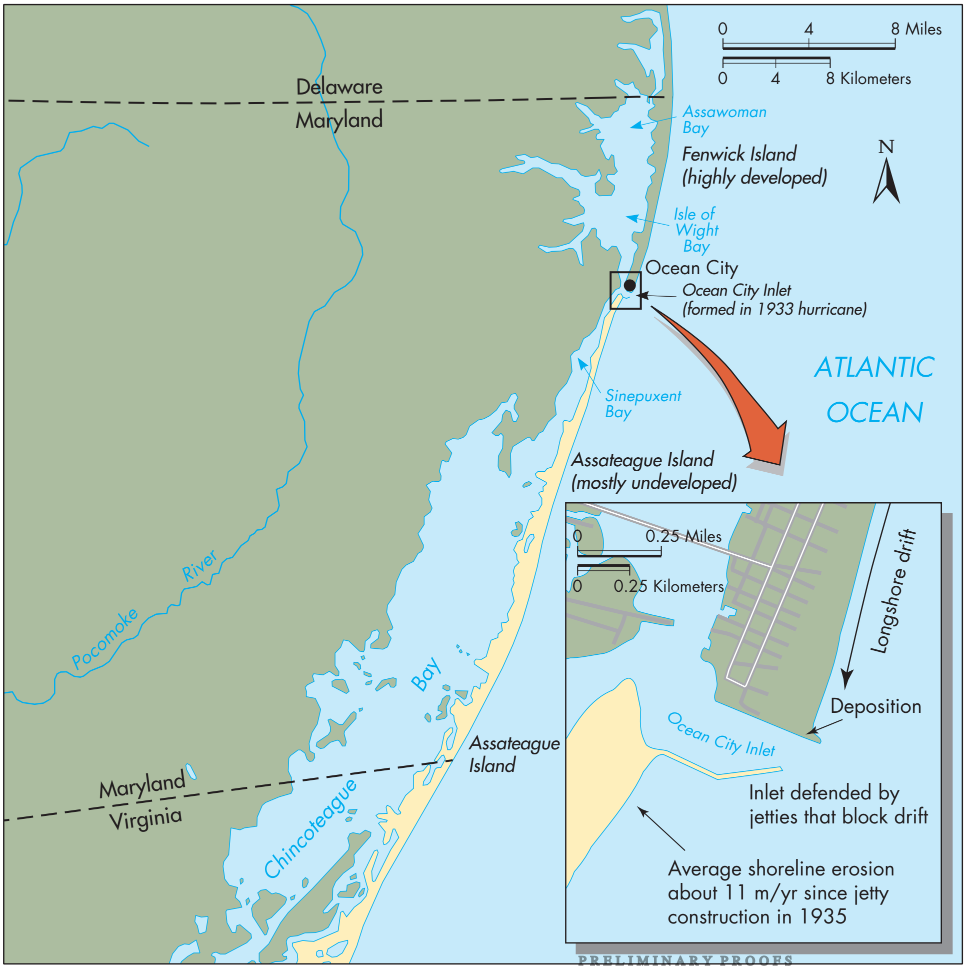

Figure 10.16 **Urban development with jetty construction increases beach erosion** The barrier island coast of Maryland. Fenwick Island is experiencing rapid urban development, and there is concern for potential hurricane damage. What will happen if a new inlet forms during a hurricane at the site of Ocean City? The inset shows details of the Ocean City inlet and effects of jetty construction.

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Assateague Island is located to the south, across the Ocean City inlet. It encompasses two-thirds of the Maryland coastline. In contrast to the highly urbanized Fenwick Island, Assateague Island is in a much more natural state. The island is used for passive recreation such as sunbathing, swimming, walking, and wildlife observation. However, the two islands are in the same littoral cell, meaning they share the same sand supply. At least, that was the case until 1935, when the jetties were constructed to stabilize the Ocean City inlet. Since construction of the jetties, coastal erosion in the northern few kilometers of Assateague Island has averaged about 11 m (36 ft) per year, which is 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.[10]

Observed changes on Maryland's Atlantic coast are clearly related to the pattern of longshore drift of sand and human interference. Longshore drift is to the south at an average annual volume of about 150,000 m^3 (196,500 yd^3). Construction of the Ocean City inlet jetties interfered with the natural southward flow of sand and diverted it 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 that block longshore transport of sediment has been cited as the most severe that can be found in the United States.[10] Thus, the fundamental principle involving environmental unity holds: Earth is a system, a set of components that function together as a whole; a change in one part of the system affects all other parts.

The Gulf Coast

Coastal erosion is also a serious problem along the Gulf of Mexico. One study in the Texas coastal zone suggests that in the last 100 years, human modification of the coastal zone has accelerated coastal erosion by 30 percent to 40 percent over prehistoric rates.[11] The human modifications that appear most responsible for the accelerated erosion are coastal engineering structures, subsidence as a result of groundwater and petroleum withdrawal, and damming of rivers that supply sand to the beaches.

The Great Lakes

Erosion is a periodic problem along the coasts of the Great Lakes and has been particularly troublesome along the Lake Michigan shoreline. Damage is most severe during prolonged periods of high lake levels that follow extended periods of above-normal precipitation. The relationship between precipitation and lake level has been documented since 1860 by the U.S. Army Corps of Engineers. The data show that the lake level has fluctuated about 2 m (6.6 ft) during this time. During a high-water stage, there is considerable coastal erosion, and many buildings, roads, retaining walls, and other structures are destroyed by wave erosion (Figure 10.17).[12] For example, in 1985 high lake levels due to fall storms caused an estimated \$15 million to \$20 million in damage.

During periods of below-average lake level, wide beaches develop that dissipate energy from storm waves and protect the shore. However, with rising lake-level conditions, the beaches become narrow, and storm waves exert considerable energy against coastal areas. Even a small lake-level rise on a gently sloping shore will inundate a surprisingly wide section of beach.[12]

Cliffs along the shores of lakes are referred to as coastal bluffs and are analogous to the seacliffs of the ocean shoreline. Long-term rates of coastal bluff erosion at many Lake Michigan sites average about 0.4 m (1.3 ft) per year.[13] The severity of erosion at a particular site depends on many factors:

- Presence or absence of a frontal dune system. Dune-protected bluffs erode at a slower rate.

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Figure 10.17 Lakes have coastal erosion problems Coastal erosion along the shoreline of Lake Michigan has destroyed this home. *(Steve Leonard/Getty Images, Inc.)*

- Orientation of the coastline. Sites exposed to high-energy storm winds and waves erode faster.
- Groundwater seepage. Seepage along the base of a coastal bluff causes slope instability, increasing the erosion rate.
- Existence of protective structures. Structures may be locally beneficial but often accelerate coastal erosion in adjacent areas.[12,13]

In recent years, beach nourishment has been attempted for some Great Lakes beaches. In some cases, sands that are coarser than the natural sands that had eroded have been added in the hope that the coarser, heavier sand will reduce the erosion potential.

10.6 Tropical Cyclones

Tropical cyclones are known as *typhoons* in most of the Pacific Ocean and **hurricanes** in the Atlantic. Tropical cyclones have taken hundreds of thousands of lives in a single storm. In November 1970, a tropical cyclone struck the northern Bay of Bengal in Bangladesh, producing a 6 m (20 ft) rise in the sea. Flooding caused by this sea-level rise killed approximately 300,000 people, caused $63 million in crop losses, and destroyed 65 percent of the total fishing capacity of the coastal region.[14] Another devastating cyclone hit Bangladesh in the spring of 1991, killing more than 100,000 people while causing more than $1 billion in damage. Hurricane Mitch, known as the deadliest Atlantic hurricane since 1780, was responsible for more than 11,000 deaths in Honduras and Nicaragua in 1998, and Hurricane Katrina in 2005 caused nearly 2,000 deaths with damages of about $100 billion to New Orleans and the Gulf Coast (see Chapter 5).

Hurricane Form and Process

The origin for the word *hurricane* possibly comes from a Caribbean Indian word for "big wind" or "evil spirit." They certainly fit the bill for the big wind! To be called a hurricane, the storm must have sustained winds of at least 119 km/hr (74 mph). Hurricanes are a variation of the tropical cyclone, which is the general term for a huge, complex series of thunderstorms that rotate around an area of low pressure, forming over warm, tropical ocean water.

Hurricanes begin as tropical disturbances, which are large areas of unsettled weather with a diameter as large as 600 km (370 mi). Within this area, there exists an

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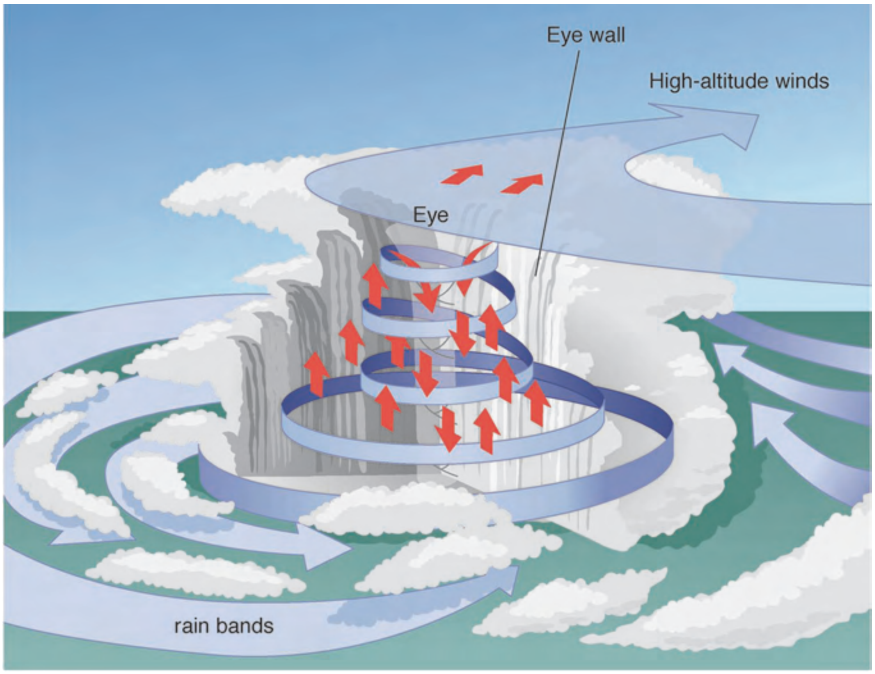

Figure 10.18 **Hurricane form and process** Energy from warm ocean water is transformed into the storm, which may have a diameter of 600 km (370 mi). Main components are rotating bands of thunderstorms; rising warm air around an eye of clear sky with subsiding air; and the eye wall as the boundary between the rotating rain bands and eye.

organized mass of thunderstorms with a general low pressure in which there is initial rotation caused by the movement of the storm and rotation of Earth. A tropical depression may grow in size and strength as warm, moist air is drawn into the depression and begins to rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The process that increases the intensity of the storm is caused by warm water that evaporates from the sea and is drawn into the storm. As this process occurs, the energy of the storm increases. As warm seawater evaporates, it is transformed from liquid water in the sea to water vapor (gas) in the air mass of the storm. When this happens, potential energy in the form of *latent heat* enters the storm. Latent heat of water is the amount of heat required to change liquid water to water vapor. Latent heat is one of the major sources of the power (time rate of energy expenditure) of a hurricane. As the moist air rises, condensation (rain) occurs as the latent heat is released, warming the air and making it lighter. As the lighter air rises, more energy from warm water is drawn in and the storm may increase in size, strength, and intensity. If wind speeds in the storm reach 63 km (39 mi), then the depression is called a tropical storm and receives a name.

Hurricanes are very high energy storms. Their size can be huge by human standards. It is not unusual to observe on satellite images a hurricane moving toward the United States that has an area nearly the size of the Gulf of Mexico, stretching from Florida to Texas and beyond.

A generalized diagram of a hurricane and the processes that occur within it are shown in Figure 10.18. The hurricane has bands of spinning storms and thunder cells with an eye where air is subsiding in the center around what is called the eye wall. As the moist air rotates within the storm, intense rain bands are produced. When a hurricane moves across an island, it is deprived of some of its energy and often weakens. When a hurricane makes landfall on a continent and moves inland, it weakens and eventually dies, but the storm and rainfall can cause serious river flooding well inland. The intense rainfall on slopes may well generate numerous landslides, producing an additional hazard.

Hurricanes are classified based upon their size and intensity. Table 10.1 is the Saffir-Simpson Hurricane Scale. It is used to estimate potential wind damage and flooding. There are five categories, with Category One being the smallest and Category Five the largest. Category Five hurricanes are capable of producing catastrophic damage, but even a Category One storm is a very serious and dangerous event.

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TABLE 10.1 The Saffir-Simpson Hurricane Scale

The Saffir-Simpson Hurricane Scale is a 1 to 5 rating based on the hurricane's present intensity. This is used to give an estimate of the potential property damage and flooding expected along the coast from a hurricane landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf in the landfall region, where the hurricane is expected to come on land.

Category One Hurricane	Winds 119 to 153 km/hr (74–95 mph). Storm surge generally 1.2 to 1.5 m (4 to 5 ft) above normal. No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some damage to poorly constructed signs. Also, some coastal road flooding and minor pier damage. Hurricanes Allison of 1995 and Danny of 1997 were Category One hurricanes at peak intensity.
Category Two Hurricane	Winds 154 to 177 km/hr (96 to 110 mph). Storm surge generally 1.8 to 2.4 m (6 to 8 ft) above normal. Some roofing material, door, and window damage of buildings. Considerable damage to shrubbery and trees, with some trees blown down. Considerable damage to mobile homes, poorly constructed signs, and piers. Coastal and low-lying escape routes flood 2 to 4 hours before arrival of the hurricane center. Small craft in unprotected anchorages break moorings. Hurricane Bonnie of 1998 was a Category Two Hurricane when it hit the North Carolina coast; Hurricane George of 1998 was a Category Two Hurricane when it hit the Florida Keys and the Mississippi Gulf Coast.
Category Three Hurricane	Winds 178 to 209 km/hr (111 to 130 mph). Storm surge generally 2.7 to 3.7 m (9 to 12 ft) above normal. Some structural damage to small residences and utility buildings, with a minor amount of wall failures. Damage to shrubbery and trees, with foliage blown off trees and large trees blown down. Mobile homes and poorly constructed signs are destroyed. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Flooding near the coast destroys smaller structures, and larger structures are damaged by battering by floating debris. Terrain continuously lower than 1.5 m (5 ft) above mean sea level may be flooded inland 13 km (8 mi) or more. Evacuation of low-lying residences within several blocks of the shoreline may be required. Hurricane Roxanne of 1995 was a Category Three hurricane at landfall on the Yucatan Peninsula of Mexico; Hurricane Fran of 1996 was a Category Three hurricane at landfall in North Carolina.
Category Four Hurricane	Winds 210 to 249 km/hr (131 to 155 mph). Storm surge generally 4 to 5.5 m (13 to 18 ft) above normal. More extensive wall failures, with some complete roof structure failures on small residences. Shrubs, trees, and all signs are blown down. Complete destruction of mobile homes. Extensive damage to doors and windows. Low-lying escape routes may be cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of structures near the shore. Terrain lower than 3.1 m (10 ft) above sea level may be flooded, requiring massive evacuation of residential areas as far inland as 10 km (6 mi). Hurricane Luis of 1995 was a Category Four hurricane while moving over the Leeward Islands; Hurricanes Felix and Opal of 1995 also reached Category Four at peak intensity.
Category Five Hurricane	Winds greater than 249 km/hr (155 mph). Storm surge generally greater than 5.5 m (18 ft) above normal. Complete roof failure on many residences and industrial buildings. Some complete building failures, with small utility buildings blown over or away. All shrubs, trees, and signs blown down. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut off by rising water 3 to 5 hours before arrival of the hurricane center. Major damage to lower floors of all structures located less than 4.6 m (15 ft) above sea level and within 458 m (500 yd) of the shoreline. Massive evacuation of residential areas on low ground within 8 to 16 km (5 to 10 mi) of the shoreline may be required. Hurricane Mitch of 1998 was a Category Five hurricane at peak intensity over the western Caribbean. Hurricane Gilbert of 1988 was a Category Five hurricane at peak intensity and is the strongest Atlantic tropical cyclone of record.

Source: Modified after Spindler, T., and Beven, J. 1999. Saffir-Simpson Hurricane Center, National Oceanic and Atmospheric Administration. www.nhc.noaa.gov.aboutsshs.html. Accessed 5/23/01.

We know when a hurricane is coming. Images from satellites and high-altitude aerial photographs show the locations of tropical depressions and tropical storms that we may monitor to see if they will become hurricanes. In order to verify satellite data, special airplanes are flown through storms, recording wind speed, air temperature, and air pressure. Once a hurricane has formed, its continual movement (called its path) is monitored. The paths of four hurricanes in 2005 are shown on Figure 10.19.

As hurricanes get close to landfall, moving over shallower water, they generally slow down. However, if they encounter warmer water, they may actually increase in intensity.

The most dangerous aspect of hurricanes is not the wind itself, although violent winds can be lethal. Often what causes the most flooding and loss of life is the **storm surge,** which arrives with the storm (Figure 10.20). The storm surge is a local rise in sea level that results when hurricane winds push water toward the coast. Storm surges may arrive as a quick rise in sea level or series of waves that may increase water depths near the coast by several meters to more than 10 m (30 ft). Storm surge is generally highest on the part of the rotating storm that pushes landward. For example, along the Gulf Coast, the storm surge and wind speed are higher to the east than west (the right front quadrant of the storm) as the hurricane rotates in a counterclockwise direction. During Hurricane Katrina (see opening Case History in Chapter 5), the storm surge east of New Orleans was significantly higher than in the central or western part of the storm. Should the storm arrive coincidentally with a high tide, then a storm surge of even greater height occurs. Most of the deaths from hurricanes are caused by storm surges as people are drowned or

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Figure 10.19 Paths of four hurricanes in 2005 *(National Hurricane Center)*

struck by solid objects within the surge. When the surge moves ashore, it is not a tall advancing line of water but is more like a continual increase in rise of sea level as a hurricane approaches and makes landfall. Having said this, the actual storm surge in places may well appear as a series of wavelike forms that inundate the land.

Most hurricanes and typhoons form in a belt between 8 degrees north and 15 degrees south of the equator, where warm surface-water temperatures exceed about 27°C (80°F). During an average year, approximately five hurricanes will develop that might threaten the Atlantic and Gulf Coasts. One of three likely storm tracks may develop (Figure 10.21):

1. A storm heads toward the east coast of Florida, sometimes passing over islands such as Puerto Rico, and then, before striking the land, it moves out into the Atlantic to the northeast.

Figure 10.20 Storm surge and high waves produced by Hurricane Gloria on September 27, 1985, in New Jersey. *(Ryan Williams/International Stock Photography Ltd.)*

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Figure 10.21 Hurricane paths Three common paths of hurricanes in the Atlantic.

2. A storm travels over Cuba and into the Gulf of Mexico to strike the Gulf Coast.
3. A storm skirts along the East Coast and may strike land from central Florida to New York. Storms that may develop into hurricanes are closely monitored from both satellites and specially designed aircraft that fly through the storms.

Hazards presented by hurricanes include high winds that may rip shingles and rafters from roofs, blow over large trees and utility lines, and generally wreak havoc on structures built by people. The processes that kill most people and often cause the most damage, however, are (1) flooding resulting from intense precipitation and landward transport of wind-driven waves of ocean waters and, as previously mentioned, (2) storm surges.[15]

The probability that a hurricane will strike a particular 80 km (50 mi) coastal segment of the Atlantic or Gulf Coast in a given year is shown in Figure 10.22. Notice that the probabilities are particularly high in southern Florida and on the Louisiana coastline.

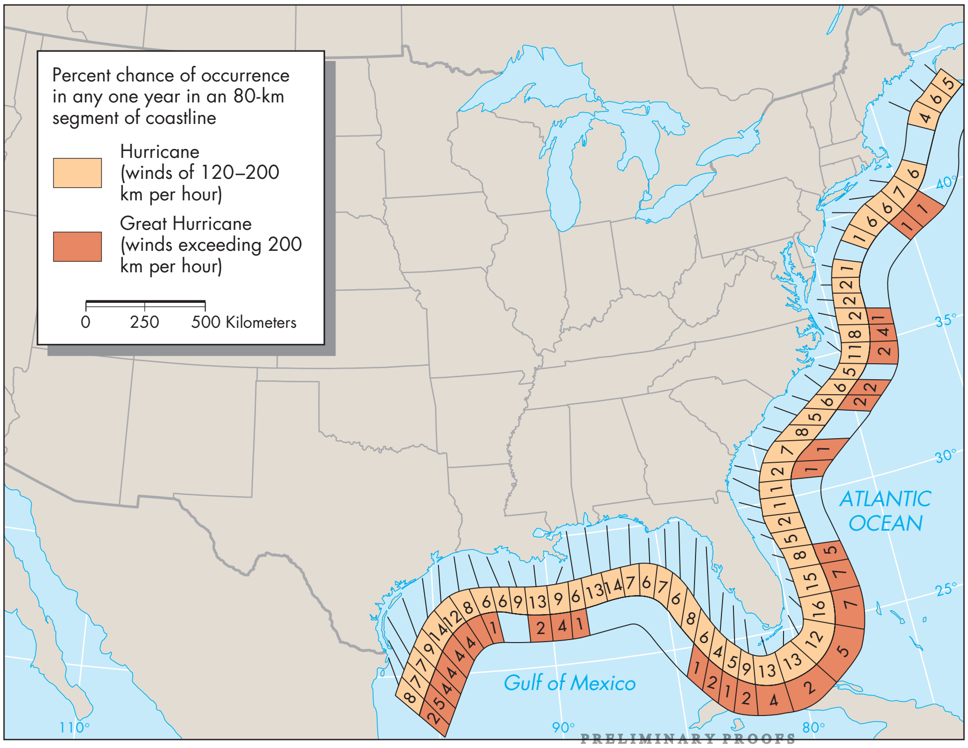

Figure 10.22 Hurricane hazard map Probability that a hurricane will strike a particular 80 km (50 mi) south Atlantic coastal segment in a given year. *(From Council on Environmental Quality, 1981. Environmental trends)*

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Property damage from hurricanes can be staggering (recall Hurricane Katrina). As another example, consider Hurricane Andrew, which struck Florida in August 1992. The storm was one of the costliest storms in U.S. history, with estimated damages in excess of $25 billion. Despite evacuation, 23 lives were lost as a direct result of the storm, and 250,000 people were temporarily rendered homeless. Damages to homes and other buildings were extensive: About 25,000 homes were destroyed as entire neighborhoods in Florida were flattened (Figure 10.23).[16] More than 100,000 buildings were damaged, including the National Hurricane Center in

(a)

(b)

(c)

Figure 10.23 Hurricane across Florida and the Gulf of Mexico (a) Hurricane Andrew, August 25, 1992, as shown on a multispectral image. The storm has left south Florida, where it did extensive damage, and is moving toward Louisiana. *(Courtesy of Hasler, Pierce, Palaniappan, Manyin/NASA Goddard Laboratory for Atmospheres)* (b) Lighthouse at Cape Florida in Biscayne Bay, Miami, Florida, before the arrival of the hurricane. *(Wingstock/Comstock Images)* (c) The same coastline after the hurricane. *(Cameron Davidson/Comstock Images)*

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Florida, where a radar antenna housed in a protective dome was torn from the roof.[16] Two hurricanes in the summer of 1996 struck the North Carolina coast. The second storm in August caused about $3 billion in property damage and killed more than 20 people. Although the population has increased along the Atlantic and Gulf Coasts, the loss of lives from hurricanes has decreased significantly because of more effective detection and warning. The amount of property damage, however, has greatly increased.

There is concern for large cities such as Miami and New Orleans (especially after experiencing Katrina in 2005). Unsatisfactory evacuation routes, building codes, and disaster preparedness may contribute to another catastrophic hurricane along the Atlantic or Gulf Coast.

10.7 Perception of and Adjustment to Coastal Hazards

Perception of Coastal Erosion

An individual's past experience, proximity to the coastline, and probability of suffering property damage all play primary roles in the perception of coastal erosion as a natural hazard. One study of coastal erosion of seacliffs near Bolinas, California, 24 km (15 mi) north of the entrance to the San Francisco Bay, established that people living close to the coast in an area likely to experience damage in the near future are generally very well informed and see the erosion as a direct and serious threat.[17] People living a few hundred meters from a possible hazard, although aware of the hazard, know little about its frequency of occurrence, severity, and predictability. Still farther inland, people are aware that coastal erosion exists but have little perception of it as a hazard.

Adjustment to Coastal Hazards

Tropical Cyclones. People adjust to the tropical cyclone hazard either by doing nothing and bearing the loss or by taking some kind of action to modify potential loss. For example, homes in hurricane-prone areas may be constructed to allow the storm surge to pass under the house (Figure 10.24). Community adjustments include attempts to modify potential loss by strengthening the environment with protective structures and land stabilization and by adapting better land-use zoning, evacuation procedures, and warning procedures.[18] Some general guidelines of what to do before, during, and after a hurricane are listed in Table 10.2.

Figure 10.24 Hurricane resistant house Home in the Florida Keys, constructed with strong blocks to withstand hurricane force wind and space below to allow the flow of a storm surge beneath the building. *(Edward A. Keller)*

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TABLE 10.2 What to Do Before, During, and After a Hurricane

Before a Hurricane	• Probably the most important thing you can do before a hurricane is to plan your evacuation route. The plan should include information concerning the safest evacuation route as well as locations of nearby shelters. Be prepared to drive inland to a safe place 13 to 31 km (20 to 50 mi).
	• Prepare a disaster kit, including flashlight with extra batteries, portable battery-operated radio, first-aid kit, emergency food and water, can opener, necessary medicines, cash and credit cards, and change of clothes, including sturdy shoes.
	• Make arrangements to care for your pets. Pets may not be allowed in emergency shelters.
	• Have a family plan on how to respond after a hurricane, and be sure that members of the family know how to turn off household gas, electricity, and water.
	• Teach young children when and how to call for emergency assistance from police or fire departments and which radio stations to listen to for emergency information.
	• Protect your windows with permanent shutters or be prepared to use plywood panels cut to fit each window. It is important to put up window protection long before the storm arrives.
	• Homeowner insurance policies do not cover damage from flooding that accompanies a hurricane, so obtain flood insurance.
	• Develop a family emergency communication plan. Family members may be separated during a disaster. Your plan should include how you are going to get back together.
	• Ask an out-of-state relative or friend to serve as your family contact. After a hurricane, it is often easier to call long distance than within your area. Be sure everyone in your family knows the name, address, and phone number of the family contact.
	• Hurricanes are generally spotted far out at sea days before they strike land. A hurricane watch is issued when there is a threat that hurricane conditions will occur within 24 to 36 hours. A hurricane warning is issued when hurricane conditions are expected in 24 hours or less.
During a Hurricane Watch	• Listen to your television or radio for hurricane progress reports.
	• Check emergency supplies.
	• Be sure there is fuel in your car.
	• Bring inside outdoor objects such as lawn furniture, toys, and garden tools. Objects that cannot be brought inside should be anchored.
	• Secure your home and other buildings by closing and boarding up windows.
	• Remove outside antennas or satellite dishes.
	• Because power outages are likely during a storm, turn your refrigerator and freezer to the coldest possible settings and open them only when absolutely necessary.
	• Store drinking water in clean bathtubs, bottles, and cooking utensils.
	• Review with your family your evacuation plan.
	• If you have a boat, be sure it is secure or moved to a designated safe place.
During a Hurricane Warning	• Listen constantly to television or radio for official instructions.
	• If you live in a mobile home, check your tiedowns and evacuate immediately.
	• Store your valuables and personal papers in waterproof containers in the highest level of your home.
	• Avoid elevators.
	• Stay inside and away from windows, skylights, and glass doors.
	• Keep a supply of flashlights and extra batteries on hand. Avoid using open flames such as candles or kerosene lamps.
	• If electrical power is lost, turn off major appliances to reduce power surges when electricity is restored.
	• If officials indicate that evacuation is necessary, leave as soon as possible, avoiding flooded roads and washed-out bridges. Secure your home by unplugging appliances and turning off electricity and the main water valve. Let someone outside the storm area know where you are going. If time permits, move furniture to protect it from flooding (if possible, move it to a higher floor). Load preassembled emergency supplies and warm protective clothing, including sleeping bags and blankets. Finally, lock up your home and leave!
After a Hurricane	• Stay tuned to local radio and television for information.
	• Assist injured or trapped persons. Do not move seriously injured persons unless they are in immediate danger. Call for help.
	• Return to your home only after authorities have advised you that it is safe to do so.
	• When you return home, be aware of the possibility of dangling power lines, and enter your home with caution. Be aware of snakes, insects, and animals that may have been driven to higher ground by floodwaters. Open your windows and doors to ventilate and dry your home. Check your refrigerator for foods that may have spoiled. Finally, take pictures of the damage to both the house and its contents for insurance purposes.

Source: Modified after Federal Emergency Management Agency Fact Sheet: Hurricanes. www.fema.gov/library/hurricaf.htm. Accessed 5/10/2001.

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Coastal Erosion. Adjustments to coastal erosion generally fall into one of three categories:

- Beach nourishment that tends to imitate natural processes, the "soft solution"
- Shoreline stabilization through structures such as groins and seawalls, the "hard" solution
- Land-use change that attempts to avoid the problem by not building in hazardous areas or by relocating threatened buildings

A preliminary process in any approach to managing coastal erosion is estimating the rates of erosion. Esimates of future erosion rates are based on historical shoreline change or statistical analysis of the oceanographic environment, such as the waves, wind, and sediment supply that affect coastal erosion. Recommendations are then made concerning setbacks considered to be minimum standards for state or local coastal erosion management programs. A setback is the distance from the shoreline to where development, such as homes, is allowed. A small number of states (including Florida, New Jersey, New York, and North Carolina) use a setback distance for buildings based on the rate of erosion (see A Closer Look: E-Lines and E-Zones).[19] The concept of setback has real merit in coastal erosion management and is at the heart of land-use planning to minimize 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 the processes of erosion. The second road involves learning to live with coastal erosion through flexible environmental planning and wise land use in the coastal zone.[20,21] The first road follows history in our attempt to control coastal erosion through the construction of engineering structures such as seawalls. In the second road, structures in the coastal zone, with such exceptions as critical facilities in certain areas, are considered temporary and expendable. Development in the coastal zone must be in the best interests of the general public rather than for a few who profit from developing the oceanfront. This philosophy is at odds with the viewpoint 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 the inappropriate development of hazardous areas and areas better suited for uses other than building. In other words, beaches belong to all people to enjoy, not only to those fortunate enough to purchase beachfront property. The state of Hawaii has taken this idea to heart: There, all beaches are public property, and local property owners cannot deny access to others.

Accepting the philosophy that, with minor exceptions, coastal zone development is temporary and expendable and consideration should first be to the general public requires an appreciation of the following five principles:[20]

1. Coastal erosion is a natural process rather than a natural hazard; erosion problems occur when people build structures in the coastal zone. The coastal zone is an area where natural processes associated with waves and moving sediment occur. Because such an environment will have a certain amount of natural erosion, the best land uses are those compatible with change. These include recreational activities such as swimming and fishing.
2. Any shoreline construction causes change. The beach environment is dynamic. Any interference with natural processes produces a variety of secondary and tertiary changes, many of which may have adverse consequences. Adverse consequences are particularly likely when engineering structures, such as groins and seawalls, that affect the storage and flow of sediment along a coastal area are used.
3. Stabilization of the coastal zone through engineering structures protects the property of relatively few people at a large expense to the general public.

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A CLOSER LOOK | E-Lines and E-Zones

Recently, a special committee of the National Research Council (NRC) at the request of the Federal Emergency Management Agency (FEMA) developed coastal zone management recommendations,[19] some of which follow.

- Future erosion rates should be estimated on the basis of historical shoreline change or statistical analysis of the oceanographic environment (that is, the waves, wind, and sediment supply that affect coastal erosion).
- E-lines and E-zones based on erosion rates should be mapped (Figure 10.D). The *E* stands for erosion; for example, the E-10 line is the location of expected erosion in 10 years. The E-10 zone is considered to be an imminent hazard where no new habitable structures should be allowed. The setback distance depends on the erosion rate. For example, if the rate is 1 m (3.3 ft) per year, the E-10 setback is 10 m (33 ft).
- Movable structures are allowed in the intermediate and long-term hazard zones (E-10 to E-60) (see Figure 10.D).
- Permanent large structures are allowed at setbacks greater than the E-60 line.
- New structures built seaward of the E-60 line, with the exception of those on high bluffs or seacliffs, should be constructed on pilings to withstand erosion associated with a high-magnitude storm with a recurrence interval of 100 years.

NRC recommendations concerning setbacks are considered to be minimum standards for state or local coastal erosion management programs. A small number of states (including Florida, New Jersey, New York, and North Carolina) use a setback based on the rate of erosion; however, most states do not require this type of setback. Nevertheless, the concept of E-lines and E-zones based on erosion-designated setbacks and allowable construction has real merit in coastal zone management.

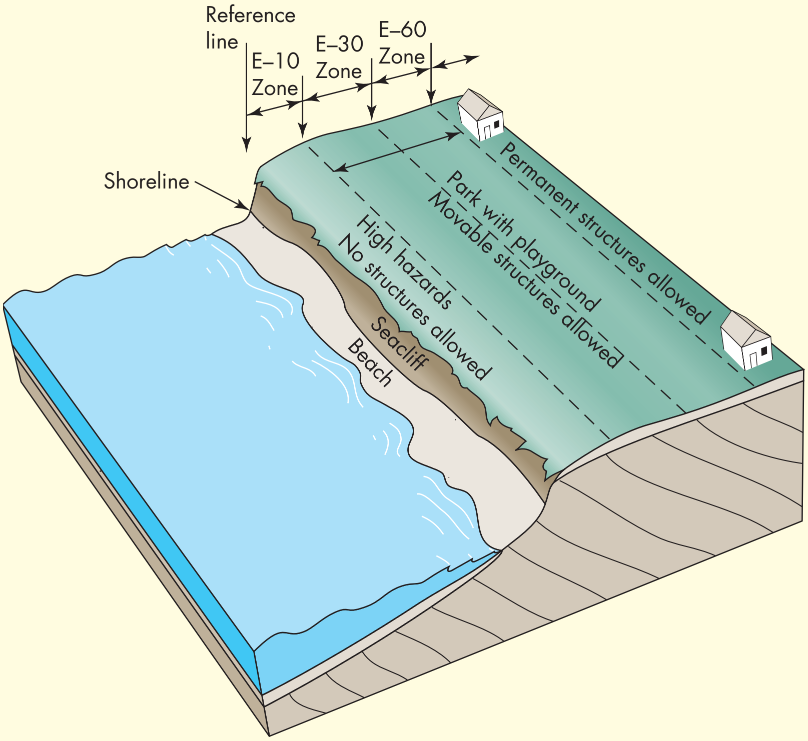

Figure 10.D Erosion hazard zones Idealized diagram illustrating the concept of the E-lines and E-zones based on the rate of coastal erosion from a reference point such as the seacliff or dune line. The width of the zone depends on the rate of erosion and defines a setback distance. Of course, even with setbacks based on 60 years of expected erosion (E-60 line), eventually, 60 years down the road, structures will be much closer to the shoreline and will become vulnerable to erosion. It is a form of planned obsolescence. *(From National Research Council. 1990. Managing coastal erosion. Washington, DC: National Academy Press)*

Engineering structures along the shoreline are often meant to protect developed property, not the beach itself. It has been argued that the interests of people who own shoreline property are not compatible with the public interest and that it is unwise to expend large amounts of public funds to protect the property of a few.

4. Engineering structures designed to protect a beach may eventually destroy it. Engineering structures often modify the coastal environment to such an

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extent that it may scarcely resemble a beach. For example, construction of large seawalls causes reflection of waves and turbulence that eventually narrow the beach.

5. Once constructed, shoreline engineering structures produce a trend in coastal development that is difficult, if not impossible, to reverse. Engineering structures often lead to additional repairs and larger structures, with spiraling costs. In some areas, the cost of the structures eventually exceeds the value of the beach property itself. For these and other reasons, several states have recently imposed severe limitations on future engineering construction intended to stabilize the coastline. As sea levels continue to rise and coastal erosion becomes more widespread, the nonstructural alternatives to the problem should continue to receive favorable attention because of both financial necessity and the recognition that the amenities of the coastal zone should be kept intact for future generations to enjoy.

If you consider purchasing land in the coastal zone, remember these guidelines:[21] (1) Allow for a good setback from the beach or seacliff; (2) be high enough above sea level to avoid flooding; (3) construct buildings to withstand adverse weather, especially high winds; and (4) if hurricanes are a possibility, be sure there are adequate evacuation routes. Remember, it is always risky to buy property where land meets water.

SUMMARY

The coastal environment is one of the most dynamic areas on Earth, and rapid change is a regular occurrence. Migration of people to coastal areas is a continuing trend, and approximately 75 percent of the population in the United States now live in coastal states.

Ocean waves are generated by storms at sea and expend their energy on the shoreline. Irregularities in the shoreline account for local differences in wave erosion; these irregularities are largely responsible for determining the shape of the coast. Beaches are most commonly formed by accumulations of sand or gravel that are deposited at the coast by rivers and shaped by wave action. Actually, beaches can form from any loose material, such as broken shells or coral or volcanic rock, located in the shore zone. Waves striking a beach at an angle result in longshore transport of the beach sediments.

Rip currents are a serious hazard to swimmers, killing up to 200 people a year in the United States. They can be recognized and avoided, and it is possible to escape from them if you do not panic.

Although coastal erosion causes a relatively small amount of property damage compared with other natural hazards such as river flooding, earthquakes, and tropical cyclones, it is a serious problem along all the coasts of the United States, including the shorelines of the Great Lakes. Factors contributing to coastal erosion include river damming, high-magnitude storms, and the worldwide rise in sea level.

Human interference with natural coastal processes such as the building of seawalls, groins, breakwaters, and jetties is occasionally successful, but in many cases it has caused considerable coastal erosion. Sand tends to accumulate on the updrift side of the structure and erode on the downdrift side. Most problems occur in areas with high population density, but sparsely populated areas along the Outer Banks in North Carolina are also experiencing trouble with coastal erosion. Beach nourishment has had limited success in restoring or widening beaches, but it remains to be seen whether it will be effective in the long term.

The most catastrophic coastal hazard is the tropical cyclone. Also called typhoons and hurricanes, tropical cyclones are violent storms that bring high winds, storm surges, and river flooding. They continue to take thousands of lives and to cause billions of dollars in property damage.

Perception of the coastal erosion hazard depends mainly on the individual's experience with and proximity to the hazard. Community and individual adjustments to tropical cyclones generally attempt to modify the environment by building protective structures designed to lessen potential damage or to encourage change in people's behavior by better land-use zoning, evacuation, and warning.

Adjustment to coastal erosion in developed areas is often the "technological fix": building seawalls, groins, and other structures or (more recently) using beach nourishment. These approaches to stabilizing beaches have had mixed success and may cause additional problems in adjacent areas. Engineering structures are very expensive, require maintenance, and, once in place, are difficult to remove. The cost of engineering structures may eventually exceed the value of the properties they protect; such structures may even destroy the beaches they were intended to save. Managing coastal erosion will benefit from careful land-use planning that emphasizes establishment of designated setbacks and allowable construction determined by predicted rates of coastal erosion.

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Revisiting Fundamental Concepts

Human Population Growth

Many populated areas are located near the coast, and human population in the coastal zone is expected to continue to increase. As a result, potential impacts of coastal hazards will increase.

Sustainability

Coastal areas contain some of the most scenic and valuable property on Earth. In order to maintain a quality environment in the coastal zone, we must develop plans to sustain our coast for future generations. Sustaining the coast will involve learning to live with and adjust to coastal hazards through land-use planning that maintains the integrity of the coastal environment.

Earth as a System

Coastal environments are complex systems where rapid change is often the norm. Learning to live with change in the coastal environment is a necessity.

Hazardous Earth Processes, Risk Assessment, and Perception

The most hazardous processes in the coastal environment are coastal erosion and erosion and flooding associated with tropical cyclones. The impacts of these hazards are increasing as a result of increased development in the coastal zone and global climate change, which is causing a rise in sea level. In general, people living in the coastal zone are aware of potential hazards and there have been many studies in coastal areas to evaluate risk and appropriate adjustments so that loss of life and property may be minimized.

Scientific Knowledge and Values

It is clear that people value the coastal environment. Scientific knowledge concerning coastal processes is a mature field of study, and in general we know where hazards are most likely to occur and what their potential impacts are. Solutions to reducing coastal hazards vary from building hard engineering structures to reduce damage, to softer approaches that allow us to live in the coastal zone and adjust to hazards. The solution we choose for a particular site depends in part upon how we value the coastal zone. For example, if a row of beach homes is being threatened by erosion, the choices may be building a seawall, which would eventually cause the loss of the beach, or moving the homes inland out of harm's way.

Key Terms

beach (p. 328)
beach-budget (p. 332)
beach nourishment (p. 336)
breakwater (p. 336)
groins (p. 336)
hurricane (p. 343)
jetties (p. 337)
longshore sediment transport (p. 330)
rip current (p. 330)
seacliff (p. 332)
seawall (p. 336)
storm surge (p. 345)
tropical cyclone (typhoon) (p. 343)

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Review Questions

1. How does wave refraction at a rocky point result in concentration of wave energy at the point?
2. What is the difference between plunging and spilling breakers?
3. What are the processes of longshore transport of sand?
4. What are some of the human activities that can increase seacliff erosion?
5. What are some of the important differences in coastal processes and beach erosion between the East and West Coasts of the United States?
6. What are the major alternatives to stabilize a coast? Which is preferred in a particular situation? Why?
7. What are seawalls and groins, and why are they constructed? What is their effect on erosion and coastal processes?
8. What are the processes important in the formation of a hurricane?
9. What is the process of beach nourishment, and what is its objective?
10. What are the major factors causing erosion problems for the Great Lakes?
11. What is storm surge, and how is it produced?
12. What are the three major adjustments to coastal erosion?
13. What are the five general principles that should be accepted if we choose to live with rather than control coastal erosion?

Critical Thinking Questions

1. Do you think that human activity has increased the coastal erosion problem? Outline a research program that could test your hypothesis.
2. Do you agree or disagree with the statements that all structures in the coastal zone (with the exceptions of critical facilities) should be considered temporary and expendable and that 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.
3. A beach park is experiencing coastal erosion. Some want to protect the park with a restaurant, parking lots, outhouse and lawn at any cost—not loose a blade of grass. That would require a hard solution such as a seawall. Others want to maintain the sand beach and use a more flexible approach to the erosion. They argue for beach nourishment and planned retreat. Both groups have clearly stated their values. What are the pros and cons for each position? Can the two views be considered simultaneously?

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